Crash avoidance by Electronic Stability Control on Australian high speed rural roads: an analysis of braking interventions

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ABSTRACT

International and Australian research has found that there are significant benefits to road safety associated with the addition of Electronic Stability Control (ESC) to passenger vehicles. The greatest benefit to Australia is for crashes on high speed rural roads that occur due to a loss of control.

An investigation of what variables in the South Australian statewide crash database are associated with high injury severity for vehicle occupants during crashes on high speed rural roads was conducted. For specifically single vehicle crashes on high speed rural roads, a higher speed limit, the hours of darkness, and an earlier crash year were found to be the major indicators of a high injury severity outcome.

A complementary investigation of high speed rural road crashes that were a result of a loss of control was also conducted. This required the development of a method for identifying loss of control crashes using available variables from the South Australian statewide crash database. It was estimated that, per year in South Australia, 561 injury crashes on high speed rural roads are the result of a loss of control including 33 fatal crashes and 208 crashes resulting in injuries requiring hospital admission.

While literature from ESC manufacturers clearly explains the theory behind how ESC operates, no research has directly investigated what braking

interventions are made by ESC during real world situations where a vehicle not equipped with ESC would have crashed. More specifically, no research has investigated how braking interventions affect vehicle trajectory and enable a collision to be avoided. Also of interest is how the effect of interventions are altered when combined with other rural road safety features such as lower travelling speeds, sealed roadside shoulders, and sealed roads.

Crash scenarios, developed based on high speed rural road crashes, were simulated using a vehicle model (with a corresponding ESC model) supplied by Bosch Australia. The simulation method included processes such as dynamic testing of the vehicle model, use of a driver model, and trajectory matching through optimisation. Each crash scenario was simulated using the vehicle model without ESC active and then again using the vehicle model with ESC active. The differences in vehicle trajectory and the braking interventions responsible for those differences were then analysed. The crash scenario simulations were also altered to represent the presence of specific rural road safety measures in order to investigate how ESC braking interventions were affected. However, this process was found to render the results unreliable and no analysis of how ESC was affected by the rural road safety measures was possible.

The results of simulating each crash scenario were presented in figures that show when braking interventions are made and how they affect vehicle trajectory. Vehicle trajectory was analysed by investigating how ESC affected vehicle sideslip, lateral offset, and yaw. The strength and duration of individual braking interventions were then analysed which included an investigation of how they were affected by travelling speed and how they compare to braking interventions elicited during ESC effectiveness tests.

STATEMENT OF ORIGINALITY

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LIST OF ABBREVIATIONS

CASR	Centre for Automotive Safety Research
ESC	Electronic Stability Control
FWD	Front wheel drive
LOC	Loss of control
NHTSA	National Highway Traffic Safety Authority
RWD	Rear wheel drive
SAPOL	South Australian Police
TARS	Traffic Accident Reporting System

1. INTRODUCTION

On the 21st of October 1997, five motoring journalists were reviewing the new Mercedes Benz A-Class in Sweden. As part of the review process the vehicle's performance during certain test manoeuvres was being evaluated. One such manoeuvre, called the 'Moose' test, simulates a situation in which a driver must suddenly swerve to avoid an object on the road and then quickly steer back into the correct lane.

Robert Collin, the driver for this particular manoeuvre, entered the course at a speed of 60 km/h. As Collin began to steer through the 'Moose' test manoeuvre the back end of the vehicle began to slide to the right. The slide to the right stopped and suddenly reversed back to the left very quickly. Collin unsuccessfully fought back with the steering wheel as the vehicle began to tip towards the drivers side. The vehicle then suddenly vaulted back up and crashed down heavily on the passenger side.

Collins's first thoughts were for his four colleagues and, after pulling himself from the vehicle, he called an ambulance. Later, he realised that this was big news and called Swedish television. The resulting media storm hit Mercedes Benz hard. The prestigious German manufacturer was initially shocked and responded slowly, but eventually implemented one of the biggest vehicle recalls in history. All A-Class vehicles would have their chassis upgraded and *be fitted with ESC.*

The events of that day are considered to have considerably increased the recognition of the need for ESC and its subsequent widespread deployment.

A motor vehicle is a complex system with many degrees of freedom. Each of the four wheels can rotate forwards and backwards, with the front wheels also able to turn left and right. Mounted upon the wheels is a suspension system that allows the vehicle cabin to pitch, roll, and soften the impact of vertical motion. Further still is a complex drive train, braking system, and steering system.

As human beings have a limited mental capacity, it would be impossible to expect any driver to intelligently control every aspect of a vehicle at once. The controls normally operated by a driver are therefore limited to steering, braking and acceleration while other more complex aspects of vehicle operation are mechanically/electrically self regulated (e.g. the differential) or fixed (e.g. the suspension spring rate). However, even the processes of steering, braking, and acceleration involve complex interactions with other aspects of the vehicle or road surface which ordinary drivers may be unaware of.

Vehicle designers have endeavoured to limit the driver's exposure to such complex interactions as much as possible and to produce a vehicle that is easy to drive. Advances in steering mechanisms, tyres, suspensions, drive trains, and general vehicle design have resulted in a vehicle that responds to a driver's inputs in a smooth and predictable fashion under normal driving conditions. For example, as a driver pushes harder upon the brake pedal there will be a corresponding quasi-linear increase in the level of braking.

However, every vehicle has a physical limit to the driving performance it can achieve. There is a limit to how quickly a vehicle can brake to a stop from a given speed, a limit to the radius of a corner a vehicle can successfully navigate at a given speed, and so on.

A critical driving situation occurs when a vehicle approaches this physical limit. This usually occurs when there is a sudden change in the driving course (e.g. an object appears that must be avoided) or when a driver misjudges what is an appropriate speed for the road ahead. During these critical driving situations, where a vehicle is close to the limit of it's driving capabilities, the response of the vehicle to the driver's inputs often becomes non-linear. The tyres may begin to skid and pushing the brake or turning the steering wheel will no longer yield the expected response. In most cases the response of the vehicle is more restrained than expected. Additionally, in a critical driving situation most drivers are overburdened with the task of stabilising the vehicle and are typically startled by the altered vehicle behaviour. This often results in the driver taking inappropriate actions which fail to stabilise the vehicle and may even cause a further reduction in stability.

In recent years modern vehicle designers have made good progress in assisting drivers through the use of in-vehicle electronic systems that intervene during critical driving situations. The systems intervene to either prevent a vehicle from entering a situation where the response to driver inputs becomes non-linear, or to adjust the response of the vehicle so that it corresponds to what the driver expects. For example an anti-lock brake system (ABS) intervenes by precisely regulating the amount of brake pressure, requested by the driver, which passes to the brakes. This ensures that the wheels do not become locked so that maximum braking and steerability are maintained.

Electronic Stability Control (ESC) is another in-vehicle electronic system which builds upon the benefits of ABS, by utilising the ability to brake individual wheels, to regulate the yaw rate of a vehicle during critical driving situations. ESC compares a driver's steering intentions with the vehicle's current heading and intervenes to reduce any difference to an acceptable level. ESC is also able to reduce engine torque and boost general braking forces if required. The actions of ESC result in a vehicle that will endeavour to steer where the driver intends and be far less likely to spin out during cornering. ESC therefore allows an ordinary driver to maintain heading and stability right up to the physical limit of their vehicle.

The first commercial vehicles were fitted with ESC in 1995 (van Zanten, 2000). Initially the system was available only on luxury model vehicles and limited to a small number of manufacturers. Over time, the number of vehicle models and manufacturers offering the system increased. By 2003, enough vehicles were equipped with ESC that it was possible to begin evaluations of effectiveness. Early studies of ESC effectiveness found large reductions in the crash rate of ESC equipped vehicles (Aga & Okada, 2003; Tingvall et al., 2003). However, these early results were viewed with scepticism as sample sizes were small and tended to consider only luxury model vehicles which were not representative of the general vehicle fleet. Another reason for scepticism was that early evaluations of the effectiveness of ABS technology showed large crash reductions but later studies, that were able to use a greater sample size and conduct more thorough analyses, concluded that the effectiveness was actually much smaller (Kahane & Dang, 2009).

This was not the case with ESC and subsequent studies of effectiveness continued to find large reductions in the crash rate of ESC equipped vehicles (Bahouth, 2005, 2006; Dang, 2004, 2007; Farmer, 2004, 2006; Green & Woodrooffe, 2006; Lie et al., 2005; Scully & Newstead, 2007; Thomas, 2006; Thomas & Frampton, 2007). Despite each of the effectiveness studies utilising differing methods and data sources all concluded similar results; most notably, a significant reduction of up to 50 per cent in single vehicle crash rates for vehicles equipped with ESC. Even greater effectiveness was reported for specific types of crash, such as those that occurred on high speed roads, those that occurred due to a loss of control, and especially for those that resulted in fatal injuries. As a result, the main benefits of ESC for Australia are expected to be on the extensive high speed, rural road network upon which over half of annual road fatalities occur (Infrastructure and Surface Transport Policy, 2009).

The way in which ESC uses braking interventions to improve the lateral stability of a vehicle is clearly understood (van Zanten, 2000; van Zanten et al., 1995, 1999). Furthermore, the effect that ESC braking interventions have on common test track manoeuvres have been explored (Forkenbrock et al., 2005) and a criteria that dictates a minimum satisfactory level of effectiveness during one such test manoeuvre has been developed (Forkenbrock & Boyd, 2007; Forkenbrock et al., 2006). However, in any particular critical driving situation the actions of an ESC system will depend on many factors. The vehicle, the environment (road surface friction, road alignment, etc), and the driver will all affect how an ESC system responds. As such, the effectiveness of an ESC system's actions will vary uniquely from situation to situation.

A more comprehensive investigation of how ESC braking interventions affect crashes than that provided by the evaluation studies mentioned earlier may therefore be of interest. A better understanding of the role that ESC braking interventions play in altering vehicle trajectory should be sought. Furthermore, the interaction between these braking interventions and other rural road safety conditions should be investigated.

Through an understanding of how braking interventions are able to keep a vehicle stable during a critical driving situation, where it would have otherwise crashed, the full potential of ESC can be realised. By also understanding how ESC effectiveness is altered by other rural road safety conditions, road infrastructure can be designed to take advantage of the benefits it provides (or to cover the areas where the benefit is limited) and road safety funding can be allocated appropriately. For example, success of ESC could lead to a switch of infrastructure treatments from midblock lengths of road to intersections.

This thesis seeks to investigate what braking interventions are made by ESC during high speed rural road crashes in Australia and how the interventions affect vehicle trajectory. In addition, the interaction between ESC and rural road safety measures, such as slower travelling speeds, sealed shoulders, and sealed roads, will also be investigated. Finally, the appropriateness of the minimum ESC effectiveness criteria will be explored by comparing the interventions made in response to high speed rural road crashes to those made during the appropriate test manoeuvre.

Chapters 2 and 3 provide background on the topic for the reader and are useful in understanding the methods and results presented in the main analysis chapters. An overview of the principles of vehicle dynamics relevant to the operation of ESC are presented in Chapter 2. Building upon this, the operation of ESC is then explained with reference to how individual braking interventions are applied. Chapter 3 presents a review of relevant existing research regarding ESC and the effect it has on crashes. The extensive literature on the effectiveness of ESC in avoiding crashes is summarised and discussed. Studies that investigate methods to assess the performance of ESC during test manoeuvres are also reviewed.

The relationship between crash severity and other crash variables during high speed rural road crashes is explored in Chapter 4 using data from the South Australian statewide crash database. As an extension to this, Chapter 5 establishes a method for identifying loss of control crashes in the statewide database to estimate the prevalence of crashes that are likely to be affected by the widespread implementation of ESC.

The concept of using crash simulations to investigate the interventions made by ESC is introduced and explored in Chapter 6. Suitable simulation software is identified and two vehicle models with corresponding ESC models were supplied for use by BOSCH Australia. The validity of these vehicle and ESC models are explored through various means. Next, a set of ten loss of control scenarios typical of high speed rural roads in South Australia are defined based on in-depth crash investigation data. Finally, methods to identify simulation parameter values that accurately model the environment, circumstances, and loss of control trajectory in each scenario are developed.

These methods are put into practise in Chapter 7 where, for each scenario, simulations using a vehicle without ESC are compared to simulations using a vehicle with ESC. The resulting change in vehicle trajectory as a consequence of ESC is presented and the ways in which these changes would have altered the outcome of each scenario are discussed.

The details of the braking interventions made by ESC during the simulation of each scenario are presented in Chapter 8. The characteristics of the ESC braking interventions are then discussed, along with analysis of how the characteristics are affected by vehicle speed and road surface friction.

In Chapter 9 the findings of the previous chapters are summarised and a discussion on how the thesis aims have been addressed is presented. Some suggestions for possible future work are then provided.

2. BACKGROUND

This chapter presents various background information on Electronic Stability Control (ESC). It is split into three sections. The first section explains several vehicle dynamics concepts that are necessary for a proper understanding of later chapters. The second section investigates the origins of modern ESC, and the way in which ESC operates is covered in section three.

2.1 Vehicle dynamics

This section presents an overview of four critical principles of vehicle dynamics: longitudinal wheel forces, lateral wheel forces, traction circles, and vehicle body states. This overview is intended to assist the reader's understanding in later parts of the thesis. A more complete and comprehensive description of the principles can be found in vehicle dynamics publications such as Gillespie (1992, chapters 3, 6, & 10) or Milliken & Milliken (1995, chapters 2, 5, 18, 19, & 20).

There are some differences in the mechanisms that govern low speed vehicle dynamics compared to those that govern high speed vehicle dynamics. Low speed dynamics are not of interest here and the principles explained are applicable explicitly for vehicles travelling at high speed (above approximately 50 km/h).

2.1.1 Longitudinal wheel forces

A wheel, with radius r, that is rotating freely with an angular velocity of ω has a forward velocity described by Equation 2.1. The forward velocity of a vehicle that is coasting (i.e. is not experiencing any kind of forwards or backwards force) is equal to the forward velocity of the wheels.

$$v = \omega r \tag{2.1}$$

When a wheel is braking, the tyre stretches and deforms at the contact patch due to the elastic properties of the rubber elements within the tyre. Because of this stretching and deforming, the outer edge of the tyre has a reduced forward velocity compared to the vehicle. Figure 2.1 illustrates this where ωr is the forward velocity of the circumference of the tyre and v is the forward velocity of the vehicle. For a wheel that is accelerating the mechanism is the same but in the opposite direction. This difference between wheel and vehicle forward velocity is described as 'wheel slip' and is defined by Equation 2.2. A wheel with 0% slip is free rolling, while a wheel with 100% slip is skidding (or locked).

$$\text{wheel slip} = \frac{v - \omega r}{v} \tag{2.2}$$

Figure 2.2 shows the relationship between wheel slip and the brake force supplied by the wheel. Three phases are apparent. The first is the linear phase (0% - 20% slip), where brake force increases linearly with wheel slip. The second phase (around 20% slip) is the transitional phase, where brake

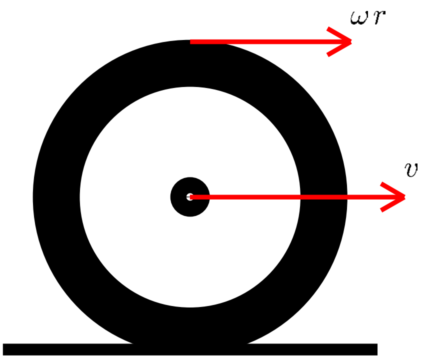


Fig. 2.1: Difference between wheel and vehicle forward velocity

force reaches its maximum. The last phase is the unstable phase (20% - 100% slip), where brake force decreases as wheel slip increases.

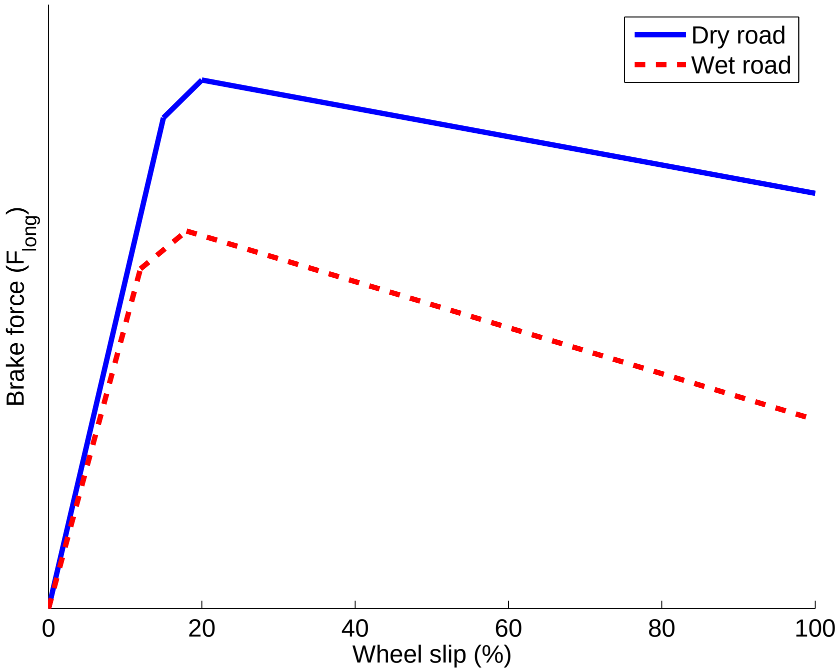


Fig. 2.2: Brake force vs wheel slip [adapted from Gillespie (1992)]

As a driver pushes the brake pedal, brake pressure builds and the amount of wheel slip increases. In the linear phase, by adjusting the amount of wheel slip, through the use of the brake pedal, it is easy to control and predict brake force. The transitional phase is a tipping point where any increase in wheel slip will move the wheel into the unstable phase. In the unstable phase the amount of wheel slip progresses very quickly towards 100%, even without any increase in brake pressure (hence the instability).

The slope in the linear phase, and the maximum brake force for a given tyre at a certain point in time, depend upon a number of wheel attributes. Some of these attributes are static in that they do not change appreciably over a short period of time: tyre construction properties, tyre condition, inflation pressure and temperature. Other attributes are dynamic, in that they can change significantly over a short amount of time. The two major dynamic attributes are the vertical force on the wheel and the coefficient of friction between the tyre-road pair.

An example of the effect of a change in one of the dynamic attributes is shown in Figure 2.2. The coefficient of friction between a tyre and a wet road is lower than that of a dry road and so the brake force, at a given level of wheel slip, is reduced. The same effect occurs if the vertical load upon the wheel is reduced.

2.1.2 Lateral wheel forces

When a wheel is turned, the contact patch with the road is stretched and deformed in the direction of travel. This is illustrated in Figure 2.3 where the wheel is travelling in the direction of the arrow. The rubber elements within the tyre are initially aligned with the direction of heading but at the contact patch the elements are stretched to run parallel with the direction of travel. Then, upon exiting the contact patch, the elements return to the direction of heading once again. This process causes a lateral force to be generated in the direction of stretching.

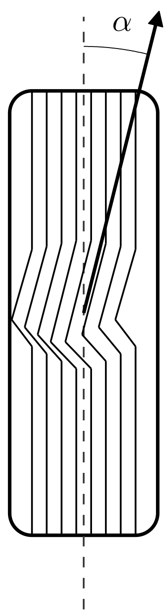


Fig. 2.3: Wheel slip angle

The angle between the wheel's direction of heading and its direction of travel is called the slip angle, α. The relationship between slip angle and lateral force is similar to that of wheel slip and longitudinal force. At low levels of slip angle (0 - 5 degrees), lateral force increases linearly. The level of lateral force then peaks in a transition zone, before decreasing for higher values of slip angle where the tyre is said to be skidding.

Within the linear phase the lateral force generated by a turning tyre can be represented by Equation 2.3, where C is a constant and depends upon the construction of the tyre.

Changes in vertical load and coefficient of friction affect lateral force in the same way that they affect longitudinal tyre force.

$$F_{lat} = C\alpha \tag{2.3}$$

2.1.3 Traction circle

A traction circle is used to visualise the result of the longitudinal and lateral force components a wheel creates during its interaction with the road surface. The forwards/backwards force in the longitudinal direction is labelled F_{long}, where acceleration is positive and braking is negative. The sideways/cornering force in the lateral direction is labelled F_{lat}, where a force to the right is positive and a force to the left is negative.

An example of a traction circle is shown in Figure 2.4. The line indicates the magnitude and direction of the force generated by the wheel as a result of the combination of F_{long} and F_{lat}. In the example shown, the wheel is braking and supplying a small force to the right.

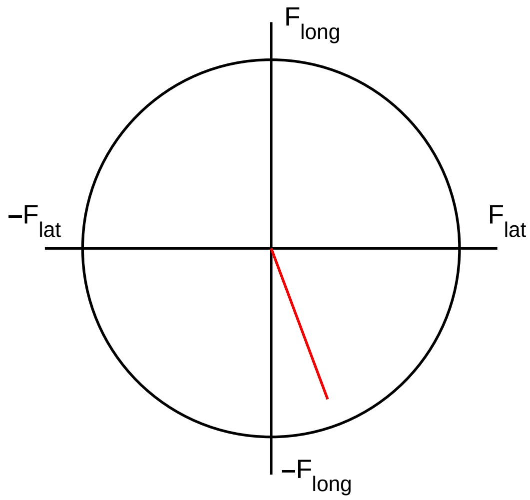


Fig. 2.4: Traction circle

The circle perimeter represents the maximum force which the tyre can supply in any given direction. The circle should, in reality, be an ellipse since a tyre can typically supply more force in the longitudinal direction than the lateral direction but will be left portrayed as a circle for simplicity. Vertical force upon the wheel and the coefficient of friction between the tyre-road pair are important factors that affect the radius of the traction circle during driving. A sudden reduction in the radius of the traction circle will reduce the effective force of the wheel, which in turn limits the overall ability of the vehicle.

A change in the vertical tyre force is usually the result of the behaviour of a vehicle's suspension system. Braking causes the rear wheels to unload while the front wheels become loaded. Conversely, accelerating causes the front wheels to unload while the rear wheels become loaded. During cornering, the inside wheels become unloaded and the outside wheels become loaded. During more drastic manoeuvres, this effect becomes more severe and abrupt.

A change in the coefficient of friction can occur where there is a change in the road surface condition (e.g. patches of water or ice) or at the interface between two surface types (e.g. the bitumen road and the gravel shoulder).

Each of the four wheels on a vehicle can be represented by its own traction circle and the force from each wheel combines to manoeuvre the vehicle. Figure 2.5 shows an example of a set of four traction circles used to describe the motion of a vehicle. The top circles correspond to the front wheels and the bottom circles to the rear. There are two indications as to the motion of the vehicle in this example. The first is that the circles at the rear and right side wheels are larger than those at the front and left side. This suggests that the vehicle is both accelerating and turning left. The second indication is the force lines themselves which confirm that the vehicle is indeed turning left and accelerating. The front wheels are producing a force to the left, generated by turning the wheels to the left. The rear wheels are producing a forward force, generated by the engine supplying a forward torque to the wheels.

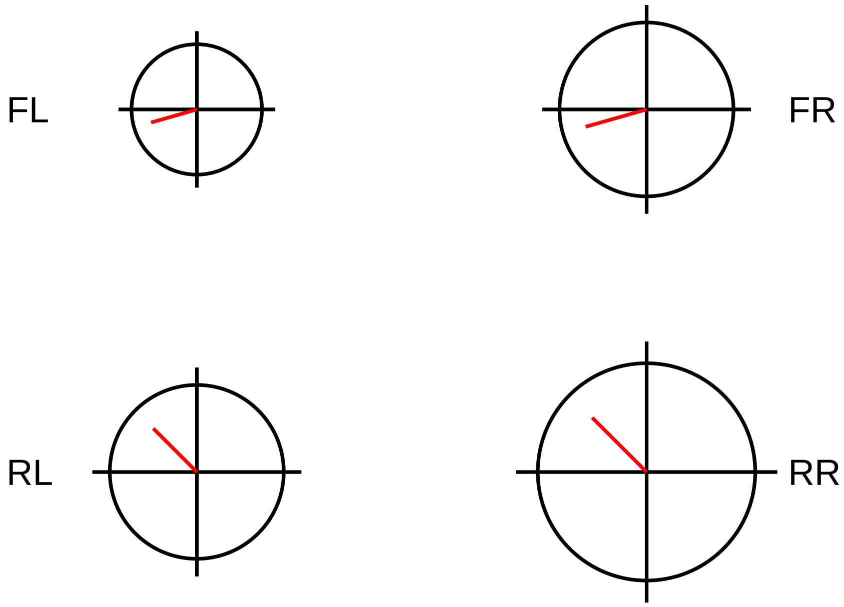


Fig. 2.5: Example of a set of traction circles

2.1.4 Vehicle body kinematics

Assuming a flat surface, the combined lateral and longitudinal forces from each of the wheels affect the kinematics of the overall vehicle body in three degrees of freedom: longitudinal motion, lateral motion and yaw. The kinematics, and characteristics of a vehicle can be represented as shown in Figure 2.6, where:

δ_{fl}: steer angle (front left)

δ_{fr}: steer angle (front right)

β: side slip angle

v_{long}: longitudinal velocity

a_{long}: longitudinal acceleration

v_{lat}: lateral velocity

a_{lat}: lateral acceleration

ω: yaw rate

L: vehicle length

l_f: distance from centre of mass to front axle

l_r: distance from centre of mass to rear axle

T: vehicle track

t_l: distance from centre of mass to left wheels

t_r: distance from centre of mass to right wheels

Two important new concepts are introduced here: yaw rate (ω) and side slip angle[1] (β). Vehicle yaw rate is the angular velocity at which the vehicle rotates about its centre of mass.

[1] Three concepts containing the word slip have now been introduced. This can be understandably confusing but it is important to differentiate between 'slip', 'side slip', and 'side slip angle'. Slip and side slip refer to the mechanism by which a wheel (tyre) generates a force in the longitudinal and lateral directions respectively. Side slip angle simply refers to the angle between the longitudinal and lateral components of velocity at a specific point on a vehicle (usually the centre of mass).

Vehicle side slip angle can be thought of similarly to slip angle for a single wheel as described above. As a vehicle turns at high speed there exists a component of lateral velocity, and this gives rise to the side slip angle as described by Equation 2.4. The overall side slip angle is typically given at the vehicle centre of mass but, due to the yaw rate, each point along the longitudinal axis will have a different lateral velocity and consequently a different side slip angle. Thus, the side slip angle at the front axle is different to the side slip angle at the rear axle.

$$\beta = tan^{-1}\left(\frac{v_{lat}}{v_{long}}\right) \tag{2.4}$$

Evaluating and then combining the forces at each of the four wheels to assess the affect upon the vehicle body kinematics is mathematically difficult. It is common to simplify the problem by utilising the 'bicycle model'. The bicycle model requires several assumptions. The first is that body pitch and roll forces are negligible so that the two wheel forces at each axle can be lumped into a single wheel force located at the axle midpoint. The second assumption is that the difference in steer angle for the left and right front wheels are negligible (i.e. that $\delta_{fl} \approx \delta_{fr}$), and thus they can be represented by a single single steer angle δ. This is appropriate at high speeds where the turning radii are large and thus the steer angles are small. Figure 2.7 shows an example of a bicycle model for a vehicle turning to the right with the front and rear wheel slip angle represented by α_f and α_r respectively. The rear slip angle is a result of the side slip angle at the rear axle, while the front slip angle is a result of both the steer angle and the side slip angle at

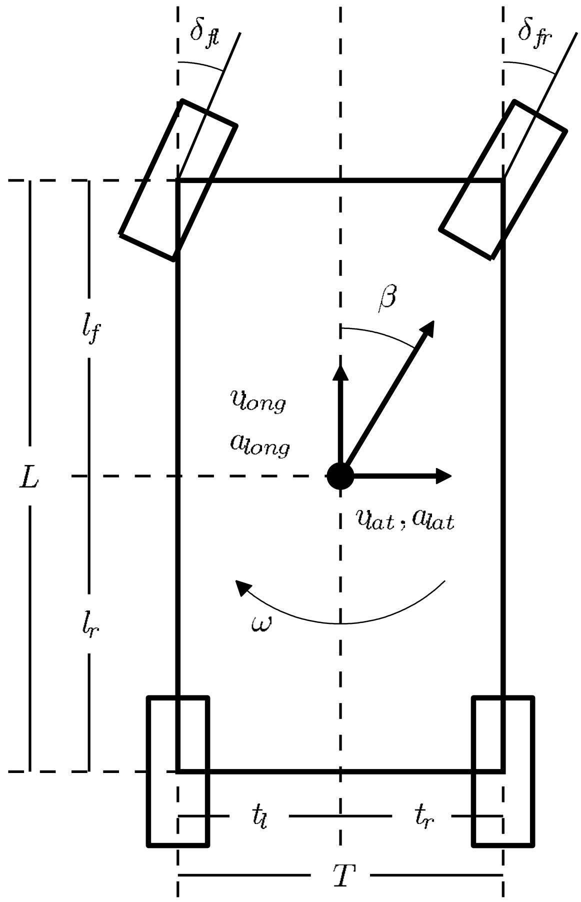


Fig. 2.6: Vehicle body kinematics

the front axle.

The lateral stability of a vehicle is defined by the ability of steering changes (made by the driver) to adjust the lateral motion and yaw of the vehicle. A vehicle with good lateral stability will possess the ability to adjust lateral motion and yaw in response to a change in steering angle quickly, accurately and under a wide range of operating conditions.

Vehicle lateral stability can therefore be investigated by determining the lateral force and yaw moment that results from the forces at the wheels. Using the bicycle model, this means determining the lateral forces at the

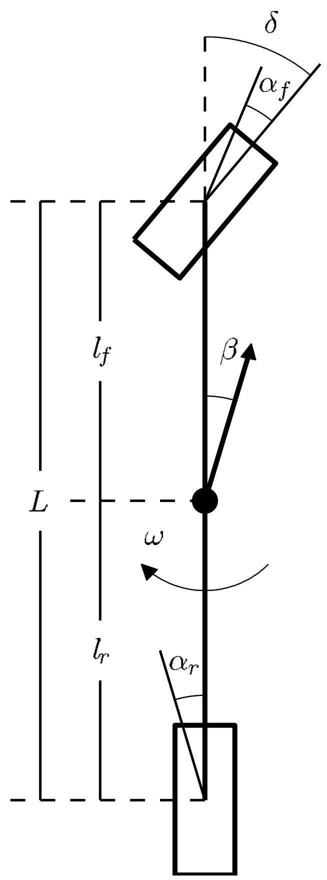


Fig. 2.7: Bicycle model

front and rear axels.

Under steady state cornering, and using the small angle approximation, the front and rear slip angle can be described by Equations 2.5 and 2.6.

$$\alpha_f = \beta + \frac{l_f \omega}{v_{long}} - \delta \tag{2.5}$$

$$\alpha_r = \beta - \frac{l_r \omega}{v_{long}} \tag{2.6}$$

The lateral force at the front and rear axles (F_{lat_f}, F_{lat_r}) can then be described by Equations 2.7 and 2.8, where C_f and C_r is the cornering stiffness of the combined front and combined rear wheels respectively.

$$F_{lat_f} = C_f\alpha_f = C_f\beta + C_f\left(\frac{l_f\omega}{v_{long}}\right) - C_f\delta \tag{2.7}$$

$$F_{lat_r} = C_r\alpha_r = C_r\beta - C_r\left(\frac{l_r\omega}{v_{long}}\right) \tag{2.8}$$

The equations of motion for the bicycle model can therefore be defined. The lateral force (Y) is described by Equation 2.9 and the yaw moment (N) is described by Equation 2.10.

$$\begin{aligned} Y &= F_{lat_f} + F_{lat_r} \\ &= C_f\beta + C_f\left(\frac{l_f\omega}{v_{long}}\right) - C_f\delta + C_r\beta - C_r\left(\frac{l_r\omega}{v_{long}}\right) \\ &= (C_f + C_r)\beta + \frac{1}{v_{long}}(l_fC_f - l_rC_r)\omega - C_f\delta \end{aligned} \tag{2.9}$$

$$\begin{aligned} N &= F_{lat_f} - F_{lat_r} \\ &= C_f\beta + C_f\left(\frac{l_f\omega}{v_{long}}\right) - C_f\delta - C_r\beta - C_r\left(\frac{l_r\omega}{v_{long}}\right) \\ &= (l_fC_f - l_rC_r)\beta + \frac{1}{v_{long}}(l_f^2C_f + l_r^2C_r)\omega - l_fC_f\delta \end{aligned} \tag{2.10}$$

Since C_f, C_r, l_f, l_r, and v_{long} are constants, the principal of superposition can be used to rewrite the lateral force to be described by Equation 2.11 and the yaw moment to be described by Equation 2.12.

$$\begin{aligned} Y &= \left(\frac{\partial Y}{\partial \beta}\right)\beta + \left(\frac{\partial Y}{\partial \omega}\right)\omega + \left(\frac{\partial Y}{\partial \delta}\right)\delta \\ &= Y_{\beta}\beta + Y_{\omega}\omega + Y_{\delta}\delta \\ &= f(\beta, \omega, \delta) \end{aligned} \tag{2.11}$$

$$\begin{aligned} N &= \left(\frac{\partial N}{\partial \beta}\right)\beta + \left(\frac{\partial N}{\partial \omega}\right)\omega + \left(\frac{\partial N}{\partial \delta}\right)\delta \\ &= N_{\beta}\beta + N_{\omega}\omega + N_{\delta}\delta \\ &= f(\beta, \omega, \delta) \end{aligned} \tag{2.12}$$

It has been shown then that the lateral force and yaw moment of a vehicle are both functions of the steer angle, the yaw rate and the side slip angle. During steady state turning, where yaw rate is constant, lateral force and yaw moment become functions of steer angle and side slip angle only. In such circumstances, further analysis of the relationship between lateral force, yaw moment, steer angle, and side slip angle (beyond the scope of this thesis) reveal important considerations for vehicle lateral stability.

As side slip angle increases, the ability of the steer angle to affect the lateral force and yaw moment of the vehicle diminishes. This phenomenon is exacerbated when the vehicle is braking, accelerating, or the wheels move beyond operating within linear region such that C_f, C_r, and v_{long} are no longer constant.

This has important implications for the lateral stability of vehicles during high speed driving where a large side slip angle is required to negotiate bends of large radii. Indeed, a vehicle with a large side slip angle has less ability to respond to outside disturbances (tightening curve, object avoidance, etc).

2.2 Origin of ESC

ESC resulted from the desire to solve the issue of reduced lateral stability that can occur as a consequence of a large side slip angle. Improvements in lateral stability were sought using two methods. Early efforts focussed on restraining the side slip angle to zero. This was achieved through the use of a vehicle with steerable rear wheels. By intelligently controlling the angle of the rear wheels in conjunction with the angle of the front wheels, vehicle side slip angle can be eliminated. Several implementations of this method, called four wheel steer (4WS), showed that it was able to successfully increase lateral stability (Horiuchi et al., 1996; Ro & Kim, 1996; Shibahata et al., 1986; Wakamatsu et al., 1997; Yuhara et al., 1991).

Later efforts to increase vehicle lateral stability focussed on actively controlling side slip angle to an acceptable level. The work of Shibahata et al. (1993) and also Inagaki et al. (1994) describe how to predict what level of side slip angle is appropriate for a given driving situation. Shibahata et al. (1993), Inagaki et al. (1994), and others (Abe et al., 1998; Alberti & Babbel, 1996; Koibuchi et al., 1996) were then able to develop control theories that governed vehicle yaw moment, and thus yaw rate and side slip angle, through the braking of individual wheels. This method, called direct yaw control (DYC), was also shown, in simulations, to successfully improve lateral stability.

Abe (1999) compared the effectiveness of the 4WS and DYC methods proposed by earlier studies. While both methods improved lateral stability, it was concluded that DYC was superior to 4WS at higher side slip angles and lateral accelerations where vehicle characteristics become non-linear. It was noted however, that even greater lateral stability improvements may be possible by integrating a 4WS method with a DYC method, as suggested by Nagai et al. (1997).

van Zanten et al. (1995, 1996, 1999) and van Zanten (2000) describe the development of a system of sensors, actuators and control algorithms designed to implement the theoretical DYC model. The system was tested and results showed that it did indeed improve vehicle lateral stability. This system would eventually become known as ESC and the first commercial vehicle to be equipped with the feature was manufactured in 1995 (the Mercedes Benz W140 S-Class).

The number of vehicle models equipped with ESC increased over time (Krafft et al., 2009) such that the effectiveness of ESC in preventing crashes could be evaluated (see Section 3.2).

2.3 ESC operation

The primary purpose of ESC is to improve vehicle lateral stability. A vehicle with good lateral stability will be able to adjust its yaw and lateral motions under a wide range of driving conditions (e.g. at faster speeds, or on low coefficient of friction roads). The explanation of how ESC improves lateral stability provided here is based upon publications detailing the operation of the ESC system developed by Bosch (van Zanten, 2000; van Zanten et al., 1995, 1996, 1999).

The general operating concept for ESC is to compare the actual vehicle state to a desired vehicle state, based on the driver's inputs, and intervene to correct for any differences by adjusting the yaw moment through braking individual wheels. The physical ESC system comprises several sensors and actuators, along with an electronic control unit (ECU) as shown in Table 2.1. The sensors detect the actual and desired vehicle states which the ECU uses to calculate the required response to be realised by the actuators.

Tab. 2.1: Major components of the ESC system

Component
Electronic control unit (ECU)
Sensors
Wheel speed (for all wheels)
Steering wheel angle
Brake position
Throttle position
Yaw rate
Lateral acceleration
Actuators
Brake primer pump
Brake pressure modulator
Engine management
Transmission control

In order to explain what vehicle parameters are monitored and controlled, consider Figure 2.8 where the vehicle at position 1, travelling at a steady forward speed, is given a fixed steering input. To navigate the curve successfully the vehicle must achieve the appropriate change in yaw angle and lateral position. The yaw rate of the vehicle must be such that it matches what the driver requests based on the angle of the steering wheel and the speed of the vehicle. Using the bicycle model and assuming linear cornering stiffness this requested 'nominal yaw rate' can be calculated by Equation 2.13, as shown in Appendix A.1. The constant v_{ch} is the characteristic speed of the vehicle and represents the speed at which the steer angle (δ) required to negotiate any turn is twice the Ackerman angle. More simply, the characteristic speed is a reference point that defines the steering characteristic of the vehicle.

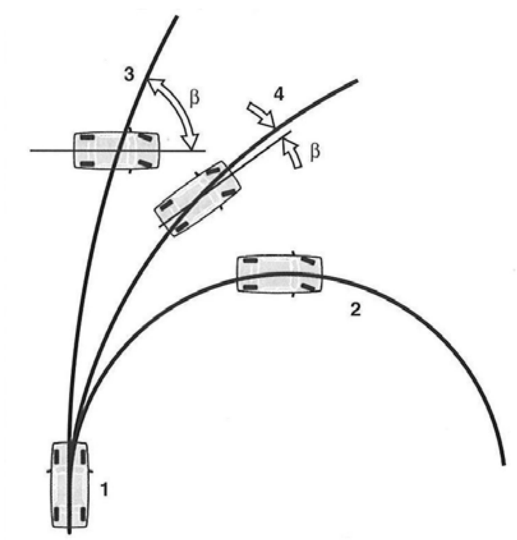


Fig. 2.8: Dynamic lateral response [adapted from van Zanten et al. (1999)]

$$\omega_{nominal} = \frac{v_{long}\delta}{L\left[1 + \left(\frac{v_{long}}{v_{ch}}\right)^2\right]} \tag{2.13}$$

By interrogating the wheel speed and steering wheel angle sensors, real time values for v_{long} and δ can be obtained. Appropriate values for L and v_{ch} are programmed into the memory of the ECU. It is therefore possible to calculate the nominal yaw rate ($\omega_{nominal}$) in real time and compare it to the actual yaw rate (ω_{actual}) measured by the yaw rate sensor.

If position 2 represents the desired vehicle position based on the nominal yaw rate then controlling the actual yaw rate such that it matches the nominal yaw rate would seem to ensure that this position is always achieved. However, the appropriateness of the nominal yaw rate with respect to the lateral acceleration of the vehicle must also be considered.

Controlling the actual yaw rate to match the nominal yaw rate on a road where the coefficient of friction between the tyre-road pair is not sufficient to generate the lateral acceleration required to counteract the centripetal force of travelling through the curve will result with the vehicle at position 3. In this case, the nominal yaw rate is not appropriate for the lateral acceleration which can be visualised as an increasing side slip angle.

By controlling the actual yaw rate to approach the nominal yaw rate while also maintaining the side slip angle within a certain threshold, the vehicle will result at position 4. Here, the tightest curve that can be navigated, given the coefficient of friction, is achieved and heading stability is maintained.

No sensor exists that is able to detect side slip angle and thus it must be estimated from other known parameters. Using relative motion, the lateral acceleration (a_{lat}) of the vehicle can be described by Equation 2.14. Through integration, v_{lat} can be calculated and an estimate for side slip angle can then be obtained from Equation 2.4.

$$\dot{v_{lat}} = a_{lat} - \omega_{actual} v_{long} \tag{2.14}$$

If the side slip angle is detected to be beyond a predefined nominal side slip angle (explained below) a check is made to determine whether action is required. When the side slip angle is found to be increasing, based on the rate of side slip angle, the yaw moment is controlled such that the side slip angle is returned to its nominal value. Assuming steady state cornering, rate of side slip angle can be described by Equation 2.15 as shown in Appendix A.2.

$$\dot{\beta} = \frac{a_{lat}}{v_{long}} - \omega_{actual} \tag{2.15}$$

Each ESC system is specifically designed and tuned to the vehicle in which it is installed. The nominal, or allowed, level of side slip angle for a vehicle during specific situations can be predicted as mentioned earlier. However, the value can also be further customised by the manufacturers for each individual vehicle model. Depending on the type of vehicle, the nominal side slip angle may be customised to elicit ESC behaviour that is sharper or more subtle.

Through a knowledge of the nominal yaw rate, nominal side slip angle, actual yaw rate and actual side slip angle, the ECU is able to calculate an appropriate braking intervention. This braking intervention is used to affect the yaw moment as explained below.

2.3.1 Interventions

ESC is able to brake individual wheels and by applying asymmetric braking forces yaw moment can be produced. By braking an individual wheel, the forces generated by that wheel in the longitudinal and lateral directions are manipulated. In Figure 2.9(a) a wheel is initially generating a maximum

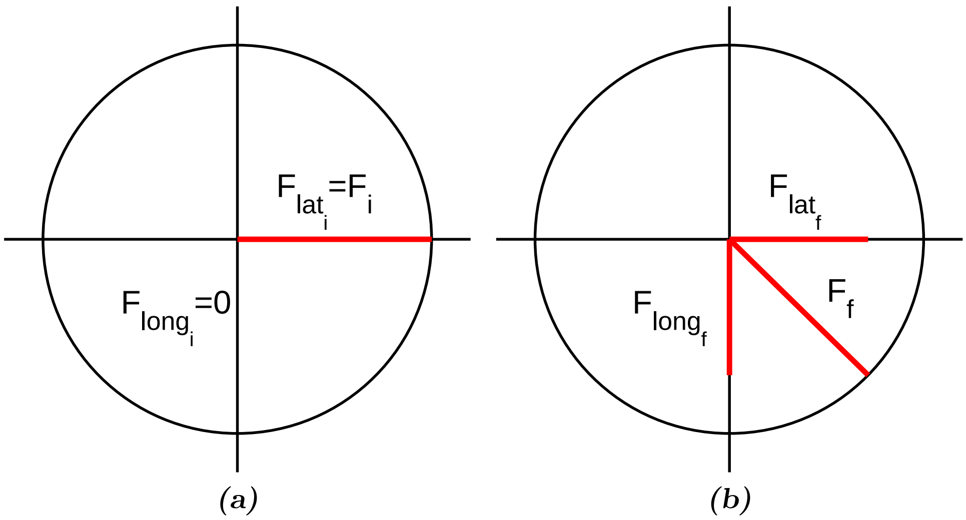


Fig. 2.9: Wheel force manipulation through braking intervention

lateral force such that $F_{lat_i} = F_i$, while $F_{long_i} = 0$. But when a brake force is applied such that a F_{long_f} is generated, the lateral force is reduced to F_{lat_f} as shown in Figure 2.9(b). The two effects (increase in F_{long} and decrease in F_{lat}) caused by a braking intervention are used to control the yaw moment of the vehicle.

If, for example, the front left wheel of the vehicle in Figure 2.6 was generating the forces in Figure 2.9(a), the resultant yaw moment from that wheel would be $F_{lat_i}l_f$ in a clockwise direction. When the intervention is applied such that the wheel is generating the forces in Figure 2.9(b), the resultant yaw moment is now $F_{lat_f}l_f - F_{long_f}t_l$ in a clockwise direction.

By manipulating the brakes of all the wheels on the vehicle in this way, a yaw moment that generates the required yaw rate can be achieved. Some consideration must be given to which wheels are utilised in different circumstances however. There are three general scenarios that can cause a vehicle to lose lateral stability (understeer, oversteer and split mu) and each elicits a different combination of interventions at the four wheels. The interventions typical for each of the scenarios are explained below.

It should be mentioned here that an ESC system is able to determine the coefficient of friction for the surface that a vehicle is travelling on. It does this by slightly braking a single wheel (such that it is un-noticed by the driver) and recording the corresponding change in braking coefficient. This change is then compared to a catalogue of wheel slip curves which the system has stored in memory. Once the system finds a match (or an approximation) it is then able to accurately predict the response to stronger braking interventions.

It should also be noted here that the interventions of an ESC system are proactive rather than reactive. To aid in the explanation of ESC actions the examples presented below deliberately use exaggerated situations of loss of control. However, in actuality ESC predicts lateral instability long before a loss of control situation and acts to decrease the likelihood of such an occurrence (as opposed to only responding during an active loss of control situation).

2.3.2 Understeer

An understeer situation can occur when one or both of the front wheels are skidding. The vehicle responds slowly or not at all to the driver input and continues to travel straight ahead. An example of understeer is shown in Figure 2.10. The vehicle is turning left in an attempt to end up in position A but instead understeers, skids forwards and finishes in position B.

Manoeuvres which unload or cause a large amount of wheel slip on the front wheels can cause understeer. Under real conditions, understeer is often

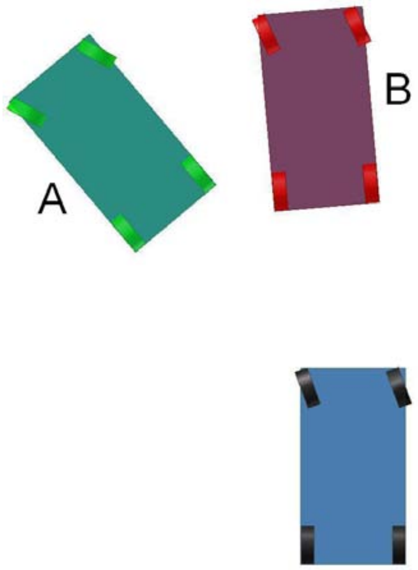


Fig. 2.10: Understeer example

the result of negotiating a tight curve at an excessive speed or steering under heavy braking.

An example of how ESC responds to an understeer situation is shown in Figure 2.11. The blue lines on the traction circle diagram show the state of the vehicle before any ESC intervention. More force than is available is being requested at the front wheels and the vehicle may be about to understeer. The ESC system senses that the vehicle is not turning to the left as much as the driver would like. The ESC system has the option of braking either the front left or rear left wheel in order to produce the extra anti-clockwise yaw moment required. The front left wheel is already on the verge of skidding however and requesting a greater force would exacerbate the problem. The rear left wheel is therefore selected by the ESC system to brake and stabilise the vehicle. This intervention at the rear left wheel is shown by the red line in the traction circle diagram.

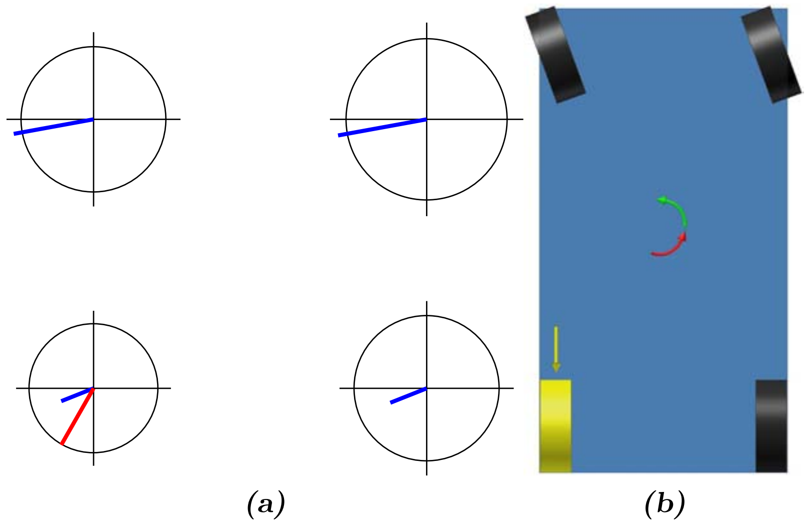


Fig. 2.11: Example of understeer and ESC response

The response of the ESC system to a situation of understeer is not always as effective as the response to other situations. This is especially obvious when a vehicle is understeering under heavy braking. When a vehicle is braking, the weight is shifted from the rear wheels onto the front wheels. As the vertical force on the rear wheels reduces, so does the diameter of the corresponding traction circles, and in turn the maximum available braking force. There is therefore a decreased potential yaw moment available to correct the understeer.

2.3.3 Oversteer

An oversteer situation can occur when one or more of the rear wheels are skidding. The back end of the vehicle flicks out and the heading of the vehicle becomes difficult for the driver to control. An example of oversteer is shown in Figure 2.12. The vehicle is turning left in an attempt to end up in position

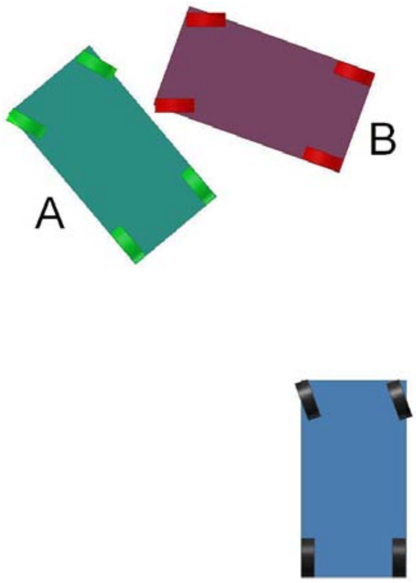
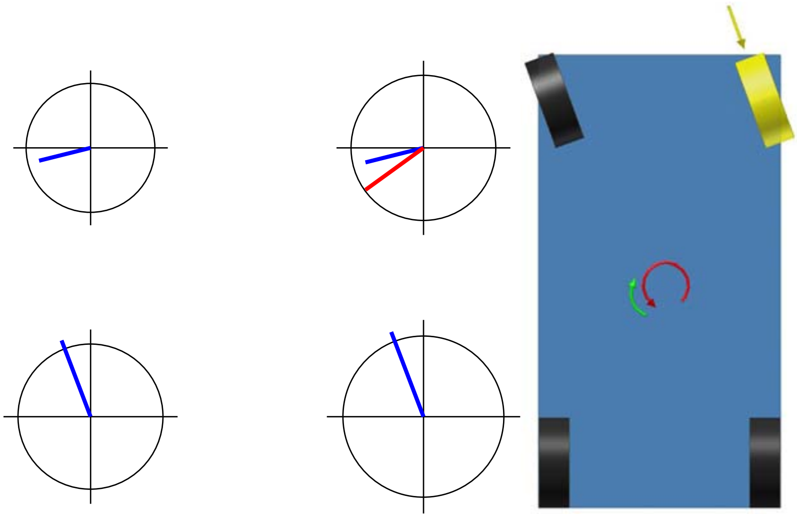


Fig. 2.12: Oversteer example

A but instead oversteers, spins out and finishes in position B.

Manoeuvres which unload or cause a large amount of wheel slip on the rear wheels can cause oversteer. Under real conditions, oversteer is often the result of sudden weight shift due to rapid counter steering or hard acceleration during cornering in a rear wheel drive vehicle.

An example of how ESC responds to oversteer is shown in Figure 2.13. The blue lines on the traction circle diagram show the state of the vehicle before any ESC intervention. More force than is available is being requested at the rear wheels and the vehicle may be about to oversteer. The ESC system senses that the vehicle is turning to the left more than the driver would like. The ESC system has the option of braking either the front right or rear right wheel in order to produce the counter acting clockwise yaw moment required. The rear right wheel is already on the verge of skidding however and requesting a greater force would exacerbate the problem. The front



(a) *(b)*

Fig. 2.13: Example of oversteer and ESC response

right wheel is therefore selected by the ESC system to brake and stabilise the vehicle. This intervention at the front right wheel is shown by the red line in the traction circle diagram.

The response of the ESC system to a situation of oversteer is usually quite effective. This is because, as a vehicle is braking, the weight is moved from the rear wheels onto the front wheels. As the vertical force on the front wheels increases, so does the diameter of the corresponding traction circles, and in turn the maximum available braking force. There is therefore more greater potential yaw moment available to correct the oversteer.

2.3.4 *Split Mu*

A split mu situation can occur when one or both of the wheels on one side of the vehicle are on a different surface type to the wheels on the other side of the vehicle. The vehicle may respond erratically and steer more or less than

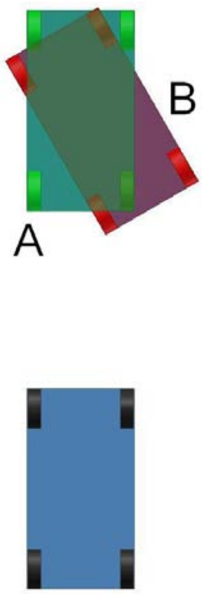


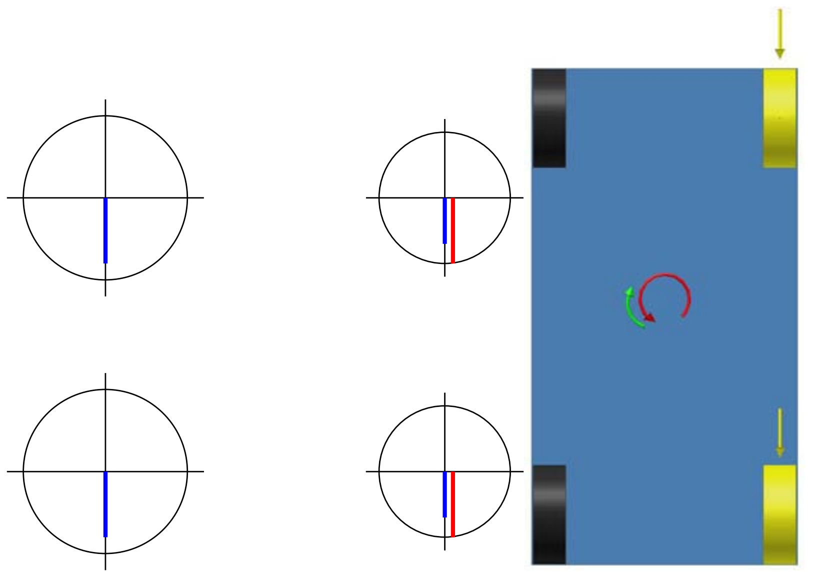
Fig. 2.14: Split mu example

the driver wishes. The vehicle may even begin to turn without any steering input from the driver at all. An example of split mu is shown in Figure 2.14. The vehicle is driving straight ahead in an attempt to end up in position A but instead passes over a difference in surface type and begins to yaw in an anti-clockwise direction and finishes in position B.

As mentioned above, the main cause of a split mu situation is one side of the vehicle travelling over a different surface type to the other side. Some surface types will have a lower coefficient of friction, like an icy or wet road. Other surface types will 'grab' at the wheels, like deep gravel or pooled water. In either case, a difference in the surface type from one side of the vehicle to the other can cause a split mu situation.

An example of how ESC responds to a split mu situation is shown in Figure 2.15. The blue lines on the traction circle diagram show the state of the vehicle before any ESC intervention. The size of the traction circles for the right side wheels indicate that this side of the vehicle is travelling over a surface with a lower coefficient of friction than that on the left side. The lower friction reduces the amount of natural forward resistance encountered by the right side wheels and may cause the vehicle to yaw anti-clockwise. The ESC system senses that the vehicle is yawing anti-clockwise without the driver turning the steering wheel in that direction. The ESC system is able to use both right side wheels in this case to produce the required clockwise yaw moment. This intervention to both right side wheels is represented by the red lines in the traction circle diagram (which have been offset so that the blue lines remain visible).

The effectiveness of the response of the ESC system to a situation of split mu is entirely dependent on the degree of difference between the surface types being travelled upon. In many cases there is only a small difference in the coefficient of friction between the two surfaces and the ESC response is quite effective. However, during emergency manoeuvres, vehicles may travel off the side of the road and onto the road shoulder where there may be a greater disparity in the friction of the surface types. In addition to this, a vehicle undertaking an emergency manoeuvre may also be encountering weight transfer from one side of the vehicle to the other, due to significant steering inputs, which may complicate the situation further.



(a) *(b)*

Fig. 2.15: Example of split mu and ESC response

3. LITERATURE REVIEW

This chapter presents a review of the literature covering Electronic Stability Control (ESC). It is split into four sections. In Section one early literature that either investigates the effectiveness of ESC on an individual level (i.e. with a specific vehicle and a specific driver) or estimates the potential effectiveness of ESC based on the prevalence of crashes that are sensitive to ESC are reviewed. A thorough review of literature evaluating the overall effectiveness of ESC across the entire vehicle fleet is presented in section two. Breakdowns of effectiveness by crash type and various driving conditions is presented. Section three investigates a test method for assessing the performance of individual ESC systems. The final section presents a summary of the literature and highlights the areas that this thesis is focused upon.

3.1 Individual evaluations and estimates of ESC effectiveness

Two studies evaluated the effectiveness of ESC on an individual level (Papelis et al., 2004; Yamamoto & Kimura, 1996). In each, ordinary drivers were asked to complete ESC sensitive manoeuvres. The difference in the outcomes of these manoeuvres for vehicles equipped with ESC and not equipped with ESC were analysed.

Yamamoto & Kimura (1996) had ordinary drivers complete two emergency driving manoeuvres on a test track. The drivers were divided into two groups where one group used a vehicle without ESC fitted while the other group used the same vehicle with ESC fitted. The results showed that those drivers who made appropriate steering actions had much less chance of losing control while driving the vehicle fitted with ESC. For those drivers who did not steer away from danger, or panicked and did nothing at all, ESC was of no benefit.

Using the National Advanced Driving Simulator in Iowa, Papelis et al. (2004) had ordinary drivers complete three driving scenarios that had the potential to result in a loss of control. Two vehicles that could be simulated as either being equipped with ESC or not equipped with ESC were used. The drivers were divided between the two vehicles and then divided again between having their vehicle equipped with ESC or not. Across all three driving scenarios and both vehicles there was an 88 per cent reduction in loss of control events for the drivers of vehicles equipped with ESC. It should be noted however, that the validity of driving simulators in such experiments is controversial (Kemeny & Panerai, 2003).

When evaluating ESC performance at a vehicle population level, two studies chose to investigate the maximum potential effectiveness of ESC. This approach to evaluating the effectiveness of ESC was used while the low numbers of ESC fitted vehicles in the fleet precluded a more formal evaluation.

Sferco et al. (2001) obtained information on 1,674 crashes (involving vehicles that were not equipped with ESC) in five European countries and asked experts to 'judge' how the addition of ESC would have affected the outcome. It was judged that 18 per cent of the injury crashes and 34 per cent of the fatal crashes would have benefitted from the addition of ESC. The judged benefits of ESC were even greater, 42 per cent and 67 per cent for injury and fatal crashes, when the sample was restricted to only those crashes that were identified as being due to a loss of control.

Langwieder et al. (2003) analysed German crash databases to identify the prevalence of ESC sensitive crashes. It was discovered that 40 - 60 per cent of single vehicle crashes involved skidding, 70 per cent of drivers took several steering manoeuvres during crashes on bends, and only 50 per cent of drivers braked during the pre-crash phase. It was concluded that in all these types of crash an ESC system would have provided a benefit to the driver and potentially prevented a collision.

3.2 Statistical evaluations of ESC effectiveness

The majority of statistical evaluations of ESC effectiveness, looking at performance at an overall level, compare crash rates of vehicles not equipped with ESC to the crash rate of vehicles that are equipped with ESC. The following subsections discuss the methodology and results of these studies which are also summarised in Table 3.1. This table was constructed based on a similar review of effectiveness evaluation literature by Ferguson (2007), but has been modified to present clearly the ESC effectiveness associated with specific crash types and crash severities in each study. Several extra studies were also added to the table. Furthermore, the method of splitting the discussion of effectiveness by crash type, such as single vehicle and multiple vehicle, was also based on Ferguson (2007) but was again expanded upon to include extra relevant crash types.

Two more statistical studies were identified (Page & Cuny, 2006; Unselt et al., 2004) but were not included in the table as they were relatively small, included few vehicles models, and were not able to conclude any findings of significance.

3.2.1 Methods of evaluation and confounding factors

In the following sections the word 'studies' refers to those studies in Table 3.1 unless the context makes it clear that it refers to some other study.

Each of the studies evaluates the effectiveness of ESC by comparing the crash rate of vehicles fitted with ESC to that of vehicles not fitted with ESC. As such, the first step in any evaluation was to identify which vehicles are fitted with ESC. If the make, model and year are known then ESC fitment, as a standard feature, can be established though consultation with vehicle manufacturers. However such details are rarely recorded in mass crash databases. Thus, most studies rely on the vehicle identification number (VIN) associated with a vehicle which is, in most cases, routinely recorded in mass crash databases.

Like most new technologies, ESC was initially fitted to only a few vehicles. Manufactures such as Mercedes Benz, BMW, Audi, Jaguar, Lexus, Alfa Romeo, Saab, and Peugeot were the early adopters of ESC technology. These manufacturers represent the more expensive end of the market and usually fit ESC to their luxury vehicle models. As luxury vehicles tend to include many other safety features and be driven by a different demographic of driver (older, wealthier, well educated), it was therefore not appropriate to simply compare the crash rate of these ESC fitted vehicles with the rest of the non ESC fitted vehicle fleet.

Early studies overcame this by analysing vehicles that were not fitted with ESC in one model year and then had ESC fitted in the next (Aga & Okada, 2003; Bahouth, 2005, 2006; Dang, 2004, 2007; Farmer, 2004, 2006; Kahane, 2014; Padmanaban, 2007; Sivinski, 2011; Thomas, 2006; Thomas & Frampton, 2007). Efforts were made to identify vehicle models that were alike apart from the addition of ESC from one year to the next. This was sometimes made difficult as side curtain airbags were also being slowly introduced and it was common for manufacturers to install both safety features together. In addition, the fitment of ESC requires that a vehicle also be fitted with ABS and traction control. Some studies, analysing vehicles that did not change only ESC fitment from one model year to the next, chose to instead match ESC fitted vehicles with non ESC fitted vehicles that had similar attributes (Lie et al., 2005; Tingvall et al., 2003). As more and more vehicles (including common family sedans and less expensive models) began to fit ESC, later studies assumed that vehicles fitted with ESC had a similar representation to vehicles not fitted with ESC and no longer needed complete matching (Chouinard & Lécuyer, 2011; Green & Woodrooffe, 2006; MacLennan et al., 2008; Scully & Newstead, 2007, 2010).

One point of potential complication that many of the studies mentioned was that some vehicles were advertised with ‘optional’ ESC that could be fitted as an extra at the time of purchase. As there was no way to determine whether a vehicle with optional ESC was actually fitted with ESC or not these vehicles would need to be analysed differently. Farmer (2004) suggested that optional ESC was installed by relatively few purchasers. Moreover, it may be the case that those drivers who do opt for additional safety features are usually safety conscious and would be more cautious drivers, but this effect could not be reliably quantified. Many studies simply removed any vehicle with optional ESC from the analysis sample (Chouinard & Lécuyer, 2011; Dang, 2004, 2007; Kahane, 2014; Scully & Newstead, 2007, 2010; Sivinski, 2011; Thomas, 2006; Thomas & Frampton, 2007), while others chose to analyse them as an additional independent group (Farmer, 2004, 2006; MacLennan et al., 2008). Dang (2004, 2007) stated that upon re-analysis, with the addition of vehicle models with optional ESC, there was little change in the overall result.

Once the two sets of vehicle groups had been identified, each study used one of two different methodologies. The methods differed in the way they measured exposure. In an ideal world, a reliable measure of exposure such as the number of kilometres travelled in various locations and conditions would be known for each of the vehicles being analysed. This would allow a proper comparison of the crash rate of the two vehicle groups without being biased if, for example, one group had spent more time on the road (and thus been exposed to more crashes) or spent more time driving on higher speed roads. However, this type of information is rarely available and so alternative measures of exposure are required.

The first methodology, called direct exposure, assumes that the vehicles in each of the groups are driven around a similar amount of time and thus have a similar overall exposure. Thus, only the relative size difference in the number of vehicles needs to be controlled for. This was done by either controlling for vehicle years (Aga & Okada, 2003), or registration years (Farmer, 2004, 2006).

The second methodology, called induced exposure, accepts that no proper measure of exposure is possible and instead uses a proxy measure. A full explanation of the method is given by Evans (1986, 1998), but for use in the current circumstances involves finding a crash type that is unaffected by ESC. This crash type is then used as a measure of exposure and acts as a control crash which can be compared to other crash types. There was a large variation in the control crash types used by the various studies which used the induced exposure method. Table 3.1 lists the control crash types used in each of the studies, but some some examples are; rear end crashes (Bahouth, 2005, 2006; Lie et al., 2005; Scully & Newstead, 2007, 2010; Tingvall et al., 2003), multi-vehicle crashes (Dang, 2004), or crashes involving a vehicle that was parked, reversing, stopped, or slow moving (Thomas, 2006; Thomas & Frampton, 2007). Note that it is not impossible that some of these control crash types may still be affected by ESC in some way (e.g. a reduction in crash speed) and this would result in an underestimate of ESC effectiveness.

As with any complex analysis, there are many confounding factors that must be addressed. Some factors can be quantified and controlled for (e.g. vehicle age). When comparing a previous vehicle model (not fitted with ESC) to a current vehicle model (with ESC) it is clear that the vehicle group without ESC fitted will be older. Newer vehicles are known to have a lower crash rate (and less severe crashes) for various reasons such as greater mass, additional safety features, and more mature drivers. This effect has been quantified (Blows et al., 2003; Poindexter, 2003) and the majority of the studies made efforts to control for it.

Other factors are more difficult to quantify but must, at the very least, be acknowledged. Infrastructure changes over time, such as installation of guardrails, traffic lights, or speed reductions could all change the way people drive and thus the apparent effectiveness of ESC. So too could changes in weather, or traffic density.

Another suggestion is that drivers who purchase a vehicle equipped with ESC may be more safety conscious and drive overall more cautiously. Conversely, it has been suggested that some drivers may drive more aggressively or riskily if they know their vehicle is equipped with ESC. Two studies investigated this potential factor. In the first study, Canadian drivers of ESC equipped vehicles were identified via insurance records and invited through mailed correspondence (in order to preserve privacy) to participate in a survey (Rudin-Brown et al., 2009). There were 1,017 respondents who then completed the telephone survey which included questions regarding how their behaviour has changed since they began driving a vehicle equipped with ESC. The results, which were weighted by age, gender, and region of residence to be representative of the Quebec and British Columbia population of ESC equipped vehicle owners, revealed that 63 per cent of drivers were aware of ESC and knew that their vehicle was equipped with the technology. Of this subset of 'aware' drivers, 23 per cent reported noticing changes in their driving behaviour since they began driving a vehicle with ESC. Furthermore, it was reported that 68 per cent of these behaviour changes were long lasting.

The types of driving behaviour changes reported were varied. Only a very small number of drivers reported overtly dangerous behaviour changes such as driving more aggressively, driving closer to the vehicle in front, or cornering at a higher speed. However, large numbers of drivers (up to 24%) reported behaviour changes that had the potential to offset the benefits of ESC such as driving with more confidence, feeling safer while driving, and driving faster (though not speeding). It was also interesting to note that the benefits of ESC may also be enhanced in some cases as a number of drivers (up to 18%) reported behaviour changes that were safer such as driving more carefully or driving slower. The reasons for these improved driving behaviours were not explored by the study.

The second study, by Vadeby et al. (2011), used a similar method of surveying drivers. There were 959 drivers surveyed including owners of vehicles equipped with ESC and vehicles not equipped with ESC. During the survey each driver was presented with two scenarios and asked whether they would perform a specific manoeuvre that was considered somewhat risky if they were driving a vehicle with ESC or if they were driving a vehicle without ESC. It was found that the drivers were more likely to perform the risky manoeuvres when they imagined themselves in a vehicle with ESC. Additionally, it was found that the drivers who owned vehicles with ESC were overall more likely to perform the risky manoeuvres regardless of whether they imagined themselves in an ESC equipped vehicle or not. The study concluded from these results that the benefits of ESC may be reduced by changes in driver behaviour.

Based on the findings of these studies, the suggestion that drivers may take greater risks when driving a vehicle with ESC should be given some consideration. None of the reviewed studies controlled for this effect but given it has not yet been quantified this is not surprising.

Each ESC system is designed and calibrated specifically for the vehicle to which it is to be fitted. Thus, each system is different and will have its own unique level of effectiveness. No study has addressed this factor as it is unlikely that the analysis of a sample consisting of only a single vehicle model would be able to conclude a result that is significant with any confidence. A more appropriate method for evaluating individual ESC performance is to use assessments of test manoeuvres, on a vehicle by vehicle basis. This is discussed in Section 3.3 below.

The age and gender of a driver may also have an effect on the effectiveness of the system. Green & Woodrooffe (2006) analysed these factors for both fatal, single vehicle crashes and loss of control crashes. They found that the effectiveness of ESC differed by age, but not by gender. For passenger vehicles, the effectiveness of ESC in preventing loss of control crashes was the lowest for young drivers, increased to a maximum at around age 40, and then continued to declined slightly as age increased. Thomas (2006) along with Scully & Newstead (2007, 2010) analysed the effectiveness of ESC by gender and found a slightly larger effect for males over females but many of the results were non significant. Conversely, Kreiss et al. (2005) found that the effect was larger for females than it was for males.

Further confounding factors such as the type of road, the type of vehicle, the road condition, the speed zone, the injury severity, and the crash type were all deemed to be significant enough that many of the studies disaggregated their analysis to investigate their effects individually.

The findings of the studies, which have been collated into several categories, are presented and discussed in the subsections below.

3.2.2 Effect on all crash types

The overall effectiveness of ESC in preventing all crashes of any severity (including non-injury crashes) is negligible. Farmer (2004, 2006) concluded a non-significant decrease in crash rate of 1-2%, while Thomas & Frampton (2007) and Sivinski (2011) quoted a larger decrease of 6-7%. Interestingly, Scully & Newstead (2007, 2010) found that the overall crash rate of ESC equipped vehicles had increased by 7% in their earlier study but this had fallen to a non-significant increase of 1% in the followup study.

The effectiveness improves slightly to a reduction of between 3% and 10% when considering only those crashes which resulted in an injury (Farmer, 2004, 2006; Scully & Newstead, 2007, 2010; Thomas, 2006). Effectiveness improves further to between 15% and 50% for crashes which resulted in a fatal injury (Bahouth, 2006; Farmer, 2004, 2006; Sivinski, 2011; Thomas, 2006; Thomas & Frampton, 2007).

It is likely that the low overall effectiveness of ESC is due to the large number of low speed, multiple vehicle crashes on metropolitan roads. As discussed in the section on multiple vehicle crashes below, these types of crash are far less influenced by the effects of ESC than some other types of crash. Multiple vehicle crashes are also less likely than single vehicle crashes to result in severe injuries (see Chapter 4). This is likely the reason that ESC effectiveness increases as crash severity increases. It is interesting to note that the effectiveness of ESC is 22% when considering all crashes that resulted in an injury apart from the common, multiple vehicle crash type of rear end (Lie et al., 2005; Tingvall et al., 2003).

Three types of road surface condition were considered. For all crashes that resulted in an injury on dry roads, non-significant decreases of 9% and 2% were concluded by Tingvall et al. (2003) and Thomas (2006) respectively. On wet roads, estimates of the effectiveness of ESC on crashes that resulted in an injury varies across different studies. Tingvall et al. (2003) found a decrease of 32%, while Thomas (2006) found only a 4% decrease. Crashes that resulted in an injury on snowy or icy roads benefitted particularly from the effects of ESC. Decreases in crash rate of 38% (Tingvall et al., 2003) and 25% (Lie et al., 2005) were found.

Further analysis of crashes under difference surface conditions is given by Tingvall et al. (2003) and Kreiss et al. (2005). Tingvall et al. (2003) investigated the effectiveness of ESC on crashes that resulted in an injury on wet, snowy, or icy roads by different types of vehicle. Large front wheel drive vehicles showed the greatest benefit with a decrease of 59%, followed by large rear wheel drive vehicles (46%), and small front wheel drive vehicles (25%). Kreiss et al. (2005) investigated the effectiveness of ESC on all crash types on dry and wet roads by different types of location. ESC showed more effectiveness on dry roads outside of built up areas (decrease of 42%), than within built up areas (decrease of 28%). The opposite was true for roads that were wet, where the effectiveness was greater within built up areas (decrease of 31%) compared to outside of built up areas (decrease of 20%).

Many studies disaggregated their analysis by type of vehicle, providing results for passenger vehicles, commercial vehicles, and SUVs or 4WDs. Considering all crashes involving passenger vehicles that resulted in an injury, Farmer (2006) and Scully & Newstead (2007, 2010) found a decrease between 2% and 9%, though none of the results were significant. Scully & Newstead (2010) additionally investigated all crashes involving commercial vehicles that resulted in an injury and found a 29% decrease but this too was non-significant. For all crashes involving an SUV or 4WD that resulted in an injury, Farmer (2006) and Scully & Newstead (2007, 2010) concluded a decrease of between 7% and 34%. A decrease in all fatal crashes involving passenger vehicles of 38%, 14%, and 23% were found by Farmer (2006), Dang (2007), and Sivinski (2011) respectively. Only one study analysed all fatal crashes involving SUVs and concluded a decrease of 46% (Farmer, 2006).

3.2.3 Effect on single vehicle crashes

Every study listed in Table 3.1 except one assessed the effectiveness of ESC on single vehicle crashes in one way or another.

Estimates of the overall effectiveness of ESC in preventing single vehicle crashes across all severity levels ranges from 27% to 50% (Aga & Okada, 2003; Farmer, 2004, 2006; Scully & Newstead, 2007, 2010; Sivinski, 2011; Thomas & Frampton, 2007). For single vehicle crashes that resulted in an injury, significant decreases of 32% to 45% have been found (Farmer, 2004, 2006; Scully & Newstead, 2007, 2010). ESC has been found to be the most effective in fatal single vehicle crashes with significant decreases of 56% to 69% (Bahouth, 2006; Farmer, 2004, 2006; Sivinski, 2011).

Most of the studies disaggregated their single vehicle crash analysis by vehicle type. Estimates of reductions in single vehicle crashes involving a passenger vehicle are between 19% and 35% (Dang, 2004, 2007; Farmer, 2004; Scully & Newstead, 2007, 2010). Effectiveness estimates are even greater for all single vehicle crashes involving an SUV or 4WD which range between 49% and 67%. Farmer (2006) and Scully & Newstead (2007, 2010) investigated single vehicle crashes involving passenger vehicles that resulted in an injury and found decreases of between 23% and 33%. The same studies also analysed single vehicle crashes involving SUVs or 4WDs that resulted in an injury and found decreases of between 56% and 68%. When considering fatal single vehicle crashes, the effectiveness estimates were greater again. Reductions in fatal single vehicle crashes involving a passenger vehicle of 30% to 53% have been found (Dang, 2004, 2007; Farmer, 2006; Green & Woodrooffe, 2006; Kahane, 2014; Sivinski, 2011). Reductions in fatal single vehicle crashes involving SUVs or 4WDs have been estimated to be 50% to 63% (Dang, 2004; Farmer, 2006; Green & Woodrooffe, 2006). For fatal single vehicle crashes involving commercial vehicles, a reduction of 45% was found (Kahane, 2014).

3.2.4 Effect on rollover crashes

Rollover crashes are commonly associated with high severity injuries to vehicle occupants. Several of the studies considered rollover crashes while a few focused specifically on them. The investigation of rollover crashes was often split into the analysis of specifically single vehicle rollover crashes or the analysis of all crashes involving a rollover event (including multi-vehicle crashes). In the majority of cases ESC showed a greater effect on single vehicle rollover crashes compared to all rollover crashes.

Farmer (2004, 2006) and Sivinski (2011) found that ESC reduced all single vehicle rollover crashes by between 67% and 76%. In contrast, MacLennan et al. (2008) found a more conservative reduction of 39%. The effectiveness of ESC in preventing all rollover crashes has been estimated to be between 36% and 56% (MacLennan et al., 2008; Scully & Newstead, 2010; Thomas & Frampton, 2007).

When disaggregating rollover crashes by vehicle type, SUVs and 4WDs benefitted equally as well as passenger vehicles. ESC effectiveness in single vehicle rollover crashes involving passenger vehicles has been estimated to be between 64% and 72% (Dang, 2007; Farmer, 2006; Sivinski, 2011), while for SUVs or 4WDs effectiveness estimates ranged between 60% and 77% (Farmer, 2006; MacLennan et al., 2008). For all rollover crashes involving passenger vehicles MacLennan et al. (2008) and Scully & Newstead (2010) found ESC effectiveness to be between 32% and 34%. Similarly Kallan & Jermakian (2008) and Scully & Newstead (2010) found ESC effectiveness for all rollover crashes involving SUV's or 4WDs to be between 67% and 82%.

The reduction in fatal single vehicle rollover crashes were found to be between 72% and 87% (Farmer, 2004, 2006; Sivinski, 2011). Reductions in single vehicle rollover crashes involving passenger vehicles were found to be between 56% and 77% (Dang, 2007; Farmer, 2006; Kahane, 2014; Sivinski, 2011). The effectiveness was greater still for fatal single vehicle rollover crashes involving SUVs which were reduced by 80% (Farmer, 2006). A similar reduction of 74% was found for fatal single vehicle crashes involving commercial vehicles (Kahane, 2014).

The decrease in crash rate for all fatal rollover crashes involving passenger vehicles was found to be between 40% and 53%, and for all fatal rollover crashes involving SUVs was found to be 73% (Green & Woodrooffe, 2006; Padmanaban, 2007).

MacLennan et al. (2008) looked specifically at tripped rollover crashes in which a vehicle was sliding sideways before the wheels contacted an obstruction which initiated a roll. It was found that for all tripped rollover crashes, the addition of ESC resulted in a crash rate decrease of 41%. For single vehicle, tripped rollover crashes the decrease was 46%. The results were then disaggregated by vehicle type. All tripped rollover crashes involving passenger vehicles showed a decrease of 40%, and all single vehicle, tripped rollover crashes involving passenger vehicles showed a non significant decrease of 32%. For all tripped rollover crashes involving SUVs or vans the decrease was 53%, and for all single vehicle, tripped rollover crashes involving SUVs or vans the decrease was 64%.

3.2.5 Effect on loss of control crashes

Green & Woodrooffe (2006) found that the effectiveness of ESC in preventing all loss of control crashes involving passenger vehicles was estimated to be 55%. For all loss of control crashes involving SUVs, the effectiveness was estimated to be 70%. Green & Woodrooffe (2006) also disaggregated by surface wetness and found that ESC was far more effective at preventing loss of control crashes on non-dry roads compared to dry roads.

3.2.6 Effect on multiple vehicle crashes

The effectiveness of ESC on multiple vehicle crashes appears to be limited, apart from those that result in fatal injuries. Many of the studies found non significant results despite large sample sizes and small confidence intervals. When the results were disaggregated by vehicle type, there was little detectable difference in effectiveness between passenger vehicles and SUVs or 4WDs.

The reason for the limited effectiveness in low severity multiple vehicle crashes is thought to be because low speed, intersection type crashes, which make up the majority of multiple vehicle crashes, are not affected by ESC. Crashes which involve driver misjudgement, like poor gap selection or inattention, often occur regardless of vehicle stability and result in rear end or right angle type collisions. Furthermore, some results have indicated that ESC may, in fact, increase multiple vehicle crash rate. The reason for this is yet to be investigated.

For all multiple vehicle crashes the effectiveness of ESC was found to be an increase in crash rate of 3% - 15% (Farmer, 2004, 2006; Scully & Newstead, 2007, 2010; Sivinski, 2011). When considering multiple vehicle crashes that resulted in an injury, the results ranged between an increase of 3% and a decrease of 2% and none were significant (Farmer, 2004, 2006; Scully & Newstead, 2007, 2010).

For fatal multiple vehicle crashes a decrease of around 33% was found by Farmer (2004, 2006), along with a non-significant decrease of 6% by Sivinski (2011). A decrease of 16% was found for fatal multiple vehicles crashes involving passenger vehicles or commercial vehicles where the driver of the ESC vehicle was considered to be culpable Kahane (2014).

Two of the studies further disaggregated the multiple vehicle results by crash type and both looked specifically at head on crashes. Aga & Okada (2003) found a decrease of 30% in head on crashes of all severities, while Scully & Newstead (2010) found a smaller decrease of only 5%. Scully & Newstead (2010) also investigated head on crashes that resulted in an injury and concluded a non-significant decrease of 3%.

3.2.7 Effect in Australia

Only two studies were conducted in Australia, using Australian data. Scully & Newstead (2007, 2010) investigated the effectiveness of ESC using data from New South Wales, Queensland, South Australia, Victoria, Western Australia and New Zealand. The results were similar to the findings of other overseas studies. While such a comparison may not be altogether valid given the variance in study methodologies, it was noted that the Australian results were slightly more conservative compared with the overseas results.

3.2.8 Reviews of effectiveness

Ferguson (2007) presented a thorough review of literature concerning the effectiveness of ESC. The review discusses the methodological differences among the literature and examines the findings according to vehicle type, crash type, crash severity and road conditions. All of the literature reviewed is included within the literature review presented here.

Erke (2008) applied a meta analysis to the results of several of the studies reviewed here and found significant amounts of heterogeneity, especially for single vehicle crashes. Using a sensitivity analysis it was revealed that the results for single vehicle crashes are likely being affected by publication bias that could produce an overestimation of the real effect. It was suggested that the overestimation by published studies may be the result of using methodologies that do not account for factors such as vehicle properties, time trends, and driver behaviour.

The meta analysis by Erke was repeated by Høye (2011) who used a greater number of studies, including some that were updated versions of earlier studies. The results again showed that there is likely to be some kind of publication bias affecting the reported ESC effectiveness in reducing single vehicle crashes, along with rollover and run-off-road crashes. Conversely, publication bias was unlikely to be affecting the reported ESC effectiveness in reducing multiple vehicle, pedestrian, bicycle, and animal crashes. Methodological aspects were also again found to have an effect on the accuracy of study results; those studies that controlled for driver characteristics reported ESC effectiveness results that were lower than those studies that did not.

3.2.9 Effect in combination with other technologies

At around the same period and subsequent to the introduction of ESC, several other vehicle safety technologies were brought to market including emergency brake assist (EBA), side curtain airbags, autonomous emergency braking (AEB), and lane departure warning. The majority of the studies presented above isolated the effectiveness of ESC by controlling for the effect of these other technologies. However, Flannagan & Flannagan (2009) pointed out that there will be some overlap in the types of crash that each technology will address and that this may diminish the overall effectiveness of ESC.

One study was found that explored the interaction between ESC and other vehicle safety technologies. Page et al. (2009) investigated the crash reduction benefit for different combinations of ESC, emergency brake assist (EBA), and 4 or 5 star Euro NCAP safety ratings. This enabled the analysis of how overall safety benefit is affected by the addition of ESC. There was clearly some overlap between the benefits provided by each technology. However, it was found that, regardless of the existing safety features, the addition of ESC always resulted in a greater overall crash reduction.

Tab. 3.1: Summary of ESC effectiveness studies

Study	**Country**	**Method (Control)**	**Severity**	**Type**	**Effectiveness (95% CI)**
Aga & Okada (2003)	Japan	Direct exposure (vehicle years)	All	Single vehicle crashes	-35%
			All	Head on crashes	-30%
			Moderate dmg.	Single vehicle crashes	-50%
			Moderate dmg.	Head on crashes	-40%
			Casualty	Single vehicle or head on crashes	-35%
Tingvall et al. (2003)	Sweden	Induced exposure (rear end crashes on dry roads)	Casualty	Crashes other than rear end	-22% (-1%, -43%)
			Casualty	Crashes on dry roads	-9% (+19%, -38%)ˆ
			Casualty	Crashes on wet roads	-32% (-8%, -55%)
			Casualty	Crashes on snowy/icy roads	-38% (-12%, -64%)
			Casualty	Crashes involving a small FWD vehicle	-28%ˆ
			Casualty	Crashes involving a small FWD vehicle on wet/snowy/icy roads	-25%ˆ
			Casualty	Crashes involving a large FWD vehicle	-21%ˆ
			Casualty	Crashes involving a large FWD vehicle on wet/snowy/icy roads	-59%
			Casualty	Crashes involving a large RWD vehicle	-45%
			Casualty	Crashes involving a large RWD vehicle on wet/snowy/icy roads	-46%
Dang (2004)	USA	Induced exposure (multi-vehicle crashes)	All	Single vehicle crashes involving PVs	-35% (-29%, -41%)
			All	Single vehicle crashes involving SUVs	-67% (-60%, -74%)
			Fatal	Single vehicle crashes involving PVs	-30% (-10%, -50%)
			Fatal	Single vehicle crashes involving SUVs	-63% (-44%, -81%)
Farmer (2004)	USA	Direct exposure (registration years)	All	All crashes	-1% (-7%, +4%)ˆ
			All	Multiple vehicle crashes	+5% (-1%, +11%)ˆ
			All	Single vehicle crashes	-50% (-60%, -39%)
			All	Single vehicle, rollover crashes	-74% (-88%, -46%)
			Casualty	All crashes	-3% (-12%, +7%)ˆ
			Casualty	Multiple vehicle crashes	+3% (-8%, +14%)ˆ

Continued on next page | ˆ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

Tab. 3.1: Summary of ESC effectiveness studies (*continued*)

Study	**Country**	**Method (Control)**	**Severity**	**Type**	**Effectiveness (95% CI)**
			Casualty	Single vehicle crashes	-43% (-59%, -21%)
			Casualty	Single vehicle, rollover crashes	-78% (-92%, -45%)
			Fatal	All crashes	-50% (-63%, -33%)
			Fatal	Multiple vehicle crashes	-35% (-55%, -6%)
			Fatal	Single vehicle crashes	-69% (-82%, -47%)
			Fatal	Single vehicle, rollover crashes	-87% (-96%, -66%)
Bahouth	USA	Induced exposure	All	Multiple vehicle, frontal crashes	-12% (-2%, -21%)
(2005)		(rear end crashes)	All	Single vehicle crashes	-53% (-43%, -63%)
Kreiss et al.	Germany	Induced exposure	All	ESC sensitive crashes	-32%
(2005)		(crashes involving	Fatal	ESC sensitive crashes	-56% (-31%, -71%)
		vehicles turning	All	Crashes on dry roads	-36%†
		on/off road, or	All	Crashes on wet roads	-24%†
		stationary)	All	Crashes on icy roads	-19%ˆ †
			All	Crashes on dry roads in built up areas	-28%†
			All	Crashes on wet roads in built up areas	-31%†
			All	Crashes on icy roads in built up areas	+10%ˆ †
			All	Crashes on dry roads outside built up areas	-42%†
			All	Crashes on wet roads outside built up areas	-20%†
			All	Crashes on icy roads outside built up areas	-29%ˆ †
			All	Crashes on roads in built up areas	-27%†
			All	Crashes on roads outside built up areas	-34%†
			All	Crashes involving male drivers	-31%†
			All	Crashes involving female drivers	-44%†

Continued on next page | ˆ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

Tab. 3.1: Summary of ESC effectiveness studies (*continued*)

Study	**Country**	**Method (Control)**	**Severity**	**Type**	**Effectiveness (95% CI)**
Lie et al. (2005)	Sweden	Induced exposure (rear end crashes on dry roads)	Casualty	Crashes other than rear end	-23% (-32%, -14%)
			Fatal and serious	Crashes other than rear end	-27% (-41%, -13%)
			Casualty	Single vehicle, oncoming/overtaking crashes	-31% (-41%, -21%)
			Fatal and serious	Single vehicle, oncoming/overtaking crashes	-41% (-56%, -26%)
			Fatal and serious	Single vehicle crashes	-44% (-64%, -25%)
			Fatal and serious	Single vehicle, oncoming/overtaking crashes on dry roads	-25% (-51%, +1%)ˆ
			Fatal and serious	Single vehicle, oncoming/overtaking crashes on wet roads	-56% (-80%, -33%)
			Fatal and serious	Single vehicle, oncoming/overtaking crashes on snowy/icy roads	-49% (-79%, -19%)
			Fatal and serious	Single vehicle, oncoming/overtaking crashes on wet/snowy/icy roads	-53% (-71%, -35%)
			Fatal	Single vehicle, oncoming/overtaking crashes on wet/snowy/icy roads	-53% (-98%, -8%)
Bahouth (2006)	USA	Multiple (rear end crashes, and vehicle registrations)	Fatal and serious	All crashes	-53% (-73%, -18%)
			Minor injuries	All crashes	-31% (-43%, -15%)
			Fatal	All crashes	-34% (-40%, -26%)
			Fatal	Single vehicle crashes	-56% (-64%, -47%)
Farmer (2006)	USA	Direct exposure (registration years)	All	All crashes	-2% (-5%, 0%)ˆ
			All	Crashes involving PVs	-1% (-5%, +2%)ˆ
			All	Crashes involving SUVs	-3% (-6%, +1%)ˆ
			All	Multiple vehicle crashes	+3% (0%, +6%)ˆ
			All	Multiple vehicle crashes involving PVs	+3% (-1%, +7%)ˆ
			All	Multiple vehicle crashes involving SUVs	+4% (0%, +7%)ˆ
			All	Multiple vehicle crashes in adverse conditions	+1% (-3%, +6%)ˆ
			All	Multiple vehicle crashes in adverse conditions involving PVs	+3% (-3%, +10%)ˆ
			All	Multiple vehicle crashes in adverse conditions involving SUVs	-1% (-7%, +6%)ˆ
			All	Single vehicle crashes	-41% (-56%, -36%)
			All	Single vehicle crashes involving PVs	-33% (-40%, -25%)
			All	Single vehicle crashes involving SUVs	-49% (-55%, -43%)
			All	Single vehicle, rollover crashes	-76% (-84%, -66%)

Continued on next page | ˆ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

Tab. 3.1: Summary of ESC effectiveness studies (*continued*)

Study	**Country**	**Method (Control)**	**Severity**	**Type**	**Effectiveness (95% CI)**
			All	Single vehicle, rollover crashes involving PVs	-72% (-87%, -42%)
			All	Single vehicle, rollover crashes involving SUVs	-77% (-85%, -66%)
			Injury	All crashes	-5% (-9%, -1%)
			Injury	Crashes involving PVs	-2% (-8%, +4%)^
			Injury	Crashes involving SUVs	-7% (-12%, -1%)
			Injury	Multiple vehicle crashes	+2% (-3%, +6%)^
			Injury	Multiple vehicle crashes involving PVs	+2% (-4%, +9%)^
			Injury	Multiple vehicle crashes involving SUVs	+1% (-5%, +8%)^
			Injury	Multiple vehicle crashes in adverse conditions	+2% (-5%, +10%)^
			Injury	Multiple vehicle crashes in adverse conditions involving PVs	+4% (-7%, +15%)^
			Injury	Multiple vehicle crashes in adverse conditions involving SUVs	0% (-10%, +11%)^
			Injury	Single vehicle crashes	-45% (-52%, -38%)
			Injury	Single vehicle crashes involving PVs	-33% (-45%, -20%)
			Injury	Single vehicle crashes involving SUVs	-56% (-64%, -46%)
			Injury	Single vehicle, rollover crashes	-77% (-86%, -64%)
			Injury	Single vehicle, rollover crashes involving PVs	-75% (-91%, -41%)
			Injury	Single vehicle, rollover crashes involving SUVs	-78% (-88%, -62%)
			Fatal	All crashes	-43% (-51%, -33%)
			Fatal	Crashes involving PVs	-38% (-51%, -22%)
			Fatal	Crashes involving SUVs	-46% (-56%, -34%)
			Fatal	Multiple vehicle crashes	-32% (-44%, -18%)
			Fatal	Multiple vehicle crashes involving PVs	-25% (-44%, +1%)^
			Fatal	Multiple vehicle crashes involving SUVs	-37% (-51%, -18%)
			Fatal	Multiple vehicle crashes in adverse conditions	-33% (-53%, -4%)
			Fatal	Multiple vehicle crashes in adverse conditions involving PVs	-48% (-70%, -12%)
			Fatal	Multiple vehicle crashes in adverse conditions involving SUVs	-16% (-49%, +39%)^
			Fatal	Multiple vehicle crashes on high speed roads	-47% (-60%, -30%)
			Fatal	Multiple vehicle crashes on high speed roads involving PVs	-28% (-55%, +12%)^
			Fatal	Multiple vehicle crashes on high speed roads involving SUVs	-56% (-70%, -36%)

Continued on next page | ^ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

Tab. 3.1: Summary of ESC effectiveness studies (*continued*)

Study	Country	Method (Control)	Severity	Type	Effectiveness (95% CI)
			Fatal	Single vehicle crashes	-56% (-66%, -44%)
			Fatal	Single vehicle crashes involving PVs	-53% (-68%, -32%)
			Fatal	Single vehicle crashes involving SUVs	-59% (-72%, -42%)
			Fatal	Single vehicle, rollover crashes	-79% (-87%, -67%)
			Fatal	Single vehicle, rollover crashes involving PVs	-77% (-91%, -49%)
			Fatal	Single vehicle, rollover crashes involving SUVs	-80% (-89%, -64%)
Green & Woodrooffe (2006)	USA	Induced exposure (many - see paper)	Fatal	Single vehicle crashes involving PVs	-31% (-48%, -13%)
			Fatal	Single vehicle crashes involving SUVs	-50% (-69%, -30%)
			Fatal	Off road crashes involving PVs	-35% (-52%, -18%)
			Fatal	Off road crashes involving SUVs	-56% (-75%, -37%)
			Fatal	Rollover crashes involving PVs	-40% (-60%, -19%)
			Fatal	Rollover crashes involving SUVs	-73% (-85%, -61%)
			Fatal	Crashes on non dry roads involving PVs	-25% (-73%, +22%)ˆ
			Fatal	Crashes on non dry roads involving SUVs	-30% (-92%, +31%)ˆ
			All	Loss of control crashes involving PVs	-55% (-68%, -41%)
			All	Loss of control crashes involving SUVs	-70% (-83%, -58%)
			All	Loss of control crashes on dry roads involving PVs	-40% (-61%, -19%)
			All	Loss of control crashes on non dry roads involving PVs	-75% (-91%, -59%)
			All	Loss of control crashes on dry roads involving SUVs	-53% (-75%, -30%)
			All	Loss of control crashes on non dry roads involving SUVs	-88% (-100%, -76%)
Thomas (2006)	Great Britain	Induced exposure (vehicle that was parked, reversing, stopped or slow moving)	Casualty	All crashes	-3% (-6%, -1%)
			Fatal and serious	All crashes	-19% (-27%, -8%)
			Fatal	All crashes	-15% (-37%, +26%)ˆ
			Casualty	Crashes on wet roads	-4%ˆ
			Fatal and serious	Crashes on wet roads	-34%
			Fatal	Crashes on wet roads	-50%
			Casualty	Crashes on dry roads	-2%ˆ

Continued on next page | ˆ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

Tab. 3.1: Summary of ESC effectiveness studies (*continued*)

Study	Country	Method (Control)	Severity	Type	Effectiveness (95% CI)
			Fatal and serious	Crashes on dry roads	-9%ˆ
			Fatal	Crashes on dry roads	+22%ˆ
			Casualty	Crashes on snowy/icy roads	-25%
			Fatal and serious	Crashes on snowy/icy roads	-53%
			Casualty	Crashes involving skidding	-20%
			Fatal and serious	Crashes involving skidding	-40%
			Casualty	Rollover crashes	-50%
			Casualty	Single vehicle crashes	-2%ˆ
			Fatal and serious	Single vehicle crashes	-1%ˆ
			Fatal	Single vehicle crashes	-24%ˆ
			Casualty	Crashes involving male drivers	-5%
			Fatal and serious	Crashes involving male drivers	-21%
			Fatal	Crashes involving male drivers	-40%
			Casualty	Crashes involving female drivers	+1%ˆ
			Fatal and serious	Crashes involving female drivers	-17%
			Fatal	Crashes involving female drivers	+26%ˆ
			Casualty	Crashes involving frontal collisions	-10%
			Fatal and serious	Crashes involving frontal collisions	-18%
			Casualty	Crashes involving side collisions	-7%
			Fatal and serious	Crashes involving side collisions	-28%
			Fatal	Crashes involving side collisions	+38%ˆ
Dang (2007)	USA	Induced exposure (many - see paper)	All	Single vehicle crashes involving PVs	-26%
			Fatal	Single vehicle crashes involving PVs	-36%
			All	Single vehicle, run off road crashes involving PVs	-45%
			Fatal	Single vehicle, run off road crashes involving PVs	-36%
			All	Single vehicle, rollover crashes involving PVs	-64%
			Fatal	Single vehicle, rollover crashes involving PVs	-70%
			All	Multi-vehicle, culpable party crashes involving PVs	-13%

Continued on next page | ˆ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

Tab. 3.1: Summary of ESC effectiveness studies (*continued*)

Study	**Country**	**Method (Control)**	**Severity**	**Type**	**Effectiveness (95% CI)**
			Fatal	Multi-vehicle, culpable party crashes involving PVs	-19%ˆ
			All	Crashes involving PVs	-8%
			Fatal	Crashes involving PVs	-14%ˆ
Padmanaban (2007)	USA	Induced exposure (many - see paper)	Fatal	Rollover crashes involving PVs	-53% (-74%, -15%)
			Fatal	Single vehicle, rollover (first harmful event) crashes involving PVs	-69% (-89%, -17%)
			Fatal	Single vehicle, rollover (not first harmful event) crashes involving PVs	-55% (-78%, -6%)
			Fatal	Multiple vehicle, rollover crashes involving PVs	+8% (-63%, +216%)ˆ
			Fatal	Side impact with fixed object, non rollover crashes involving PVs	-61% (-83%, -12%)
			Fatal	Single vehicle crashes involving PVs	-27% (-50%, +5%)ˆ
			Fatal	Single vehicle, non rollover crashes involving PVs	-13% (-41%, +28%)ˆ
			Fatal	Multiple vehicle crashes involving PVs	+5% (-23%, +43%)ˆ
			Fatal	Multiple vehicle, non rollover crashes involving PVs	+5% (-23%, +44%)ˆ
Scully & Newstead (2007)	Australia	Induced exposure (rear end crashes)	All	All crashes	+7% (+2%, +13%)
			Driver injury	All crashes	-10% (-14%, +2%)ˆ
			All	Crashes involving PVs	+8% (+3%, +14%)
			Driver injury	Crashes involving PVs	-9% (-20%, +4%)ˆ
			All	Crashes involving 4WDs	-3% (-16%, +13%)ˆ
			Driver injury	Crashes involving 4WDs	-25% (-53%, +20%)ˆ
			All	Single vehicle crashes	-29% (-35%, -21%)
			Driver injury	Single vehicle crashes	-32% (-45%, -17%)
			All	Single vehicle crashes involving PVs	-24% (-32%, -16%)
			Driver injury	Single vehicle crashes involving PVs	-27% (-41%, -9%)
			All	Single vehicle crashes involving 4WDs	-55% (-66%, -39%)
			Driver injury	Single vehicle crashes involving 4WDs	-68% (-84%, -35%)
			All	Multiple vehicle crashes	+15% (+9%, +21%)
			Driver injury	Multiple vehicle crashes	-2% (-14%, +12%)ˆ
			All	Multiple vehicle crashes involving PVs	+15% (+9%, +22%)

Continued on next page | ˆ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

Tab. 3.1: Summary of ESC effectiveness studies (*continued*)

Study	Country	Method (Control)	Severity	Type	Effectiveness (95% CI)
			Driver injury	Multiple vehicle crashes involving PVs	-3% (-15%, +11%)ˆ
			All	Multiple vehicle crashes involving 4WDs	+13% (-3%, +32%)ˆ
			Driver injury	Multiple vehicle crashes involving 4WDs	+4% (-31%, +89%)ˆ
Thomas & Frampton (2007)	Great Britain	Induced exposure (struck vehicle that was parked, stopped or slow moving)	All	All crashes	-7%
			Slight	All crashes	-6%
			Serious	All crashes	-11%
			Fatal	All crashes	-25%ˆ
			All	Crashes on wet roads	-9%
			Slight	Crashes on wet roads	-7%
			Serious	Crashes on wet roads	-22%
			Fatal	Crashes on wet roads	-38%ˆ
			All	Crashes on dry roads	-5%
			Slight	Crashes on dry roads	-5%
			Serious	Crashes on dry roads	-3%ˆ
			Fatal	Crashes on dry roads	-17%ˆ
			All	Crashes on snowy/icy roads	-20%
			Slight	Crashes on snowy/icy roads	-19%
			Serious	Crashes on snowy/icy roads	-30%ˆ
			All	Crashes involving skidding	-23%
			Slight	Crashes involving skidding	-21%
			Serious	Crashes involving skidding	-33%
			All	Rollover crashes	-36%
			Slight	Rollover crashes	-33%
			Serious	Rollover crashes	-59%
			All	Single vehicle crashes	-27%
			Slight	Single vehicle crashes	-17%ˆ
			Serious	Single vehicle crashes	-91%ˆ
			All	Crashes involving male drivers	-7%

Continued on next page | ˆ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

Tab. 3.1: Summary of ESC effectiveness studies (*continued*)

Study	**Country**	**Method (Control)**	**Severity**	**Type**	**Effectiveness (95% CI)**
			Slight	Crashes involving male drivers	-6%
			Serious	Crashes involving male drivers	-10%ˆ
			Fatal	Crashes involving male drivers	-48%
			All	Crashes involving female drivers	-5%
			Slight	Crashes involving female drivers	-4%
			Serious	Crashes involving female drivers	-15%ˆ
			Fatal	Crashes involving female drivers	-19%ˆ
			All	Crashes involving frontal collisions	-10%
			Slight	Crashes involving frontal collisions	-10%
			Serious	Crashes involving frontal collisions	-2%ˆ
			Fatal	Crashes involving frontal collisions	-23%ˆ
			All	Crashes involving side collisions	-9%
			Slight	Crashes involving side collisions	-7%
			Serious	Crashes involving side collisions	-22%ˆ
			Fatal	Crashes involving side collisions	+27%ˆ
MacLennan et al. (2008)	USA	Induced exposure (number of vehicle crashes)	All	Rollover crashes	-38% (-50%, -23%)
			All	Tripped rollover crashes	-41% (-54%, -25%)
			All	Rollover crashes involving SUVs/vans	-53% (-66%, -36%)
			All	Tripped rollover crashes involving SUVs/vans	-53% (-67%, -34%)
			All	Rollover crashes involving PVs	-32% (-51%, -7%)
			All	Tripped rollover crashes involving PVs	-40% (-57%, -16%)
			All	Single vehicle, rollover crashes	-39% (-54%, -18%)
			All	Single vehicle, tripped rollover crashes	-46% (-61%, -24%)
			All	Single vehicle, rollover crashes involving SUVs/vans	-60% (-74%, -39%)
			All	Single vehicle, tripped rollover crashes involving SUVs/vans	-64% (-78%, -41%)
			All	Single vehicle, rollover crashes involving PVs	-23% (-47%, +12%)ˆ
			All	Single vehicle, tripped rollover crashes involving PVs	-32% (-55%, +2%)ˆ

Continued on next page | ˆ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

Tab. 3.1: Summary of ESC effectiveness studies (*continued*)

Study	Country	Method (Control)	Severity	Type	Effectiveness (95% CI)
Scully & Newstead (2010)	Australia	Induced exposure (rear end crashes)	All	All crashes	+1% (-2%, +5%)^
			Driver injury	All crashes	-8% (-15%, -1%)
			All	Crashes involving PVs	+5% (+1%, +9%)
			Driver injury	Crashes involving PVs	-3% (-11%, +5%)^
			All	Crashes involving CVs	-10% (-28%, +11%)^
			Driver injury	Crashes involving CVs	-29% (-62%, +33%)^
			All	Crashes involving 4WDs	-13% (-19%, -6%)
			Driver injury	Crashes involving 4WDs	-34% (-47%, -18%)
			All	Single vehicle crashes	-27% (-32%, -23%)
			Driver injury	Single vehicle crashes	-32% (-39%, -23%)
			All	Single vehicle crashes involving PVs	-19% (-24%, -13%)
			Driver injury	Single vehicle crashes involving PVs	-23% (-32%, -12%)
			All	Single vehicle crashes involving CVs	-10% (-37%, +27%)^
			Driver injury	Single vehicle crashes involving CVs	-15% (-61%, +85%)^
			All	Single vehicle crashes involving 4WDs	-56% (-62%, -49%)
			Driver injury	Single vehicle crashes involving 4WDs	-65% (-74%, -52%)
			All	Rollover crashes	-56% (-63%, -47%)
			Driver injury	Rollover crashes	-60% (-69%, -48%)
			All	Rollover crashes involving PVs	-34% (-46%, -19%)
			Driver injury	Rollover crashes involving PVs	-46% (-60%, -26%)
			All	Rollover crashes involving CVs	-54% (-83%, +27%)^
			Driver injury	Rollover crashes involving CVs	-19% (-74%, +148%)^
			All	Rollover crashes involving 4WDs	-82% (-87%, -74%)
			Driver injury	Rollover crashes involving 4WDs	-80% (-88%, -67%)
			All	Multiple vehicle crashes	+8% (+4%, +12%)
			Driver injury	Multiple vehicle crashes	+1% (-7%, +10%)^
			All	Multiple vehicle crashes involving PVs	+10% (+6%, +14%)
			Driver injury	Multiple vehicle crashes involving PVs	+4% (-5%, +13%)^
			All	Multiple vehicle crashes involving CVs	-11% (-29%, +12%)^

Continued on next page | ^ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

Tab. 3.1: Summary of ESC effectiveness studies (*continued*)

Study	**Country**	**Method (Control)**	**Severity**	**Type**	**Effectiveness (95% CI)**
			Driver injury	Multiple vehicle crashes involving CVs	-38% (-70%, +29%)ˆ
			All	Multiple vehicle crashes involving 4WDs	+1% (-7%, +9%)ˆ
			Driver injury	Multiple vehicle crashes involving 4WDs	-13% (-31%, +10%)ˆ
			All	Head on crashes	-5% (-15%, +7%)ˆ
			Driver injury	Head on crashes	-3% (-21%, +18%)ˆ
			All	Head on crashes involving PVs	+13% (-1%, +28%)ˆ
			Driver injury	Head on crashes involving PVs	+10% (-12%, +37%)ˆ
			All	Head on crashes involving CVs	-70% (-91%, -6%)
			Driver injury	Head on crashes involving CVs	-8% (-80%, +314%)ˆ
			All	Head on crashes involving 4WDs	-42% (-55%, -25%)
			Driver injury	Head on crashes involving 4WDs	-47% (-69%, -10%)
Chouinard & Lécuyer (2011)	Canada	Induced exposure (all crashes not sensitive to ESC, including almost 95% of multiple vehicle crashes)	All	All ESC-sensitive crashes	-41%
			All	Single vehicle, ESC-sensitive crashes	-19%
			All	Multiple vehicle, ESC-sensitive crashes	-23%
			All	All ESC-sensitive crashes involving PVs	-29%
			All	All ESC-sensitive crashes on dry roads	-36%
			All	All ESC-sensitive crashes on wet roads	-36%
			All	All ESC-sensitive crashes on ice/snow/slush covered roads	-51%
			Injury	All ESC-sensitive crashes	-55%
			Injury	Single vehicle, ESC-sensitive crashes	-49%
			Injury	Multiple vehicle, ESC-sensitive crashes	-28%
			Injury	All ESC-sensitive crashes involving PVs	-44%
			Injury	All ESC-sensitive crashes on dry roads	-47%
			Injury	All ESC-sensitive crashes on wet roads	-50%
			Injury	All ESC-sensitive crashes on ice/snow/slush covered roads	-71%

Continued on next page | ˆ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

Tab. 3.1: Summary of ESC effectiveness studies (*continued*)

Study	Country	Method (Control)	Severity	Type	Effectiveness (95% CI)
Sivinski	USA	Induced exposure	All	All crashes	-6%
(2011)		(many - see paper)	All	Single vehicle crashes	-50%
			All	Single vehicle, rollover crashes	-67%
			All	Single vehicle, impact with fixed object crashes	-58%
			All	Multiple vehicle crashes	0%^
			All	All crashes involving PVs	-5%^
			All	Single vehicle crashes involving PVs	-32%^
			All	Single vehicle, rollover crashes involving PVs	-72%
			All	Single vehicle, impact with fixed object crashes involving PVs	-30%^
			All	Multiple vehicle crashes involving PVs	+1%^
			Fatal	All crashes	-18%
			Fatal	Single vehicle crashes	-49%
			Fatal	Single vehicle, rollover crashes	-72%
			Fatal	Single vehicle, impact with fixed object crashes	-39%
			Fatal	Multiple vehicle crashes	-6%^
			Fatal	All crashes involving PVs	-23%
			Fatal	Single vehicle crashes involving PVs	-50%
			Fatal	Single vehicle, rollover crashes involving PVs	-56%
			Fatal	Single vehicle, impact with fixed object crashes involving PVs	-47%
			Fatal	Multiple vehicle crashes involving PVs	-8%^
Kahane	USA	Induced exposure	Fatal	Single vehicle crashes (excluding rollovers) involving PVs	-31%
(2014)		(many - see paper)	Fatal	Single vehicle crashes (excluding rollovers) involving CVs	-46%
			Fatal	Single vehicle crashes involving PVs	-60%
			Fatal	Single vehicle crashes involving CVs	-74%
			Fatal	Multiple vehicle crashes where culpable involving PVs	-16%
			Fatal	Multiple vehicle crashes where culpable involving CVs	-16%

^ known to be non significant, † value estimated from graph | PV = passenger vehicle, SUV = sports utility vehicle, CV = commercial vehicle

3.3 Assessment of ESC performance

In the previous section the estimated effectiveness of ESC in preventing certain types of crash were impressive but there is no suggestion that vehicles equipped with ESC are completely immune to crashing. Indeed, several studies have specifically identified crashes involving ESC equipped vehicles (Eyges et al., 2010; Lie, 2012; Padmanaban et al., 2008). If follows, then, that some measure of ESC effectiveness should be sought.

Furthermore, each ESC system associated with a specific vehicle model is unique. The software within an ESC system that decides when and how hard to apply braking interventions is calibrated individually for each vehicle model based on its design and dynamics. In addition, the calibration may be adjusted based on the style of the vehicle. For example some 'sporty' vehicles may be equipped with an ESC system that allows a small amount of sideways sliding before an intervention while an ESC system in a family sedan might intervene early at the first sign of trouble.

The US National Highway Traffic Safety Administration (NHTSA) recognised that a method of objectively assessing the effectiveness of individual ESC systems was required. The NHTSA Light Vehicle Handling and ESC research program aimed to identify an appropriate test manoeuvre for assessing ESC performance and develop a method of assessing ESC effectiveness (Forkenbrock et al., 2005).

Forkenbrock et al. considered that a test manoeuvre with the ability to determine whether a vehicle is equipped with ESC, and be able to assess its performance, would possess the following attributes:

- Be repeatable and reproducible
- Impose a high level of severity on the test vehicle and its respective ESC
- Consider lateral stability and responsiveness

Twelve candidate test manoeuvres were rated based on how well they addressed these attributes. Four were identified as those with the best potential for assessing ESC performance: the increasing amplitude sine, the sine with dwell, the yaw acceleration steering reversal, and the increasing amplitude yaw acceleration steering reversal.

Forkenbrock et al. (2005) then turned their attention to how the results of such manoeuvres could be used to assess the effectiveness of ESC. It was acknowledged that ESC counteracts both understeer and oversteer but the focus was to develop a method to identify when a manoeuvre resulted in a 'spin out' caused exclusively by oversteer, while ignoring understeer. ESC was expected to primarily prevent oversteer and thus the presence or absence of a spin out during a test manoeuvre presented a measure of ESC performance.

Spin out was defined to occur when the final heading of a vehicle at the end of a test manoeuvre was at least 90 degrees different from the heading of the vehicle at the start of the manoeuvre. The heading of a vehicle is difficult to determine easily however, and an alternate indication of spin out was sought.

During testing, Forkenbrock et al. discovered that the yaw rate of vehicles that met the spin out criterion would remain high long after the manoeuvre steering inputs were completed. This phenomenon was explored and developed into the yaw rate ratio (YRR) that is described by Equation 3.1, where $\omega(t)$ is the vehicle yaw rate at time t after the test manoeuvre steering inputs are complete and ω_{peak} is the peak yaw rate of the vehicle during the test manoeuvre. A logistic regression analysis of various values of YRR and t showed specific combinations of YRR and t had the potential to predict spin out.

$$YRR = 100 \times \left(\frac{\omega(t)}{\omega_{peak}} \right) \tag{3.1}$$

Research into assessing the effectiveness of individual ESC systems was continued when on September 18, 2006 NHTSA announced a proposal that would require ESC to be fitted on all new light vehicles by model year 2012 (NHTSA, 2006). This proposal, Federal Motor Vehicle Safety Standard 126 (FMVSS126), also required an ESC compliance test with a minimum effectiveness criterion.

Based on the previous work from 2004, a final test manoeuvre for assessing ESC and a specific criterion for how a vehicle equipped with ESC should perform during the test was developed (Forkenbrock & Boyd, 2007; Forkenbrock et al., 2006).

The sine with dwell test manoeuvre was selected, in preference to the three other test manoeuvres identified as potential candidates, for its ability to elicit excessive yaw from the test vehicle using relatively low steering angles.

Further analysis of the relationship between the values of YRR and t in predicting spin out, using data from tests with an extensive set of vehicles models, enabled a spin out prediction model to be constructed. This model predicted the likelihood of spin out based on the values of YRR and t. The ESC minimum effectiveness criteria was based on two pairs of YRR and t values that predicted a 95% chance that no spin out would have occurred. To pass the ESC minimum effectiveness criteria a vehicle must achieve both of the following targets during the sine with dwell test:

- At $t = 1.00$ seconds, $YRR \leq 35\%$
- At $t = 1.75$ seconds, $YRR \leq 20\%$

A third minimum effectiveness criterion was then sought with the justification that the benefits of ESC should not come at the expense of the vehicle not sufficiently responding to the driver's steering inputs. This was curious because, despite stating explicitly that understeer would be ignored, 'responsiveness to a driver's steering inputs' appeared to be acting as a proxy for the ability to prevent understeer.

After investigating several options, vehicle lateral displacement (d_{lat}) at the completion of the third quarter cycle of the sine with dwell steering input was selected as the definition of responsiveness. A small amount of displacement would indicate low responsiveness and a large amount of displacement would indicate high responsiveness.

In order to choose a minimum criteria, the lateral displacements of the vehicles that were used to construct the spin out prediction model were analysed and the responsiveness of each vehicle model was calculated. The minimum criteria for responsiveness was then chosen as the minimum level of responsiveness achieved by this group of vehicles (which included several types of vehicles not equipped with ESC such as vans, SUVs, and a limousine). The minimum level of responsiveness was thus a lateral displacement at the completion of the third quarter cycle of the sine with dwell steering input of 1.83 metres.

The third ESC minimum effectiveness criterion was therefore defined as the ability to match the minimum responsiveness of the general non-ESC equipped vehicle fleet at the time of the study. The justification for this undemanding criterion was that it would ensure vehicle responsiveness in the future did not degrade beyond that achieved by contemporary vehicles.

In 2007, NHTSA published the final version of FMVSS126 which included the minimum ESC effectiveness criteria discussed above (NHTSA, 2007). In June of 2009, the Department of Infrastructure and Transport of the Australian Government published Australian Design Rule 31/02 covering braking systems for passenger cars (Department of Infrastructure and Transport, 2009). This rule requires all new vehicle models to be equipped with ESC by November 2011, and all vehicle models to be equipped with ESC by November 2013. As part of the rule all ESC equipped vehicles must comply with the NHTSA minimum ESC effectiveness criteria.

3.4 Discussion of literature

Effectiveness studies of ESC show it to be highly effective in reducing some types of crashes. Relatively consistent results were found among the studies despite the use of several different methodologies and diverse data sets. The effect of ESC on all crashes overall was found to be negligible, but significant reductions were found after disaggregating the results by crash type.

Single vehicle crashes were estimated to have been reduced by between 27% and 50%, while for multiple vehicle crashes an estimated increase of between 3% and 15% was found. More specific crash types like rollover and loss of control were reduced by between 39% and 76%, and between 55% and 70% respectively. The effectiveness for each crash type was altered after further disaggregating by injury severity, vehicle type, and surface type.

ESC effectiveness increased for higher levels of injury severity. Fatal crashes were especially receptive to the effects of ESC, with fatal single vehicle crashes being reduced by between 56% and 69%.

Larger vehicle types such as SUVs and 4WDs benefitted more from ESC than passenger vehicles. For example, in single vehicle crashes the effectiveness for passenger vehicles was estimated to be between 19% and 35% while for SUVs/4WDs the effectiveness was estimated to be between 49% and 67%.

Overall, ESC effectiveness appeared to increase for surface types with a lower coefficient of friction. Crashes on snowy and/or icy roads in particular benefitted greatly from the effects of ESC.

Even further disaggregation of results by factors such as driver sex, geographical area, speed zone, weather conditions, and collision orientation was given by some studies.

Studies conducted using Australian crash data found results that were comparable (though slightly more conservative) with the studies conducted in other countries.

Meta analyses of ESC effectiveness studies suggested some caution in accepting the large crash reductions attributed to ESC due to the possibility of publication bias. If a publication bias does exist then the large crash reductions may not last, or be a true indication of the effects of ESC. Several reasons why ESC effectiveness may be overestimated were suggested including new vehicle properties (ESC only being equipped on recent vehicle models), time trends, and driver behaviour. Indeed, two studies found that there was evidence that drivers of ESC equipped vehicles changed their behaviour in ways that could potentially alter the effectiveness of ESC.

In summing up ESC effectiveness, the major benefits appear to be in reducing single vehicle crashes on high speed roads and reducing crashes on surfaces with a low coefficient of friction. Due to Australia's climate, the benefits of ESC for crashes on surfaces with a low coefficient of friction are likely to be minor. However, Australia's extensive rural road network has a great potential to benefit from the advantages of ESC on crashes that occur on high speed roads.

While it is clear from the effectiveness studies that ESC has a positive effect on crashes that occur on high speed roads, no research has investigated the potential effect ESC braking interventions have on individual crashes of this type. That is, how the number, location (i.e. which wheel), strength, and duration of braking interventions on vehicles actually involved in crashes on high speed roads would have altered the trajectory, and to what extent a collision would have been avoided or the severity of a collision reduced.

As a result of this gap in research little is known about which types of high speed crashes ESC may be specifically suited (or not suited) to preventing or how ESC will interact with the broader rural road safety picture. For example, the way in which ESC might interact with other rural road safety initiatives like reducing speeds, sealing roadside shoulders, constructing safety barriers, and implementing clear zones has not been studied explicitly. In addition, the effect of the trade off between oversteer and understeer in terms of high speed crash avoidance is not clear.

Assessment of individual ESC systems was pursued by NHTSA in a two-phase program that first sought a suitable test manoeuvre and then a minimum effectiveness criteria for ESC fitted vehicles. This test and minimum ESC effectiveness criteria was then used in legislation that required ESC to be fitted to all new vehicle models in both the United States and Australia.

The minimum ESC effectiveness criteria provides a lateral stability benchmark that must be achieved by vehicles fitted with an ESC system. There is no direct indication however, of the effectiveness of ESC in crash avoidance. Forkenbrock et al. (2005) acknowledges that the correlation between a loss of control (presumably due to insufficient lateral stability) and vehicle safety is not known, but argues that skidding is attributed as a contributing factor to many crashes. Indeed there is little doubt that an increase in lateral stability is associated with a reduced crash propensity in situations of high speed driving, but the relationship is not clear.

While a minimum effectiveness benchmark for ESC is crucial, there may be greater potential to develop a process with a more quantitative output by analysing how braking interventions effect high speed crashes. That is, a process that rates the effectiveness of ESC in avoiding crashes based on the braking interventions made during a test manoeuvre could be developed.

The opinion that there is potential for improving upon the ESC effectiveness test was also held by Hjort et al. (2009) who suggested that an effectiveness test should also measure the benefits of reduced understeer, reduced collision speed, and improved vehicle roll stability.

4. HIGH SPEED RURAL ROAD CRASHES

This chapter presents an investigation into rural road crashes in South Australia along with an brief analysis of Australian literature on rural road safety. South Australia was chosen as the statewide crash database was readily available to the author. The aim of the investigation was to analyse the rural road safety situation and identify any relationships between high severity injury to vehicle occupants and other crash variables.

4.1 Method

For this investigation, a rural road was defined as any road outside the greater Adelaide metropolitan area as defined by local government boundaries. A high speed rural road was then defined by excluding any roads with a speed limit of less than 80 km/h such as those in rural towns and cities. There was no distinction made between rural and remote roads.

The data used for this investigation were obtained from the Traffic Accident Reporting System (TARS) which is described below. The records for crashes during the years 2008 to 2012, that occurred on a high speed rural road as per the definition described above, were extracted from the database. The five year time frame was selected to ensure enough data were available to detect any significant effects. After removing non casualty crashes, as well as crashes involving pedestrians and non-motorised vehicles (including parked vehicles), 4,565 records remained.

The injury severity of each crash was determined by the highest category of injury sustained by an occupant/rider of any vehicle involved in the crash. There are four categories of injury severity in TARS and these were aggregated into categories of 'high' and 'low' severity (Table 4.1).

Tab. 4.1: Categories of Injury Severity

Category	**Severity**	**Description**
Doctor	Low	Treated by local doctor
Treated	Low	Treated at hospital
Admission	High	Admitted to hospital
Fatal	High	Died as a result of crash (within 30 days)

The results presented below are divided into two sections. The first analyses the relationship between individual categorical variables in the TARS database and crash injury severity. The second presents a logistic regression to identify what combination of variables are indicative of a single vehicle high injury severity crash.

4.1.1 TARS database

Crashes on South Australian roads involving either an injury or total crash damage over a certain threshold ($1,000 before July 2003 and $3,000 thereafter) are recorded by the South Australia Police (SAPOL) on a per-report basis in their vehicle collision computer database system. This data is then further processed by the Department for Transport, Energy and Infrastructure (DTEI) and entered into the TARS database. The processing involves amalgamating different reports of the same crash together, coding up new variables from the data supplied by the police and locating the crashes using road names and geocoded coordinates.

The TARS database is a three tiered database which contains CRASH data, UNIT data and CASUALTY data. Each crash contains a CRASH record, a UNIT record for each vehicle, pedestrian, animal, or object involved, and may contain one or more CASUALTY records for any injured participants. The data recorded in each tier consists of a set of categorical variables. Each CRASH record also contains a free text field where a general crash description may be entered. This description often provides details on the vehicle movements before and after a collision, the impact configuration, the damage and injuries sustained, along with possible reasons for the collision.

Unfortunately, as is common with such mass crash databases (Hutchinson, 1987, chapter 4), some variables are recorded unreliably or contain missing data. Most notably for the TARS database, blood alcohol concentration (BAC) of the driver and seatbelt usage by casualties is often missing.

It should also be noted that the TARS database does not facilitate the recording of multiple events during a crash, such as a rollover followed by an impact with a tree. Typically, the most injurious or severe event will be described in the recorded data and other events are only mentioned in the free text field.

The TARS database is large enough that it is representative of the South Australian road safety situation and flexible enough that analyses on specific crash circumstances can be conducted.

4.2 Results: Categorical variables

4.2.1 Overview

The breakdown of the high speed rural road data set selected according to the method section, by year and severity category, is shown in Table 4.2. The proportion of the total number of crashes accounted for by each of the severity categories is also shown. Of the 4,565 crashes on high speed rural roads, 5 per cent were fatal and 31 per cent required an admission to hospital. In comparison, only 1 per cent of the 21,711 excluded crashes (occurring in the metropolitan area and rural areas in speed zones below 80 km/h) were fatal and only 9 per cent required an admission to hospital.

Tab. 4.2: Number of 'rural road' crashes per year by severity category, 2008 - 2012

Severity	**Year**							**Excluded**	
	2008	**2009**	**2010**	**2011**	**2012**	**Total**	**%**	**crashes**	**%**
Doctor	87	78	67	70	67	369	8%	8975	41%
Treated	525	513	502	508	505	2553	56%	10710	49%
Admitted	315	304	289	280	220	1408	31%	1869	9%
Fatal	43	56	49	44	43	235	5%	157	1%
Total	970	951	907	902	835	4565	100%	21711	100%

In this table and subsequent tables in this chapter, percentages have been rounded to the nearest whole number and thus may not sum to exactly 100%

Analysis of several categorical variables is presented below. Tables in this section show both the relative frequency of the categories within each variable as well as the percentage of high injury severity crashes associated with the categories. Note that this section is descriptive in nature and thus no statistical tests are presented. Moreover, since independent variables are being considered one at a time it is likely that any positive findings from a statistical test would be confounded by other variables and rendered moot. Commentary on the results presented here is given in the Discussion section below.

4.2.2 Crash characteristics

Table 4.3 shows that single vehicle crashes accounted for 75 per cent of all crashes in the sample. Of these single vehicle crashes 'hit fixed object' was the most frequent followed by 'roll over'. Both of these crash types showed similar proportions of high injury severity outcomes.

'Right angle' crashes were the most frequent type of multiple vehicle crash, followed by 'head on'. 'Head on' crashes showed the highest proportion of high severity injuries at 50 per cent, while 'rear end' showed the lowest at 19 per cent.

Since the injury severity of any individual crash depends upon the injury severity of the most seriously injured occupant, it should be noted that the probability of a high injury severity outcome increases with the number of occupants involved. This effect should be considered when comparing single vehicle crashes with multiple vehicle crashes which would, in general, involve more occupants.

There were 2,095 crashes where a collision occurred with an object other than a motor vehicle. Table 4.4 shows the type of object hit in those crashes. Over half of the crashes involved a collision with a tree, while the majority of the remaining crashes involved a collision with 'other fixed objects' which

[2] A Stobie pole is a unique type of power line pole used extensively in South Australia. It is constructed of a concrete slab sandwiched between two steel joists.

Tab. 4.3: Proportion of casualty crashes that were high injury severity by type of crash, 2008 - 2012

Crash type	**High injury severity**	**Number of casualty crashes**	
Multiple vehicle	**33%**	**1138**	**(25%)**
Head on	50%	292	(6%)
Rear end	19%	248	(5%)
Side swipe	28%	138	(3%)
Right angle	33%	396	(9%)
Right turn	25%	64	(1%)
Single vehicle	**37%**	**3409**	**(75%)**
Hit fixed object	39%	1731	(38%)
Hit object/animal on road	30%	189	(4%)
Roll over	37%	1353	(30%)
Left road out of control	26%	136	(3%)
Other	**39%**	**18**	**(0%)**
Total	36%	4565	(100%)

includes culverts, embankments, fences, marker posts, etc. Collisions with the fixed objects tree, pole, bridge, sign post, Stobie pole[2], and guard rail showed the highest proportion of high severity outcomes. Conversely, collisions with animals and other non-fixed objects showed a lower proportion of high severity outcomes.

The analysis of crashes by day of week was split into those that occurred during daylight and those that occurred during darkness or the low light of dawn and dusk. Additionally, crashes which occurred at 5 am or earlier were attributed to the previous day of the week. This was done in an attempt to group together crashes of a similar nature; i.e. drink driving and fatigue which are known to occur late at night and into the early hours of the following day.

Over 70 per cent of the crashes occurred during hours of daylight and

Tab. 4.4: Proportion of casualty crashes involving a collision with an object that were high injury severity by type of object hit, 2008 - 2012

Object type	**High injury severity**	**Number of casualty crashes**	
Tree	41%	1064	(51%)
Traffic pole	0%	1	(0%)
Pole	40%	15	(1%)
Wild animal	38%	95	(5%)
Bridge	53%	15	(1%)
Sign post	43%	53	(3%)
Stobie pole	44%	68	(3%)
Domestic animal	24%	49	(2%)
Guardrail	46%	127	(6%)
Other fixed object	31%	553	(26%)
Other object	24%	55	(3%)
Total	38%	2095	(100%)

33 per cent of them resulted in a high severity injury. Table 4.5 shows that the number of crashes during daylight for each day of the week remained relatively constant through the weekdays but increased slightly on Friday and over the weekend. The proportion of high injury severity crashes was slightly higher on Thursday, Friday, and Saturday.

During darkness or low light, 42 per cent of crashes resulted in a high severity injury. Table 4.6 shows that the number of crashes during darkness or low light for each day of the week increased on Friday and Saturday. The proportions of high injury severity crashes on each day showed no discernable pattern. However, compared to daylight every day of the week showed a higher proportion of high injury severity crashes during darkness or low light.

Tab. 4.5: Proportion of casualty crashes that were high injury severity by day of week during daylight, 2008 - 2012

Day	**High injury severity**	**Number of casualty crashes**	
Monday	32%	445	(14%)
Tuesday	31%	417	(13%)
Wednesday	33%	411	(13%)
Thursday	36%	466	(14%)
Friday	35%	491	(15%)
Saturday	36%	493	(15%)
Sunday	30%	519	(16%)
Total	33%	3242	(100%)

Tab. 4.6: Proportion of casualty crashes that were high injury severity by day of week during darkness or low light, 2008 - 2012 (pre 5 am crashes attributed to previous day)

Day	**High injury severity**	**Number of casualty crashes**	
Monday	43%	136	(10%)
Tuesday	35%	149	(11%)
Wednesday	44%	180	(14%)
Thursday	46%	179	(14%)
Friday	40%	242	(18%)
Saturday	45%	290	(22%)
Sunday	41%	147	(11%)
Total	42%	1323	(100%)

4.2.3 Road characteristics

Table 4.7 shows that the majority of crashes on high speed rural roads occurred on roads with speed limits of 100 km/h or 110 km/h. Crashes on these roads with a higher speed limit displayed a higher proportion of high severity injuries.

Table 4.8 and Table 4.9 show that 80 per cent of crashes occurred on sealed roads and 85 per cent occurred on dry roads. Both sealed roads

Tab. 4.7: Proportion of casualty crashes that were high injury severity by speed zone, 2008 - 2012

Speed zone	**High injury severity**	**Number of casualty crashes**	
80 km/h	29%	807	(18%)
90 km/h	25%	36	(1%)
100 km/h	35%	1913	(42%)
110 km/h	40%	1809	(40%)
Total	36%	4565	(100%)

and dry roads showed a higher proportion of high injury severity crashes compared to unsealed and wet roads.

Tab. 4.8: Proportion of casualty crashes that were high injury severity by road surface type, 2008 - 2012

Surface	**High injury severity**	**Number of casualty crashes**	
Sealed	37%	3659	(80%)
Unsealed	32%	905	(20%)
Unknown	0%	1	(0%)
Total	36%	4565	(100%)

Tab. 4.9: Proportion of casualty crashes that were high injury severity by road wetness, 2008 - 2012

Wetness	**High injury severity**	**Number of casualty crashes**	
Dry	37%	3886	(85%)
Wet	31%	668	(15%)
Unknown	27%	11	(0%)
Total	36%	4565	(100%)

Table 4.10 shows that approximately 60 per cent of crashes occurred on straight sections of road, with the remainder occurring on curved sections. The direction of the curve was not recorded. The view around the curve was

recorded as either open or obscured, but is a subjective variable and likely to be unreliable. Nonetheless, roads which were curved with an open view displayed a higher proportion of high injury severity crashes compared to curves with an obscured view. This difference is unlikely to be significant however, and the proportion of high injury severity crashes for both curve types combined was 36 per cent.

Tab. 4.10: Proportion of casualty crashes that were high injury severity by road alignment, 2008 - 2012

Road alignment	**High injury severity**	**Number of casualty crashes**	
Straight	36%	2647	(58%)
Curved - view obscured	34%	759	(17%)
Curved - view open	38%	1124	(25%)
Unknown	40%	35	(1%)
Total	36%	4565	(100%)

Table 4.11 shows that the vast majority of crashes occurred on a mid-block section of road. The road feature labelled 'other' refers to railway crossings, on/off ramps, etc. Crashes which occurred at an intersection displayed a lower proportion of high injury severity crashes compared to crashes occurring on a mid-block section of road.

Tab. 4.11: Proportion of casualty crashes that were high injury severity by road feature, 2008 - 2012

Road feature	**High injury severity**	**Number of casualty crashes**	
Intersection	29%	842	(18%)
Mid-block	37%	3717	(81%)
Other	50%	6	(0%)
Total	36%	4565	(100%)

4.2.4 Vehicle characteristics

There were 5,844 vehicles involved in the high speed rural road crashes. Table 4.12 shows the frequency and the proportion of involvement in high injury severity crashes for each type of vehicle. Over 80 per cent of vehicles were passenger cars or car derivatives including panel vans, utilities, station wagons, and 4WDs. Trucks (including pickup trucks and semi-trailers) and motorised two wheelers (motorcycles and scooters) accounted for 8 per cent and 10 percent of the total respectively. Trucks and motorised two wheelers were both involved in a greater proportion of high injury severity crashes compared with cars and car derivatives.

Tab. 4.12: Proportion of involvement in high injury severity crashes by type of vehicle involved, 2008 - 2012

Vehicle type	**High injury severity**	**Number of vehicles**	
Car and derivatives	33%	4747	(81%)
Truck (all types)	41%	454	(8%)
Motorised two wheeler	51%	561	(10%)
Other	36%	47	(1%)
Unknown	49%	35	(1%)
Total	36%	5844	(100%)

Further analysis was conducted based on the age of the cars and car derivatives. Table 4.13 shows that almost half of the cars and derivatives were over 10 years old including a small proportion over 20 years old. The proportion of high injury severity outcomes increased with vehicle age. The highest proportion of high injury severity crashes was found for vehicles of unknown age. This result was unusual as high injury severity crashes are, in general, followed up more diligently. One possible explanation was that these vehicles of unknown age had left the crash scene before police arrival. In some minor severity crashes the vehicle may go unrecorded, but in serious crashes the presence of the vehicle is recorded more regularly (albeit with an unknown age).

Tab. 4.13: Proportion of casualty crashes that were high injury severity by age of vehicle (car and derivatives), 2008 - 2012

Vehicle age	**High injury severity**	**Number of vehicles with injured occupant**	
5 years or less	30%	983	(21%)
6 - 10 years	31%	1139	(24%)
11 - 15 years	32%	1068	(22%)
16 - 20 years	36%	765	(16%)
Over 20 years	39%	494	(10%)
Unknown	41%	298	(6%)
Total	33%	4747	(100%)

4.2.5 Driver characteristics

As parked vehicles were removed from the sample, there was a driver for each of the 5,844 vehicles. Table 4.14 shows that the majority of drivers held a full licence, while a smaller number of drivers held a provisional licence (a precursor to a full licence with several limitations such as a BAC of zero and a maximum speed of 100 km/h). Only a few drivers held a learners licence (for novice drivers who must be accompanied at all times by a full licence holder), a restricted licence (a special licence for particular types of agricultural vehicles that can only be driven to/from farming areas), or no licence at all. Those drivers with a restricted licence, an unknown licence type, or no licence were involved in a higher proportion of high injury severity crashes.

Tab. 4.14: Proportion of casualty crashes that were high injury severity by licence type of driver, 2008 - 2012

Licence type	**High injury severity**	**Number of drivers**	
Learners	29%	70	(1%)
Provisional	30%	945	(16%)
Full	35%	3876	(66%)
Restricted	52%	94	(2%)
None	57%	136	(2%)
Unknown	43%	723	(12%)
Total	36%	5844	(100%)

Table 4.15 shows that the majority of drivers were aged 20 to 50 years. There was no apparent trend in the proportion of high injury severity crashes relative to driver age.

Tab. 4.15: Proportion of casualty crashes that were high injury severity by age of driver involved, 2008 - 2012

Driver age	**High injury severity**	**Number of drivers**	
<16	77%	13	(0%)
16-19	28%	854	(15%)
20-29	35%	1329	(23%)
30-39	38%	986	(17%)
40-49	37%	989	(17%)
50-59	35%	788	(13%)
60-69	40%	490	(8%)
70-79	41%	210	(4%)
>79	38%	113	(2%)
Unknown	40%	72	(1%)
Total	36%	5844	(100%)

Table 4.16 shows that two thirds of the drivers were male. Male drivers were involved in a much greater number of crashes and a greater proportion of high injury severity crashes compared with female drivers.

Tab. 4.16: Proportion of casualty crashes that were high injury severity by sex of driver involved, 2008 - 2012

Driver sex	**High injury severity**	**Number of casualty crashes**	
Male	38%	3837	(66%)
Female	30%	1995	(34%)
Unknown	58%	12	(0%)
Total	36%	5844	(100%)

4.3 Results: Logistic regression

A logistic regression analysis was carried out on single vehicle crashes involving passenger cars and derivatives with the dependent variable being the probability of a crash being high injury severity (Table 4.17). Most of the variables analysed in the results section were included as predictor variables. After excluding 410 crashes with missing predictor or dependent variable data 2,348 cases were included in the analysis.

To ensure the validity of the results, the analysis was carried out several times using different categorisations and combinations of variables before settling on the final version presented here. Year of crash and vehicle age were both found to be better represented as continuous variables. Driver age was also tested as a continuous variable but found to be better represented by four categories. Day of week, speed limit, and drivers licence type were originally tested using their categorisations from the previous section, but were able to be re-grouped into a smaller number of categories for conciseness without affecting the results. There was no significant differences found between any day of the week and so they were re-grouped into weekday and weekend categories. The small number of 90 km/h crashes were found to be more sensibly categorised together with the 80 km/h crashes. Similarly, drivers with a learners and provisional type licence were found to be more sensibly categorised together and this category was labelled ‘novice’. Combining the driver sex and driver age variables into a single variable with eight categories was also tested but yielded no further detail beyond that provided by the individual variables.

It was noted that the majority of the 410 excluded crashes had missing data from either the vehicle age or drivers licence type variable. To ensure that the exclusion of this data did not bias the results in any way, a second regression analysis was conducted without the vehicle age and drivers licence type variables. The number of crashes excluded due to missing data in this second analysis was reduced to only 38. The results of the second analysis were similar to those of the main analysis in all categories, suggesting that any form of bias is unlikely.

In Table 4.17 five variables showed a highly significant ($p < 0.001$) result. The odds ratio of a casualty crash being of high severity was:

- Lower for hit animal/object and left road out of control type crashes compared to hit fixed object type crashes (although such crash types only represented 8% of the total)
- Lower as the year of crash increased
- Higher during night time compared to during daylight
- Lower on roads with a speed limit of 80 km/h or 90 km/h compared to roads with a speed limit of 100 km/h

- Higher for drivers with no licence compared to drivers with a full licence (although such drivers only represented 4% of the total)

Several other results where also significant ($p < 0.010$ or $p < 0.050$). The odds ratio of a casualty crash being of high severity was:

- Lower for unsealed roads compared to sealed roads
- Lower for wet roads compared to dry roads
- Higher as the age of the vehicle increased
- Lower for female drivers compared to male drivers
- Lower for drivers aged 20 or younger compared to drivers aged between 21 and 34
- Higher for drivers aged 35 and older compared to drivers aged between 21 and 34
- Higher for drivers with a restricted licence compared to drivers with a full licence (although such drivers only represented 2% of the total)

Commentary on these results is given in the Discussion section below.

Tab. 4.17: Logistic regression analysis of single vehicle crashes involving cars and car derivatives predicting probability of high injury severity crash (N = 2,348), 2008 - 2012

Variable (n)	B	Odds ratio	95% CI
Crash type			
Hit fixed object (1350)	-		
Hit object/animal (103)	-1.230†	0.292	0.171 - 0.500
Left road - out of control (85)	-1.119†	0.327	0.182 - 0.587
Roll over (810)	-0.129	0.879	0.721 - 1.071
Year of crash	-0.119†	0.888	0.833 - 0.947
Day of the week			
Weekday (1533)	-		
Weekend (815)	0.013	1.013	0.839 - 1.222
Lighting			
Daylight (1472)	-		
Night (876)	0.457†	1.579	1.302 - 1.915
Road surface			
Sealed (1793)	-		
Unsealed (555)	-0.327ˆ	0.721	0.563 - 0.923
Road wetness			
Dry (1944)	-		
Wet (404)	-0.336ˆ	0.715	0.558 - 0.915
Road feature			
Mid-block (2167)	-		
Intersection (181)	-0.243	0.784	0.555 - 1.108
Road alignment			
Straight (1326)	-		
Curve (1022)	-0.036	0.965	0.802 - 1.161
Speed limit			
100 km/h (1088)	-		
80 km/h, 90 km/h (334)	-0.538†	0.584	0.435 - 0.784
110 km/h (926)	0.068	1.071	0.863 - 1.329
Vehicle age	0.017ˆ	1.018	1.004 - 1.031
Driver sex			
Male (1347)	-		
Female (1001)	-0.224*	0.799	0.663 - 0.962
Driver age			
21 - 34 (704)	-		
20 or younger (618)	-0.333*	0.717	0.523 - 0.982
35 - 49 (512)	0.283*	1.327	1.031 - 1.708
50 or older (514)	0.342*	1.407	1.082 - 1.830
Driver licence type			
Full (1538)	-		
Novice (672)	0.204	1.227	0.899 - 1.673
Restricted (53)	0.745*	2.107	1.172 - 3.788
None (85)	1.045†	2.843	1.774 - 4.555
Constant	-0.590ˆ		

Significance levels: † $p < 0.001$, ˆ $p < 0.010$, * $p < 0.050$

4.4 Discussion

This investigation found that in South Australia, compared with other types of road, there is an overrepresentation of crashes which result in fatal or serious injuries on rural roads with speed limits of 80 km/h or greater. By examining the relationship between high injury severity and other crash variables, some of the characteristics of high injury severity crashes on high speed rural roads have been shown. The sections above simply presented the results without elucidation but this section provides some discussion regarding the interpretation of the results which may be of interest.

The discussion is presented in two subsections. The first looks at the results of the categorical variable analysis and the second considers the findings of the logistic regression analysis.

4.4.1 Univariate categorical variable analysis

When analysing the results of the categorical variable analysis it is important to keep in mind that a univariate investigation is likely to suffer from issues with confounding variables. The effects of such confounding variables would alter the individual categorical variable results discussed here. Some suggestion of when the results associated with a categorical variables may be affected by other confounding variables is given. However, the truth or comprehensiveness of these suggestions is unknown. A clearer picture of the individual effects of the various crash variables on the propensity of high injury severity is provided in the logistic regression analysis.

For single vehicle crashes, the two main crash types of 'roll over' and 'hit fixed object' showed little difference in the proportion of high injury severity outcomes. This may be an indication that high speed, single vehicle crashes on rural roads have a tendency to result in high severity injuries regardless of the collision mechanism. It would be expected however, that the mechanisms of injury during a 'roll over' crash and a 'hit fixed object' crash are different.

For multiple vehicle crashes, the two main crash types were 'head on' and 'right angle'. The events leading up to a head on type crash are often similar to those leading up to a single vehicle, hit fixed object type crash. That is, a driver may lose control of their vehicle but collide with an oncoming vehicle instead of a roadside object. For such a crash, the combined speed of both vehicles is the likely reason for the high prevalence of high severity injuries that result. Right angle crashes may be the result of poor driver judgement in choosing gaps at intersections, especially when entering traffic travelling at high speeds. The lower proportion of high injury severity outcomes for right angle crashes (and indeed right turn and rear end crashes) may be due to their occurrence at intersections were vehicle speed is lower.

In crashes where a vehicle collided with a tree, sign post, or Stobie pole the prevalence of high severity injuries was highest. Surprisingly, despite evidence that guardrails considerably reduce the incidence of fatal outcomes and the chance of sustaining a personal injury (Elvik, 1995), the proportion of high injury severity outcomes for collisions with guardrails was greater than for collisions with trees and Stobie poles. The reason for this conflicting result is not completely clear but it may be that many minor collisions with guardrails do not result in injuries and thus are not reported. Additionally, it may be that guardrails are only installed in dangerous locations (e.g. high speed, solid roadside objects, steep drop-off) where a crash is more likely to result in severe injuries. Thus, there may be many cases where a vehicle collided with a guardrail prior to a more severe secondary collision or rollover. For collisions with animals which are, in general, more yielding than most fixed roadside objects the proportion of high injury severity outcomes was correspondingly lower.

Crashes which occurred during hours of darkness showed an increased proportion of high injury severity outcomes across all days of the week. Crashes which occurred on Friday and Saturday during darkness displayed a greater number of crashes per day (compared with the other days). The reasons for these effects are not immediately clear; however it has been suggested in a similar study of rural road crashes in Victoria that crashes which occur during darkness may correspond with alcohol use and fatigue (Symmons et al., 2004). Reduced vision may also be a factor during night time crashes on rural roads. While these factors may be present in many cases, the relationship between crash severity and vision, alcohol use, or fatigue is unknown.

Crashes which occur in higher speed zones show a larger proportion of high injury severity outcomes. This result is consistent with a earlier study on South Australian rural roads of 80 km/h and above, which found that higher travelling speed is associated with higher casualty crash risk (Kloeden & McLean, 2001). It is noteworthy that despite a default rural speed limit of 100 km/h the number of crashes that occurred on roads with a speed limit of 110 km/h was significant.

The difference in the proportion of high injury severity crashes on wet and dry roads was substantial, with a higher proportion of dry road crashes being serious. It has been suggested that this difference may be explained by an increase in the number of low injury severity, skidding crashes on wet roads (Edwards, 1998), rather than a decrease in the risk of having a serious crash on a wet road. It may also be the case that on days when the road is wet there is a reduced number of motorised two wheelers being ridden. Since motorised two wheelers are associated with higher levels of injury severity, their reduced presence may explain some of the decrease in high injury severity crashes on wet roads.

A similar effect was seen for road surface type with a greater proportion of high severity crashes occurring on sealed roads compared with unsealed roads. It was assumed that this effect was also explained by an increased number of low injury severity, skidding crashes on unsealed roads.

Crashes which occurred on curved sections of road did not appear to show any significant difference in the proportion of high severity injuries compared with crashes which occurred on straight sections of road. However, given that the length of curved sections of road is considerably smaller than the length of straight sections of road, the number of crashes on curves is alarming. The likelihood of a crash occurring on a curved section of road appears to be much greater than on a straight section of road.

Crashes which occurred at intersections were found to have a lower proportion of high injury severity outcomes compared with those which occurred on a mid-block section of road. This is consistent with a similar study of rural road crashes in Victoria which found that crashes at intersections are less severe than crashes not at intersections (Symmons et al., 2004).

There was a large difference in the proportion of high injury severity crashes for different categories of vehicle. Both motorised two wheelers and trucks displayed an increased proportion of high injury severity crashes. For motorised two wheelers, this effect may arise from the limited protection given to riders during a crash. For trucks, this effect is likely due to their large mass which can result in severe injuries for the occupants of any vehicle with which they collide. While crashes involving cars and derivatives displayed the lowest proportion of high injury severity outcomes, the frequency of such crashes demonstrates that ESC is relevant to high speed rural roads.

An increase in vehicle age was associated with an increase in the proportion of high severity injuries to the occupants. This effect was also noted by Tziotis et al. (2006) and it has been shown through the analysis of real-world crashes that newer vehicles incorporating modern safety features better protect occupants during a crash (Newstead et al., 2008).

Drivers on a restricted licence or without a licence were involved in a greater proportion of high injury severity crashes. It is not clear why these drivers are involved in more high injury severity crashes. However, a link between recidivist drivers and alcohol use (in fact, alcohol dependence) was found by Lindsay (2012). Lindsay (2012) noted that such alcohol use has long been associated with increased crash severity.

The proportion of high injury severity crashes associated with different driver age ranges did not reveal anything conclusive. There was a small tendency for older drivers to be involved in a greater proportion of high injury severity crashes but establishing the effect was hampered by small sample sizes within the age groups. The expected result of an increased prevalence of high injury severity crashes for young drivers was noticeably absent. The reasons for this were not clear but it may be that young drivers are less likely to display the types of behaviours that result in more severe injuries when driving on high speed rural roads. For example, a young driver may be less likely to speed on a 100 km/h rural road compared to a 60 km/h road in an urban environment.

4.4.2 Multi-variate logistic regression analysis

A logistic regression analysis, restricted to single vehicle casualty crashes involving cars and car derivatives, was conducted with the dependent variable being the probability of a crash being high injury severity. While the logistic regression analysis considers a smaller data set because of the restriction, it has an advantage over the univariate analysis in that the results for each variable are not confounded by the other variables. Though it is acknowledged that the results may still be confounded by factors that were not considered such as driver blood alcohol concentration (BAC), distance between crash location and driver residence, or distance between crash location and Adelaide (where major trauma hospitals are located).

The results of the logistic regression analysis indicated that an earlier year of crash, a higher speed limit, and the hours of darkness were highly associated with high injury severity. These three predictors are likely to be the critical characteristics that differentiate between high injury severity and low injury severity in single vehicle crashes involving passenger vehicles. Also associated with high injury severity crashes (though to a lesser degree) were sealed road, dry roads, older vehicles, male drivers, and older drivers.

It is suggested that these results can be interpreted on the premise that injury severity is a product of impact severity and occupant frailty. Impact severity itself can be defined as a product of impact speed and the crash performance of the vehicle. Therefore, it is theorised that the propensity for injury severity is a consequence of travelling speed, the level of protection provided by the vehicle, and occupant frailty.

This theory corresponds well with the logistic regression results. Variables that were indicative of an increased travelling speed, a reduced level of vehicle protection, and an increase in occupant frailty were found to be associated with higher severity injury outcomes.

The link between increased travelling speed and higher speed limits is clear. Beyond speed limit, it is suggested that night time, sealed roads, and dry roads are also indicative of an increase in travelling speed. At night there is less traffic so driving at or above the speed limit is easier. Similarly, sealed roads and dry roads off favorable conditions where driving at or above the speed limit is more likely that on wet or unsealed roads. An increase in travelling speed may also be indicated by earlier crash years. Kloeden & Woolley (2014) investigated travelling speeds on several 100 km/h and 110 km/h rural roads in South Australia roads between 2008 and 2012. Table 4.18 shows the changes in mean travelling speed and the percentage of vehicles exceeding the speed limit from one year to the next.

The statistically significant reduction in overall mean travelling speed between 2011 and 2012 are modest. However, the significant reductions in the percentage of vehicles exceeding the speed limit between 2009 and 2010 as well as between 2011 and 2012 are more considerable. Such reductions in speeding may well have resulted in reductions in impact speed for some

Tab. 4.18: Change in mean speed and percentage of vehicles exceeding the speed limit for 100 km/h and 110 km/h rural roads, 2008 - 2012 [Kloeden & Woolley (2014)]

Speed limit	**2008-2009**	**2009-2010**	**2010-2011**	**2011-2012**
100 km/h				
Mean speed	0.04	-0.21	0.58	-0.86*
% 1+ km/h over	-0.45	-0.73	2.65	-4.48*
% 6+ km/h over	-0.44	-0.59	0.95	-3.89*
% 11+ km/h over	-0.31	-0.58	0.38	1.70*
% 16+ km/h over	0.00	-0.20	0.12	-0.87*
110 km/h				
Mean speed	0.15	-0.36	0.62*	-1.55*
% 1+ km/h over	0.24	-1.45	0.70	-5.91*
% 6+ km/h over	0.06	-0.67*	0.44	-3.06*
% 11+ km/h over	-0.13	-0.33*	0.30	-1.09*
% 16+ km/h over	-0.05	-0.10*	0.16	-0.57*

* significant change ($p<0.05$)

crashes during the later crash years.

It was noted earlier that there is a link between vehicle year of manufacture and the level of protection provided to the occupants in the event of a collision. Thus, a reduced level of vehicle protection can be indicated by an earlier year of manufacture. Year of manufacture was not one of the analysis variables but age of vehicle and crash year were included. Both an earlier crash year and an older vehicle age are likely to be indicative of a reduced level of vehicle protection.

Occupant frailty can be the product of many factors including height, weight, age, sex, and health. A increase in frailty that is significant enough to result in a measurable increase in crash injury severity is typically associated with old age. Thus, older drivers are likely to be indicative of an increase in occupant (or at least driver) frailty.

While the results of the logistic regression analysis support the theory suggested above, it is also important to note that there are elements of the theory that were not evaluated by the analysis. That is, occupant injury severity may depend upon additional factors such as the mass of the vehicle, the mass of the occupants, and the expeditiousness of suitable medical treatment post crash. None of these factors were able to be identified using the variables included in the analysis. As such, if the suggested theory is correct then there is scope for further refinement of the results to accommodate the effects of these additional factors.

5. LOSS OF CONTROL CRASHES ON AUSTRALIAN RURAL ROADS

The effectiveness of ESC in reducing the number and severity of specifically loss of control crashes on high speed rural roads has been reported by several studies (Bahouth, 2005; Erke, 2008; Farmer, 2006; Green & Woodrooffe, 2006; Lie et al., 2005; MacLennan et al., 2008; Page & Cuny, 2006; Papelis et al., 2004; Thomas, 2006; Unselt et al., 2004). It was suggested by Langwieder et al. (2003) that through knowing the prevalence of loss of control type crashes on high speed rural roads it will be possible to estimate the maximum potential benefit of ESC. Thus, further to the investigation in Chapter 4, this chapter presents a study on the prevalence and characteristics of specifically loss of control type crashes on South Australian high speed rural roads.

5.1 Method

Unfortunately, the occurrence of a loss of control prior to a collision is not a crash variable that is explicitly recorded in the TARS database (see Section 4.1.1). The objective therefore, was to develop a model for the combination of TARS variables that are indicative of a loss of control crash. This was achieved by matching TARS records to records within an in-depth crash database (described below) that contained enough information to identify whether a crash was due to a loss of control.

An explicit definition for a loss of control crash is required here as it may not be immediately obvious and has a direct bearing on the results of the investigation. The definition presented here is not intended to account for all possible ways in which a driver may lose control of their vehicle but instead attempts to isolate only those loss of control crashes that have the potential to benefit from ESC.

A loss of control was defined to have occurred if, prior to a collision, a driver requested a lateral response from their vehicle and the vehicle failed to respond effectively. An ineffective lateral response may be either excessive yaw (oversteer) or inadequate yaw (understeer). A loss of control was also defined to have occurred if, prior to a collision, a vehicle yawed without any request for a lateral response from the driver (split mu).

No loss of control can occur if a driver does not actively request a response from the vehicle, or is in a state of mind in which they are not able to request an appropriate response. As such, crashes where the driver was not in conscious control of the vehicle (e.g. asleep, blacked out, experiencing a seizure, etc), or deliberately intended to crash (e.g. suicide) were not defined as loss of control. Note that this only includes crashes involving drivers who are deemed to be incapable of an appropriate response and does not include crashes involving drivers who may have an impaired response (e.g. those under the influence of alcohol, drugs, or fatigue).

The in-depth database was used to supply a set of crashes that were known to be either the result of a loss of control or not. Not all of the crashes in the in-depth database were suitable for use in the current investigation and only those that met the following criteria were included:

- Crashes on rural roads with a speed limit of 80 km/h or faster
- Crashes involving only cars or derivatives
- Crashes with a corresponding TARS record

There were 153 crashes that satisfied the criteria and contained enough information to determine whether a loss of control had occurred. Excessive yaw was, in most cases, easy to identify as it usually resulted in yaw marks being left on the road and a vehicle spin out. A lack of yaw was more difficult to identify as it was difficult to determine that a driver was requesting a lateral response from their vehicle, especially while braking at the same time. However, careful review of the crash evidence and driver interviews allowed all crashes to be classified satisfactorily.

From the review, 85 crashes were classified as being due to a loss of control with the remaining 68 classified as not being due to a loss of control. Each crash was then matched to its corresponding TARS record. This produced a set of crashes for which both the TARS data and the loss of control classification was known. Using this set of crashes a model of the TARS variables, or specific combination of variables, that are indicative of a loss of control crash could be developed.

5.1.1 In-depth database

Between March 1998 and February 2000, the Centre for Automotive Safety Research (CASR) investigated 238 rural road crashes on public roads within

100 km of Adelaide to which an ambulance had been called (Baldock et al., 2008). Investigations began with immediate travel to the scene of the crash by a team of two Centre personnel. The information collected from each crash included: photographs/video of the crash scene and vehicles involved, examination of the road environment, a site plan of the crash scene and vehicle movements in the crash, examination and measurements of the vehicles involved, interviews with crash participants, interviews with witnesses, interviews with police, information on the official police report, hospital injury data for the injured crash participants, and information from Coroners reports for the fatally injured participants. All collected data was checked, verified and then entered into the 'in-depth database'.

It should be noted that the in-depth database is not a completely representative sample of rural road crashes in South Australia. As mentioned, only crashes that occurred within 100 km of Adelaide were investigated. Additionally, CASR personnel were only 'on call' for crash investigation during certain time periods. The on call period was between the hours of 9am and 4pm, inclusive, every day of the week. In addition, on Thursdays and Fridays the on call period was extended to cover an entire 24 hours. As such, the database has a bias toward daytime crashes. Furthermore, fatal crashes that occurred outside the on call period were, on occasion, investigated in consultation with the police investigators who attended the scene at the time of the crash. This gives the database a bias toward fatal crashes.

5.2 Model development

Several TARS categorical variables were chosen, a priori, to be likely to indicate loss of control. These were:

- Number of motor vehicles involved
- Crash type
- Main crash error
- Road geometry
- Road alignment
- Road surface type
- Road wetness

The categories within each variable were cross tabulated by loss of control classification. This revealed that the variable ‘crash type’, shown in Table 4.3, was able to differentiate between loss of control classifications the most clearly.

Table 5.1 shows that the majority of single vehicle type crashes were due to loss of control while the majority of multiple vehicle type crashes were not. Those single vehicle type crashes that were not due to a loss of control were mainly categorised as hit fixed object crashes. Inspection of these particular hit fixed object crashes revealed that they were due to drivers being asleep, being passed out, being distracted, experiencing a heart attack, or deliberately crashing.

Tab. 5.1: Crash type for high speed rural road crashes

Crash type	Loss of control?		Total
	Yes	No	
MULTIPLE VEHICLE	**19**	**55**	**74**
Head on	17	7	24
Rear end	1	6	7
Side swipe	0	6	6
Right angle	1	25	26
Right turn	0	11	11
SINGLE VEHICLE	**66**	**13**	**79**
Hit fixed object	53	11	64
Hit object/animal on road	1	0	1
Roll over	11	1	12
Left road - out of control	1	1	2

A further analysis of TARS categorical variables was conducted for exclusively hit fixed object crashes. This analysis included investigation of the variable 'main crash error' with the category 'died sick or asleep at the wheel' expected to identify those crashes that were the result of drivers being asleep, passed out, or experiencing a critical medical incident. However, no variable was able to distinguish between hit fixed object crashes that were, or were not, due to a loss of control. For hit fixed object crashes that were not due to a loss of control the main crash error was categorised as being caused by either excessive speed, inattention, or DUI. Therefore, no further accuracy in the identification of which hit fixed object crashes were due to a loss of control was possible.

Those multiple vehicle type crashes that were due to a loss of control were mainly categorised as head on crashes. Baldock et al. (2008) also noted this and explained that many head on crashes result from similar circumstances to single vehicle loss of control crashes, except that a collision occurs with an oncoming vehicle instead of a roadside object. Inspection of those head on crashes that were not due to a loss of control showed them to be the result of vehicles being on the wrong side of the road for reasons such as overtaking, negotiating narrow roadways, and driver distraction.

A further analysis of TARS categorical variables was conducted for exclusively head on crashes. However, due to the small number of head on crashes, no significant result could be obtained. Consequently, no further accuracy in the identification of which head on crashes are due to a loss of control was possible.

It was noted that some increase in the accuracy of loss of control identification may be possible through the analysis of the TARS crash description free text field. The crash descriptions for all of the 153 crashes were analysed to identify every unique word contained within. There were 1,228 unique words identified which included several instances of mis-spellings and other typographical errors.

The number of times each word appeared (at least once) in a loss of control, or non loss of control crash description was counted. Noting that 85 cases were due to a loss of control and 68 were not, the number of times each word did not appear in a loss of control, or non loss of control crash description was also counted. An example of this is shown in Table 5.2. A Chi squared test was then performed on each unique word to measure the uniformity of its appearance in loss of control and non loss of control crash descriptions. The ten words with the highest Chi squared result are shown in Table 5.3.

Tab. 5.2: Appearance of unique word in crash description by loss of control classification

		Loss of control? Yes	No	Total
Word	**Yes**	a	b	a + b
appears?	**No**	c	d	c + d
Total		85	68	153

Tab. 5.3: Unique words in the crash description associated with the ten highest Chi squared values

Word	**Loss of control?**	
	Yes	**No**
CONTROL	46	4
2	18	39
TURN	3	19
LOST	34	5
INTERSECTION	1	12
GIVE	2	13
VEHICLE	40	10
BEND	28	4
WAY	2	12
OCCURRED	5	16

Unfortunately, the ability of the words to differentiate between loss of control classifications was highly correlated with that of the variable ‘crash type’. As such, the words did not facilitate any further accuracy in loss of control identification compared with using ‘crash type’ alone. There was also no further accuracy gained through using the words to differentiate between loss of control classifications when considering either hit fixed object or head on crashes individually.

Predicting loss of control for crashes, involving exclusively passenger vehicles or derivatives on high speed rural roads, is thus best achieved based on crash type. A model for loss of control prediction is shown below in Table

5.4 where, apart from head on and hit fixed object crashes, multiple vehicle crash types and single vehicle crash types are treated as a group. For each crash type, or group of crash types, the predicted loss of control was calculated based on the percentage of crashes that were classified as being due to a loss of control.

Tab. 5.4: Loss of control prediction model

Crash type	**Predicted loss of control**
Rear end	4%
Side swipe	4%
Right angle	4%
Right turn	4%
Head on	71%
Hit object/animal on road	87%
Roll over	87%
Left road - out of control	87%
Hit fixed object	83%

The results presented below use the loss of control prediction model to analyse the relationship between loss of control and individual categorical variables for injury crashes in the TARS database.

5.3 Results: Loss of control crash characteristics

The loss of control prediction model was applied to all casualty crashes involving exclusively passenger vehicles on high speed rural roads over the ten year period from 1998 to 2007. This period was chosen for two reasons. The first was to provide a sufficiently large data set for analysis. The second was to ensure that the model (which was developed from data collected between

1998 and 2000) was applied to an appropriate time frame, as the characteristics of loss of control crashes have the potential to change over time.

Indeed, one such potential change in the characteristics of loss of control crashes that should be noted is that caused by the increasing prevalence of mobile phones over time. The distraction caused by mobile phone usage while driving may result in an increase in single vehicle run-off-road type crashes. This type of non loss of control crash would be incorrectly categorised by the loss of control prediction model and result in an overestimate of the prevalence of loss of control. While such an effect on the results presented below cannot be ruled out, it is assumed to be small.

Overall the model suggested that a loss of control occurs in 70 per cent of casualty crashes involving exclusively passenger vehicles on high speed rural roads. The ten year sample of crashes was then used to investigate the characteristics of loss of control crashes through the analysis of several categorical variables which are presented below. Tables in this section show both the relative frequency of the categories within each variable as well as the percentage of loss of control crashes associated with the categories. Commentary on the results presented here is given in Section 5.4 below.

5.3.1 Crash characteristics

Table 5.5 shows that the annual number of injury crashes and the prevalence of loss of control has remained relatively steady.

Table 5.6 shows that crashes most commonly resulted in hospital treatment for at least one of the injured participants, followed by hospital admission and attendance with a private doctor. Crashes in which someone

Tab. 5.5: Proportion of high speed, rural road injury crashes that were due to a loss of control by year, 1998 - 2007

Year	**Loss of control**	**Number of injury crashes**	
1998	67%	757	(9%)
1999	70%	802	(10%)
2000	70%	851	(11%)
2001	70%	770	(10%)
2002	71%	840	(11%)
2003	70%	863	(11%)
2004	69%	811	(10%)
2005	71%	783	(10%)
2006	71%	746	(9%)
2007	70%	794	(10%)
Total	70%	8,017	(100%)

was killed were the least common but had the second highest loss of control prevalence, behind hospital admission severity crashes.

Tab. 5.6: Proportion of high speed, rural road injury crashes that were due to a loss of control by injury severity, 1998 - 2007

Severity	**Loss of control**	**Number of crashes**	
Private doctor	63%	877	(11%)
Hospital treatment	69%	3,826	(48%)
Hospital admission	73%	2,850	(36%)
Fatal	71%	464	(6%)
Total	70%	8,017	(100%)

Table 5.7 shows that the number of injury crashes was relatively constant from Monday to Thursday, but was slightly higher on Fridays, Saturdays and Sundays. The prevalence of loss of control was similar for each day of the week although there was a small increase towards the second half of the week.

Table 5.1 shows that the number of injury crashes during each hour of

Tab. 5.7: Proportion of high speed, rural road injury crashes that were due to a loss of control by day of week, 1998 - 2007

Day	**Loss of control**	**Number of injury crashes**	
Monday	69%	927	(12%)
Tuesday	69%	964	(12%)
Wednesday	68%	1,029	(13%)
Thursday	70%	1,002	(13%)
Friday	70%	1,292	(16%)
Saturday	71%	1,444	(18%)
Sunday	71%	1,359	(17%)
Total	70%	8,017	(100%)

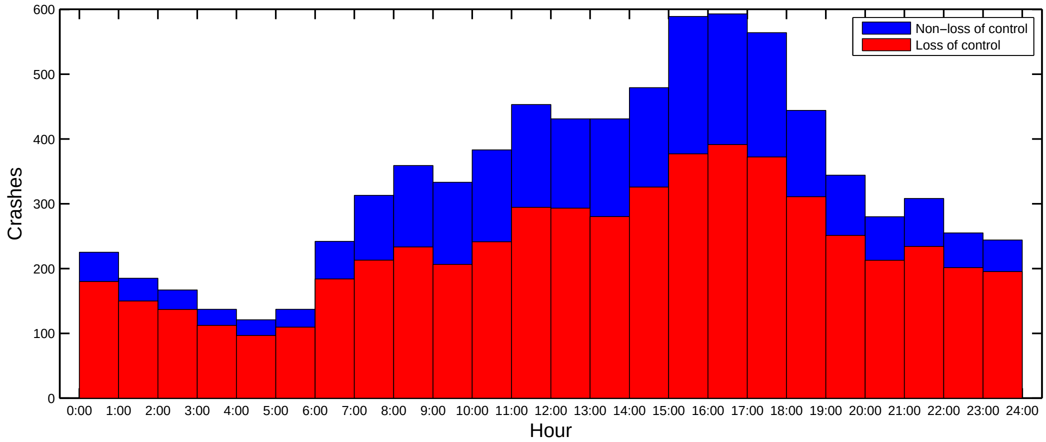


Fig. 5.1: Proportion of high speed, rural road injury crashes that were due to a loss of control by hour of day, 1998 - 2007

the day oscillates smoothly from a minimum at 4:00 - 4:59 to a maximum at 16:00 - 16:59. Conversely, the prevalence of loss of control during each hour of the day oscillates from a maximum of 82 per cent at 3:00 - 3:59 to a minimum of 62 per cent at 9:00 - 9:59.

5.3.2 Road characteristics

Table 5.8 shows that the majority of injury crashes occurred in either 100 or 110 km/h zones. 100 km/h and 110 km/h speed zones also showed the highest prevalence of loss of control (72 per cent and 73 per cent). Injury crashes in 80 and 90 km/h speed zones displayed a smaller prevalence of loss of control (56 per cent).

Tab. 5.8: Proportion of high speed, rural road injury crashes that were due to a loss of control by speed zone, 1998 - 2007

Speed zone	**Loss of control**	**Number of injury crashes**	
80 - 90 km/h	56%	1,169	(15%)
100 km/h	72%	3,156	(39%)
110 km/h	73%	3,692	(46%)
Total	70%	8,017	(100%)

Table 5.9 and Table 5.10 show that 78 per cent of injury crashes occur on sealed roads and 85 per cent occurred on dry roads. Injury crashes on unsealed roads displayed a higher prevalence of loss of control (79 per cent). The prevalence of loss of control was also higher for injury crashes on wet roads (73 per cent).

Tab. 5.9: Proportion of high speed, rural road injury crashes that were due to a loss of control by surface type, 1998 - 2007

Surface	**Loss of control**	**Number of injury crashes**	
Sealed	67%	6,282	(78%)
Unsealed	79%	1,722	(22%)
Unknown	78%	13	(0%)
Total	70%	8,017	(100%)

Tab. 5.10: Proportion of high speed, rural road injury crashes that were due to a loss of control by surface wetness, 1998 - 2007

Wetness	**Loss of control**	**Number of injury crashes**	
Wet	73%	1,231	(15%)
Dry	69%	6,785	(85%)
Unknown	87%	1	(0%)
Total	70%	8,017	(100%)

Table 5.11 shows that the majority of injury crashes occurred on straight sections of road and the prevalence of loss of control was 65 per cent. Injury crashes on curved sections of road displayed a greater loss of control prevalence of 78 per cent.

Tab. 5.11: Proportion of high speed, rural road injury crashes that were due to a loss of control by road alignment, 1998 - 2007

Alignment	**Loss of control**	**Number of injury crashes**	
Straight	65%	4,894	(61%)
Curved - view obscured	77%	1,241	(16%)
Curved - view open	78%	1,845	(23%)
Unknown	79%	37	(1%)
Total	70%	8,017	(100%)

Tab. 5.12: Proportion of high speed, rural road injury crashes that were due to a loss of control by road feature, 1998 - 2007

Feature	**Loss of control**	**Number of injury crashes**	
Intersection	13%	367	(5%)
Mid-block	73%	7,635	(95%)
Other	66%	15	(0%)
Total	70%	8,017	(100%)

5.4 Discussion

High speed rural road crashes in the CASR in-depth database were classified as either loss of control or not and then matched to their corresponding TARS record. TARS variables that were indicative of a loss of control crash were then investigated. The categorical variable 'crash type' was identified as the best single predictor of loss of control. Further prediction accuracy was then sought through the analysis of how frequently unique words appear in either loss of control or non-loss of control crash descriptions. However, no further sensitivity was obtained and a loss of control prediction model was developed based exclusively upon crash type.

Applying the loss of control prediction model to ten years of injury crashes that occurred on high speed roads in a rural location predicted an overall loss of control prevalence of 70 per cent. The prediction model was then used to analyse the characteristics of loss of control crashes by investigating the relationships between loss of control and various crash variables.

The number of injury crashes per year and the prevalence of loss of control remained relatively constant. On average, approximately 561 loss of control injury crashes were predicted to occur each year. Assuming that ESC has an effect on all loss of control crashes, this equates to 561 injury crashes which could be avoided or have their injury severity reduced. Disaggregation of the injury crashes by severity category found there was an average of 55 private doctor (11 per cent of the total), 264 hospital treatment (48 per cent), 208 hospital admission (36 per cent), and 33 fatal crashes (6 per cent) per year.

Given that single vehicle and head on crashes were shown to be associated with high injury severity in the previous chapter it is not surprising that a high proportion of crashes that resulted in hospital admission or fatal injuries were due to a loss of control.

The increase in the prevalence of loss of control crashes on Saturday and Sunday is likely due to an increase in recreational driving and associated with alcohol and fatigue as noted in the previous chapter.

The inverse relationship between the number of crashes during each hour of the day, and the prevalence of loss of control during each hour is likely due to exposure. During the late night hours there is less traffic and thus multiple vehicle, non loss of control, crashes are less likely. However, it is worth noting that even at 9am when the loss of control prevalence is at its lowest there are still more than twice as many loss of control crashes compared with at 4am when the prevalence is at its highest.

It is likely that lower speed zones have a greater number of intersections than higher speed zones. It is therefore difficult to determine whether loss of control is less common in lower speed zones due to lower risks of loss of control crashes or an increased risk of multiple vehicle, non-loss of control, intersection crashes.

Low friction surfaces like wet and unsealed roads are associated with a higher prevalence of loss of control crashes. The number of injury crashes that occur on these low friction surfaces is low but not insignificant.

Similarly, crashes on curves were also associated with a higher prevalence of loss of control. This is likely due to an increased likelihood of crashes in which a vehicle travels off the side of the road while navigating through a curve.

6. SIMULATING LOSS OF CONTROL SCENARIOS

It was shown in the preceding chapters that given the way in which ESC operates (see Chapter 2), it is likely to have a profound effect on the numerous high speed rural road crashes which occur in Australia each year (see Chapter 4) as more of the fleet becomes equipped. For rural road crashes that occur due to a loss of control (see Chapter 5), the effectiveness of ESC is likely to be even greater. However, while the effectiveness of ESC has been measured empirically (see Chapter 3), how braking interventions affect crashes on an individual level has not been the subject of much study. Furthermore, the interaction between specific crash circumstances or conditions (e.g. travelling speed or road surface friction) and ESC effectiveness is unclear. It is also not clear how braking interventions elicited during potential loss of control situations compare to the braking interventions elicited during the ESC effectiveness tests.

An investigation of how ESC braking interventions affect individual loss of control crashes on high speed rural roads can be conducted through a 'with' and 'without' comparison. That is, the comparison of a loss of control situation involving a vehicle without ESC to an identical loss of control situation involving a vehicle with ESC. An analysis of how ESC affects that specific loss of control situation can then be conducted by noting the differences between the trajectory of the vehicle with ESC and the trajectory of the vehicle without ESC. More in-depth analysis can be conducted by noting the individual braking interventions responsible for the differences in the trajectories. Additionally, the magnitude and duration of braking interventions during loss of control situations can be explored and compared to the magnitude and duration of braking interventions during ESC effectiveness testing.

This chapter describes a method for investigating the effects of ESC braking interventions during several loss of control scenarios typical to high speed rural roads in Australia through the use of computer simulations. In Section 6.1, the selection and operation of a software package capable of simulating vehicles equipped with ESC is described. Two vehicle models, with corresponding ESC models, capable of interfacing with the chosen simulation software were provided for use in the investigation by Bosch Australia. The dynamic response of the vehicle models was evaluated and validated both with and without ESC active. Additionally, the ability and validity of the ESC models were evaluated using the minimum ESC effectiveness criteria. Unfortunately, one of the vehicle models, representing a front wheel drive small car, was found to be defective and was consequently not used in the investigation. The validation of the remaining vehicle model, representing a rear wheel drive family sedan, is presented in Section 6.2.

In Section 6.3, a set of ten loss of control scenarios are developed based on data collected during the in-depth investigation of high speed, single vehicle crashes that occurred on South Australian rural roads. Each of the scenarios include details on the road environment, the circumstances preceding the loss of control, and the trajectory of the vehicle throughout the loss of control.

Section 6.4 discusses the simulation of the scenario environment. Parameters that model the road and surface coefficient of friction are presented along with methods for selecting suitable parameter values based on empirical evidence. Then in Section 6.5 the simulation of the scenario loss of control trajectory is discussed. A model of how driver braking and steering actions can be parameterised to define a simulated trajectory is presented. It was discovered that selecting parameter values to define a simulated trajectory which matched the scenario trajectory was not achievable through empirical means due to the dynamic interaction between the parameters. Thus, methods for selecting initial trajectory parameter values are presented. Then, Section 6.6 explains how an optimisation technique is used to refine these initial values such that they generate a simulated trajectory that matches the scenario trajectory.

Finally, in Section 6.7, a summary of the entire chapter on simulating loss of control scenarios is presented.

6.1 Simulation software

There were no commercially available simulation software packages that included the ability to simulate vehicle dynamics and the effects of ESC at the time this investigation was conducted. Robert Bosch Australia (Bosch) provided assistance to this investigation by supplying data and software which could integrate with the software package CarSim to enable the simulation of an ESC model and thus the dynamics of a vehicle equipped with ESC. The

CarSim software package features detailed vehicle and tyre models which allow the accurate simulation of a vehicle's trajectory in three dimensions when provided with information on steering, acceleration, and braking inputs. Road layout and surface characteristics can be modelled and the software also includes a programmable driver model which, when provided with suitable parameters, calculates an appropriate set of steering inputs for following a desired driving path. It should be noted, that CarSim is not a crash simulation package and has no facilities for simulating any type of collision between vehicles or roadside objects.

The input data required by CarSim to carry out a simulation can be split into three components. These components are vehicle data, events data and environment data. The vehicle data consists of a vehicle model that includes details such as mass, dimensions, suspension properties, and tyre properties. The events data includes all driver inputs such as accelerations, steering, and braking. The environment data consists of a three dimensional model of the roadway along with a map of friction values across the road and roadside surfaces.

To simulate a vehicle equipped with ESC an accurate vehicle model with a corresponding ESC model (tuned to the vehicle) is required. To that end, Bosch supplied two vehicle models with corresponding ESC models contained in a module called CSsim which was capable of interfacing with CarSim. During a simulation CarSim reports the current state of the vehicle to CSsim which calculates whether any braking interventions are required. Any interventions are then reported back to CarSim to affect the vehicle's response.

Figure 6.1 shows the flow of data during a simulation. Input data is supplied to CarSim, in three components, which then operates in parallel with CSsim to produce output data. The output data consist of vehicle kinematics, including braking interventions, that can be used to produce animations and plots.

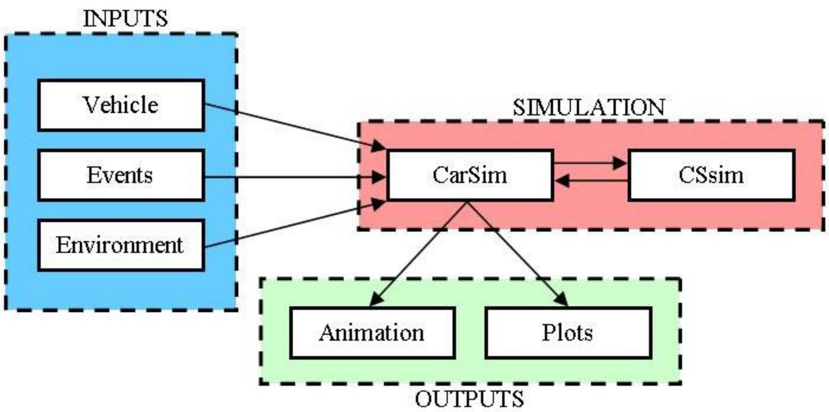


Fig. 6.1: Illustration of data flow during simulation

6.2 Validation of vehicle and ESC models

To assist with this investigation Bosch supplied two generic vehicle models with corresponding ESC system models. The first vehicle model was representative of a rear wheel drive family sedan and the second was representative of a front wheel drive small car. Both vehicle models were able to be used within CarSim and both could be simulated with or without ESC through the CSsim module.

The vehicle models, and their corresponding ESC models, were loosely based on proprietary vehicle data and so were were deliberately de-identified (apart from the basic descriptions given above) and encrypted. However, it was possible to describe the dynamic performance of the models in simulated tests of vehicle stability.

As described in Section 3.3, the sine with dwell test manoeuvre is used to assess a vehicle's stability or dynamic response. For a vehicle equipped with an ESC system that is operating correctly that dynamic response should meet the ESC minimum effectiveness criteria.

The sine with dwell test and the ESC minimum effectiveness criteria were used to assess the validity of the Bosch vehicle and ESC models in two stages. In the first stage the sine with dwell test was applied (through simulation) to the Bosch vehicle models without ESC to characterise their baseline behaviour. The dynamic response of the Bosch vehicle models were then compared to the dynamic response of several other vehicle models of various sizes and classes that were known to be valid. The Bosch models were then judged on whether their dynamic response was similar to the size and class of vehicle they were claimed to represent.

In the second stage the sine with dwell test was applied to the Bosch vehicle models with ESC and the dynamic response of the models was judged on whether they met the ESC minimum effectiveness criteria. The dynamic response of the Bosch vehicle models with ESC were also compared to the dynamic response of vehicles, of a similar size and class, that had been tested by NHTSA to further validate their performance.

The specifics of implementing the sine with dwell test and the ESC evaluation criteria are explained below in Section 6.2.1. The validation of the Bosch vehicle models without ESC is then presented in Section 6.2.2, followed by the validation of the models with ESC in Section 6.2.3.

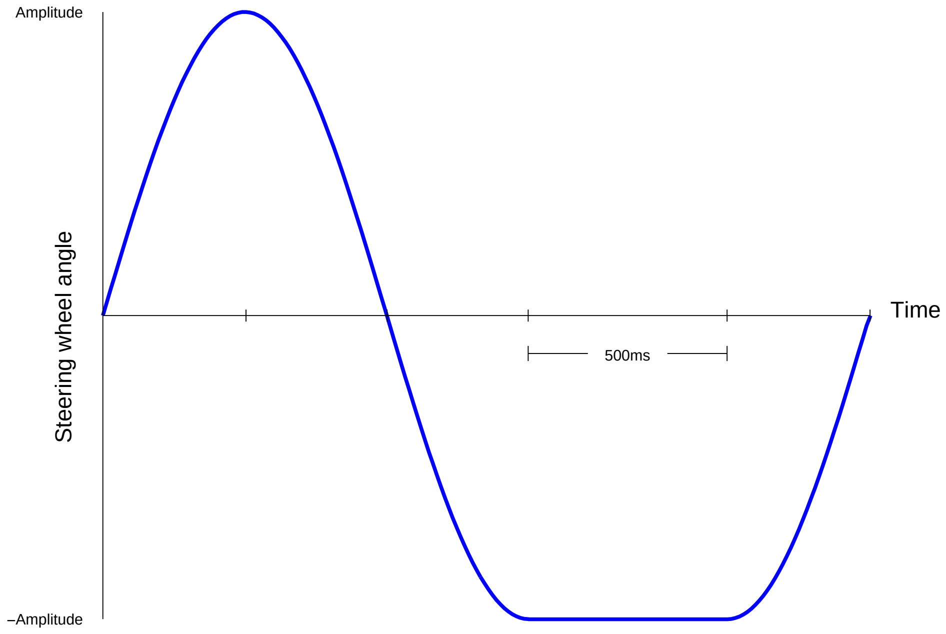


Fig. 6.2: Shape of the sine with dwell steering input

6.2.1 Sine with dwell test and minimum ESC effectiveness criteria

The sine with dwell test measures a vehicle's dynamic response (or stability) by applying a steering wheel input to the vehicle as shown in Figure 6.2. This input is derived from a 0.7 Hz sinusoid with a 500 ms pause after the completion of the third quarter-cycle. The total time to complete the entire steering input is 1.93 seconds.

The severity of the test depends upon the amplitude of the steering wheel input. However, as different vehicles have different dynamic characteristics, masses, and steering ratios, the severity of the test at a specific steering wheel amplitude will not be the same for all vehicles. Each vehicle undergoing the test must therefore have its steering response characterised. This allows the severity of the test to be set appropriately for each vehicle and allows the comparison of results between different vehicles.

To characterise a vehicle's steering response the steering wheel angle of the vehicle is increased by 13.5 degrees per second while travelling at a constant speed of 80 km/h. During this process the lateral acceleration of the vehicle is monitored and the steering wheel angle at which the lateral acceleration reaches 0.3 g is recorded. This procedure is completed for both the left and right steering directions. The average of the two recorded steering wheel angles is then designated as the vehicle's characteristic steering response and is represented by 'A'.

The value of A is used to calculate the amplitude of the steering input during the sine with dwell test. The initial speed during the assessment is 80 km/h and a sine with dwell steering input with an amplitude of $1.5A$ is applied to the vehicle. The test is then repeated for several runs, each time increasing the amplitude of the steering input by $0.5A$, until an amplitude of either $6.5A$ or more than 270 degrees is reached (whichever is greater). If an amplitude of over 300 degrees is reached then the test is run with an amplitude of exactly 300 degrees for the final run. This procedure is completed for both the left and right steering directions and the yaw rate response of the vehicle is recorded throughout all of the test runs. Through this process the dynamic response (lateral stability) of the test vehicle is characterised.

The lateral stability of a vehicle will be improved with the addition of an ESC system. However, the level of improvement can vary depending on how the system is tuned and the characteristics of the vehicle to which it is fitted. In order to ensure that a vehicle equipped with ESC achieves a certain level of lateral stability the ESC minimum effectiveness criteria are

Tab. 6.1: Description of the generic vehicle models pre-defined in CarSim

Pre-defined CarSim vehicle model	**Description**	**Drive train**
A-Class Hatch	Mini car (hatch)	Front wheel drive
B-Class Hatch	Small car (hatch)	Front wheel drive
C-Class Hatch	Medium car (hatch)	Front wheel drive
D-Class Sedan	Large car (sedan)	Front wheel drive
D-Class Minivan	Large car (minivan)	Front wheel drive
D-Class SUV	Large car (SUV)	All wheel drive
E-Class Sedan	Executive car (sedan)	All wheel drive
E-Class SUV	Executive car (SUV)	All wheel drive
F-Class Sedan	Luxury car (sedan)	All wheel drive

used. The three criteria (discussed in Chapter 3) are summarised below:

1. 1.00 second after the steering input is complete the yaw rate must be less than 35% of the peak yaw rate

2. 1.75 seconds after the steering input is complete the yaw rate must be less than 20% of the peak yaw rate

3. 1.07 seconds into the test the lateral displacement must be 1.83 m or greater (only for runs where the amplitude is $5.0A$ or more)

6.2.2 Validating the Bosch vehicle models without ESC

The sine with dwell test was applied to the Bosch vehicle models (without ESC) along with nine other generic vehicle models pre-defined in CarSim. The CarSim models represent typical vehicles in various market segments as shown in Table 6.1.

Figure 6.3 shows the lateral acceleration experienced by each vehicle model as the steering angle was increased during the characterising of each

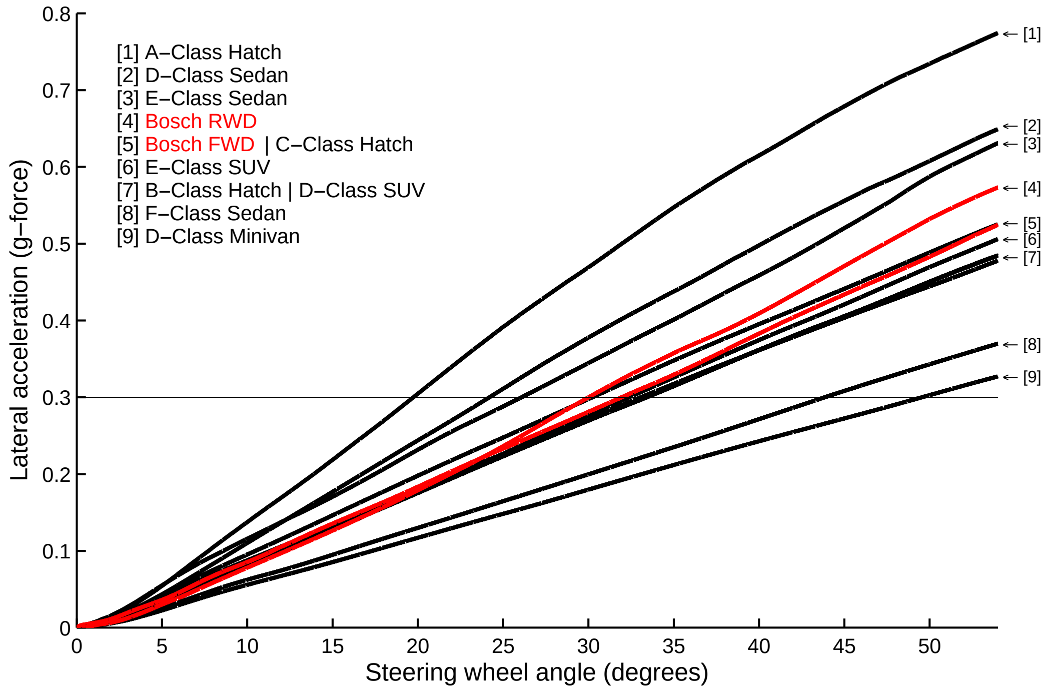


Fig. 6.3: Steering response for all vehicle models

model's steering response. A horizontal line indicates a lateral acceleration of 0.3 g and the lines associated with the front wheel drive (FWD) and rear wheel drive (RWD) Bosch vehicle models have been highlighted in red. The resulting values of A for each vehicle are summarised in Table 6.2.

The results of the sine with dwell test for the nine CarSim vehicle models are shown in Figures 6.4 to 6.12. Each of the lines represents a single run at a different amplitude of the steering input and is shown in a unique colour. The run with the lowest amplitude ($1.5A$) is shown in dark blue while the run with the highest amplitude (between 270 and 300 degrees) is shown in dark red. Each run in between progresses through the following colours: dark blue, light blue, green, yellow, orange, and red.

For any given run, a stable manoeuvre is indicated by a yaw rate that

Tab. 6.2: Steering wheel angle required by each vehicle model to achieve a lateral acceleration of 0.3 g

Vehicle model	**Angle in degrees (A)**
A-Class Hatch	19.736
B-Class Hatch	33.072
C-Class Hatch	30.228
D-Class Sedan	24.196
D-Class Minivan	49.548
D-Class SUV	32.369
E-Class Sedan	26.077
E-Class SUV	32.807
F-Class Sedan	43.851
Bosch RWD	29.900
Bosch FWD	32.541

terminates at a value of zero. Alternatively, a run that terminates with a yaw rate much different from zero indicates that the manoeuvre is unstable and that the vehicle is oversteering.

For example, in Figure 6.4 it may be observed that that the yaw rate of the CarSim A-Class Hatch model is stable for the first 6 runs, becomes unstable during the next 11 runs, and then returns to stability once again for the last 9 runs. This apparent return to stability is likely caused by understeer resulting from the high steering amplitudes of the later runs.

This pattern of stable-unstable-stable was also true for the C-Class Hatch, D-Class Sedan, E-Class Sedan, and F-Class Sedan vehicle models. The D-Class Minivan, D-Class SUV, and E-Class SUV vehicle models were stable during their low amplitude runs but at some particular amplitude became unstable and remained that way for all higher amplitude runs. The B-Class Hatch was stable for all runs through the sine with dwell test.

The results of the sine with dwell test for the Bosch vehicle models are shown in Figure 6.13 and Figure 6.14. Both models were initially stable and then became unstable.

The lateral stability of the Bosch vehicle models were compared to the CarSim models to infer what type of vehicle they may represent. It can been seen that the rear wheel drive (RWD) model appears to show a good match with the CarSim D-Class SUV and E-Class SUV vehicle models. This corresponds positively with the description of the RWD model as a large family sedan. The match with the SUV type vehicles rather than the sedan type vehicles is likely an indication that the Bosch RWD model is slightly larger and heavier than the CarSim sedan models. In contrast, the front wheel drive (FWD) model did not seem to match well any of the generic CarSim vehicle models. A vague match could be argued to exist with the D-Class Minivan or the E-Class SUV. However, these vehicle types are rather different to the description of the FWD model as a small car.

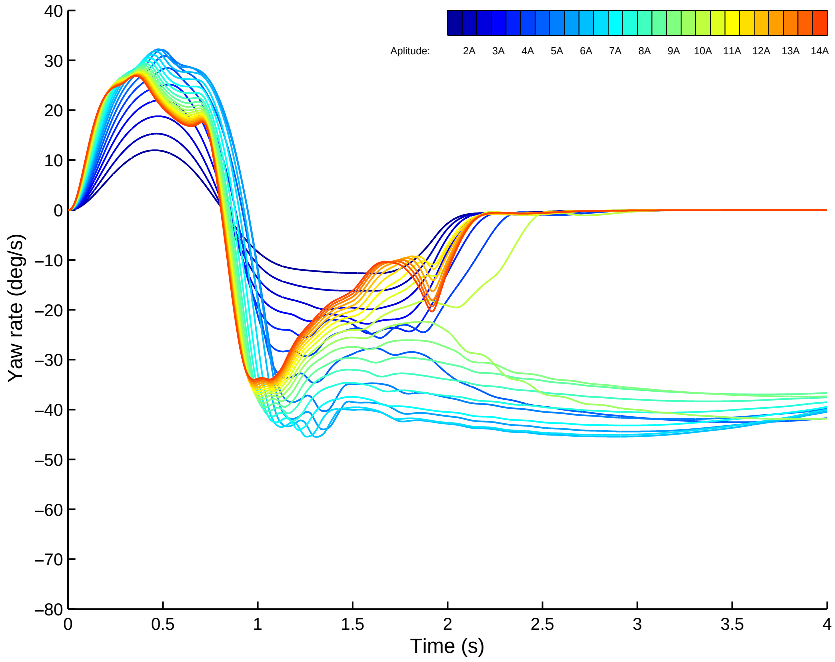


Fig. 6.4: Yaw rate during sine with dwell test for CarSim A-Class Hatch model

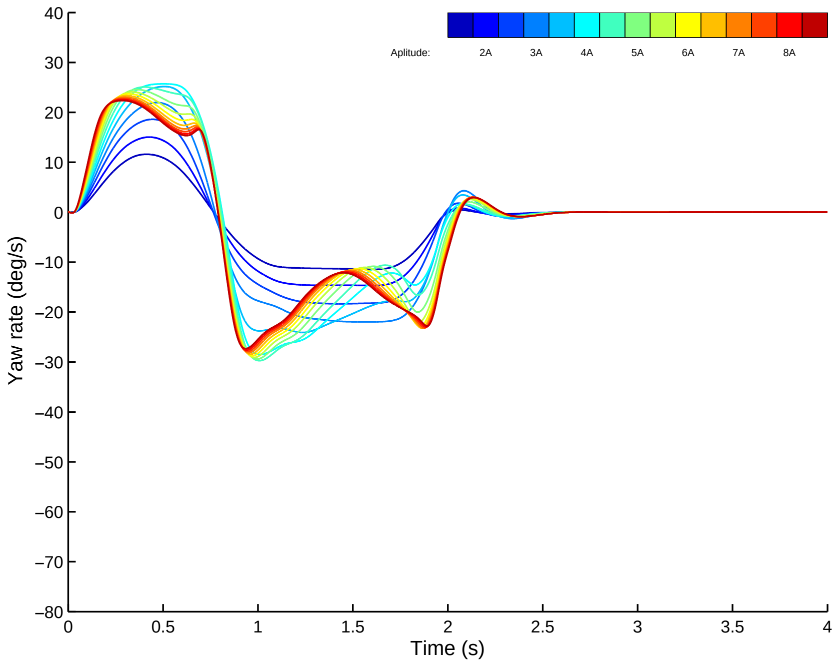


Fig. 6.5: Yaw rate during sine with dwell test for CarSim B-Class Hatch model

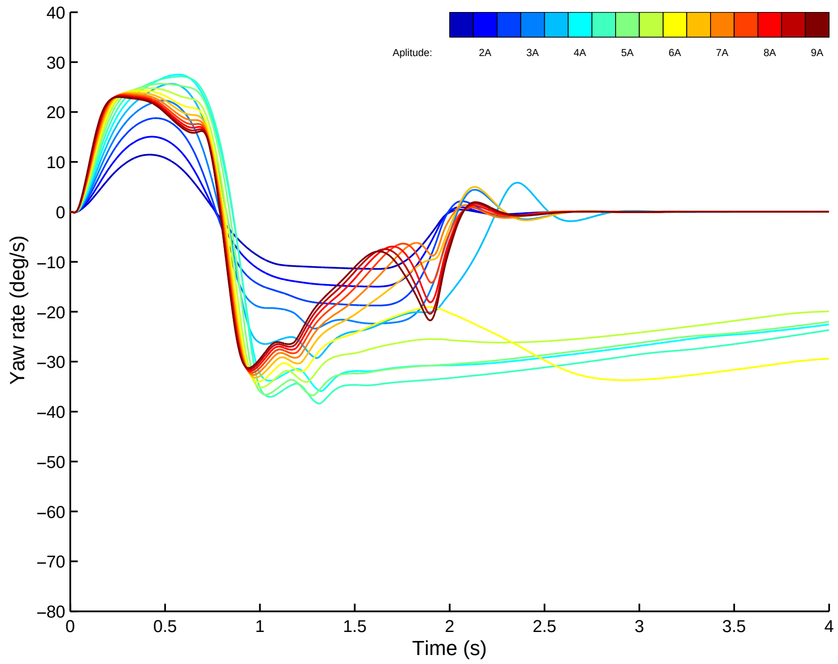


Fig. 6.6: Yaw rate during sine with dwell test for CarSim C-Class Hatch model

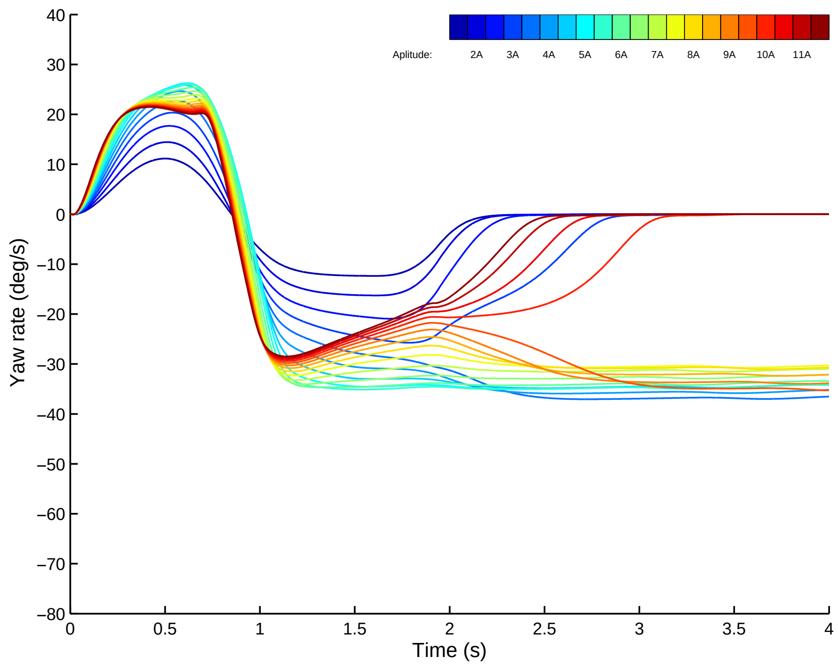


Fig. 6.7: Yaw rate during sine with dwell test for CarSim D-Class Sedan model

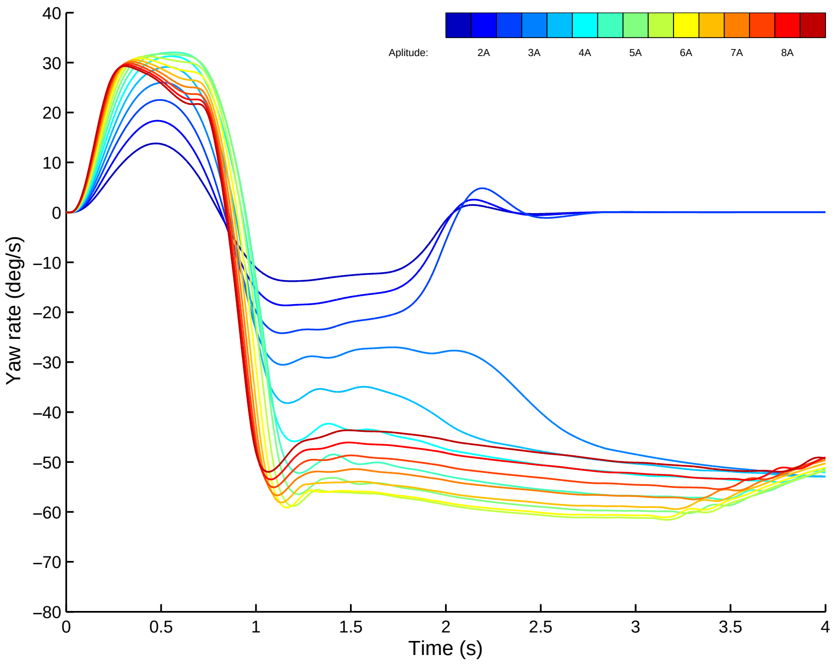


Fig. 6.8: Yaw rate during sine with dwell test for CarSim D-Class SUV model

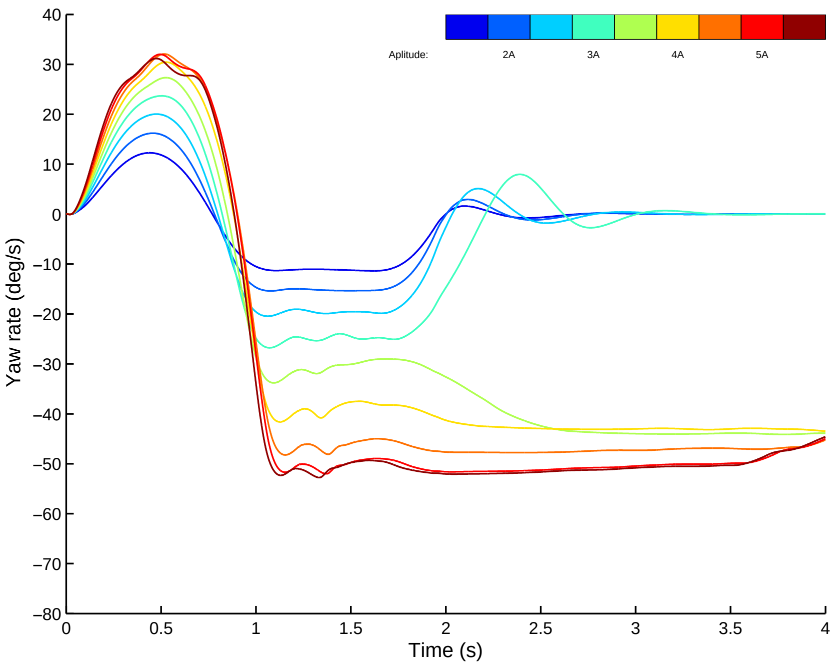


Fig. 6.9: Yaw rate during sine with dwell test for CarSim D-Class Minivan model

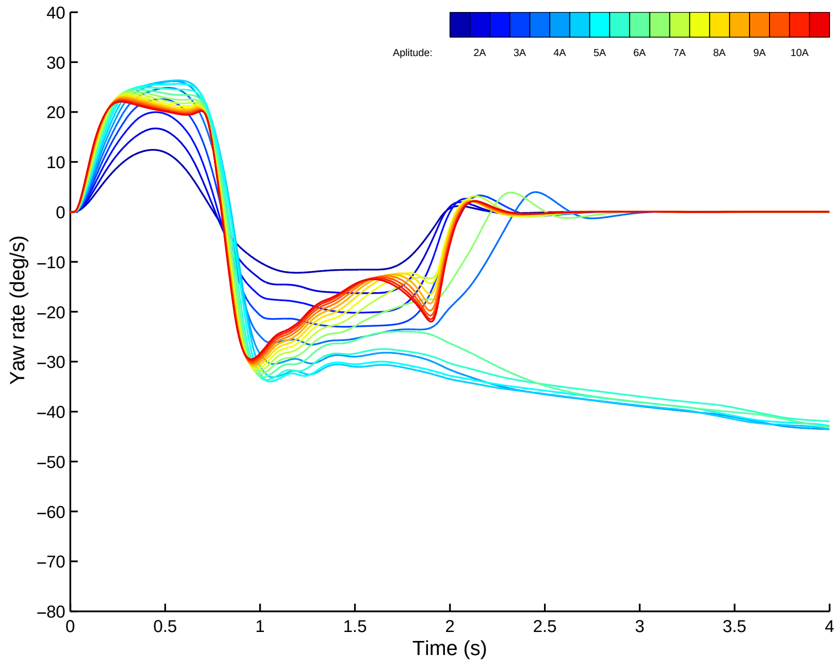


Fig. 6.10: Yaw rate during sine with dwell test for CarSim E-Class Sedan model

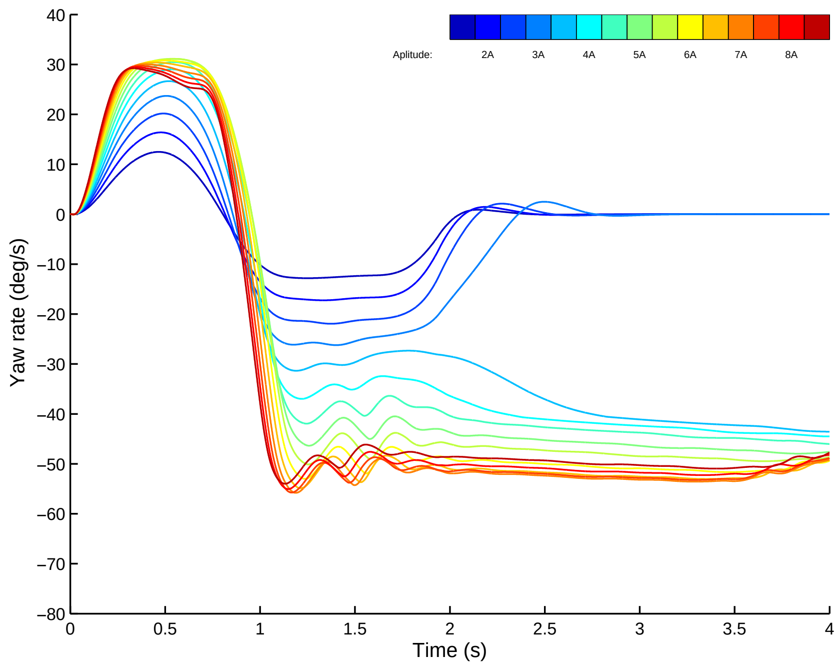


Fig. 6.11: Yaw rate during sine with dwell test for CarSim E-Class SUV model

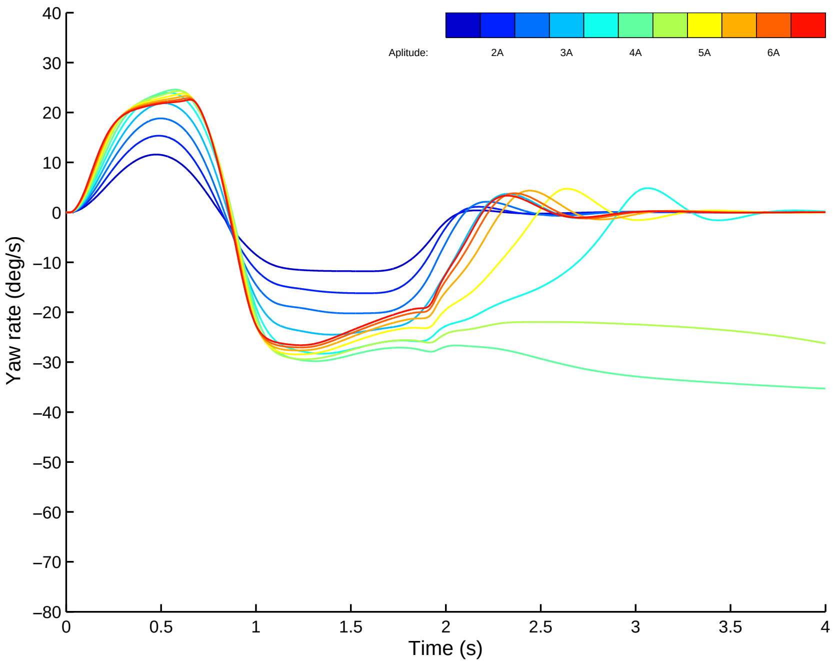


Fig. 6.12: Yaw rate during sine with dwell test for CarSim F-Class Sedan model

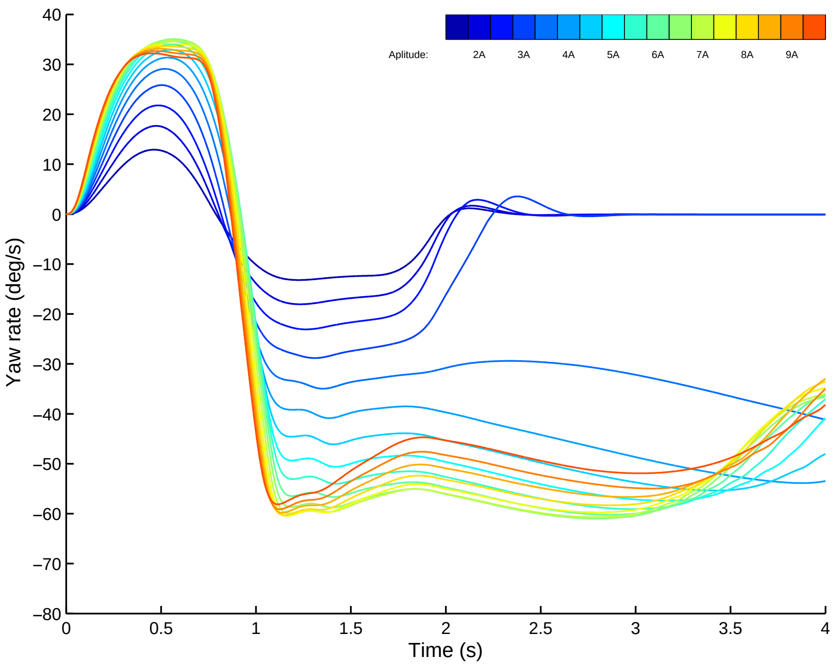


Fig. 6.13: Yaw rate during sine with dwell test for Bosch rear wheel drive model (without ESC)

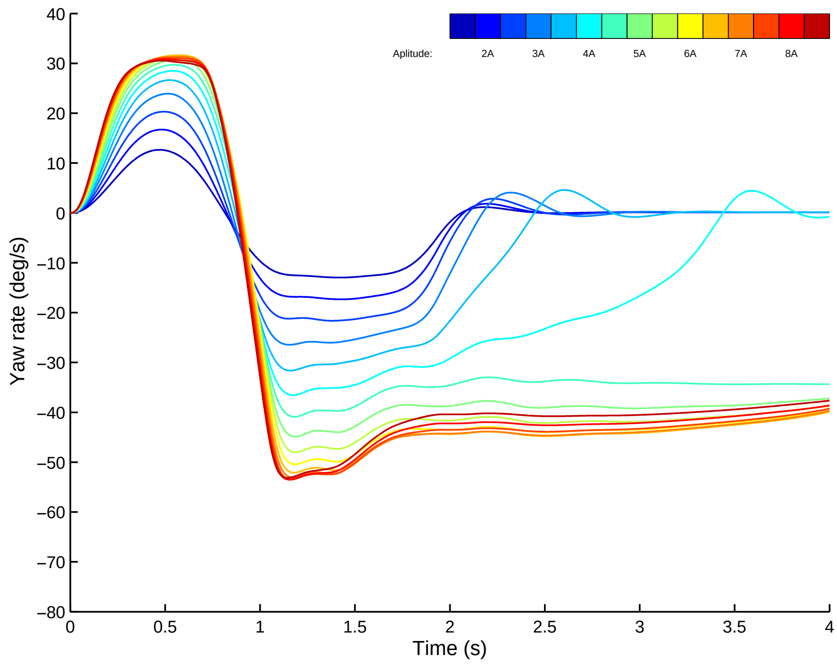


Fig. 6.14: Yaw rate during sine with dwell test for Bosch front wheel drive model (without ESC)

6.2.3 Validating the Bosch vehicle models with ESC

The sine with dwell test was also applied to the Bosch vehicle models with ESC as shown in Figure 6.15 and Figure 6.16. These results were then evaluated using the minimum ESC effectiveness criteria. Runs that passed the minimum ESC effectiveness criteria are shown as solid lines, while runs that failed the criteria are shown as dashed lines. Note that although the lateral displacement is not shown here, both vehicle models met the minimum lateral displacement criterion in all runs with an amplitude over $5.0A$.

The RWD vehicle model became more stable when equipped with ESC and passed the minimum effectiveness criteria for all runs. The FWD model became more stable during its mid-amplitude runs, but remained unstable during the higher amplitude runs and failed to pass the minimum effectiveness criteria.

After consultation with Bosch Australia it was concluded that the FWD vehicle and ESC models were not valid. No replacement model was available and thus the further use of a FWD vehicle model was not possible in this investigation.

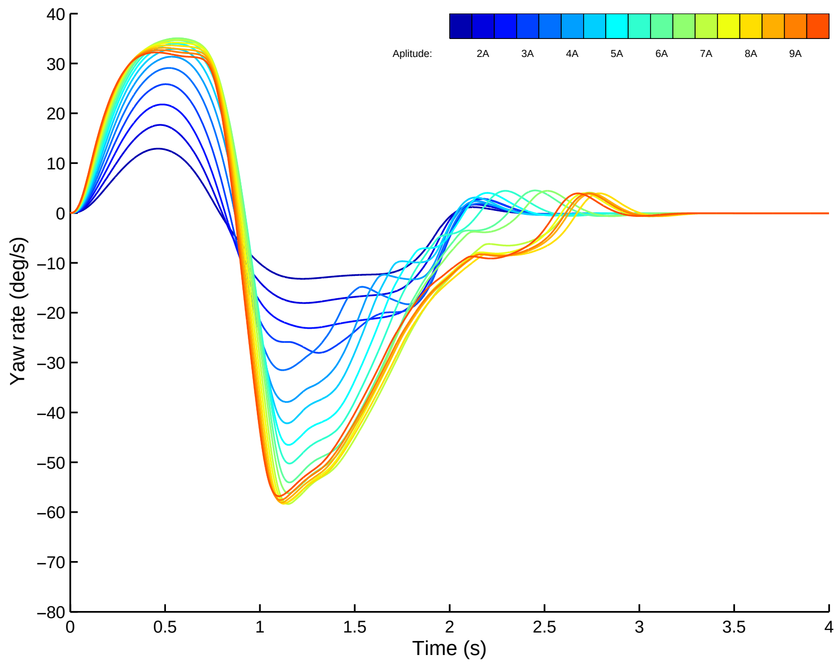


Fig. 6.15: Yaw rate during sine with dwell test for Bosch rear wheel drive model (with ESC)

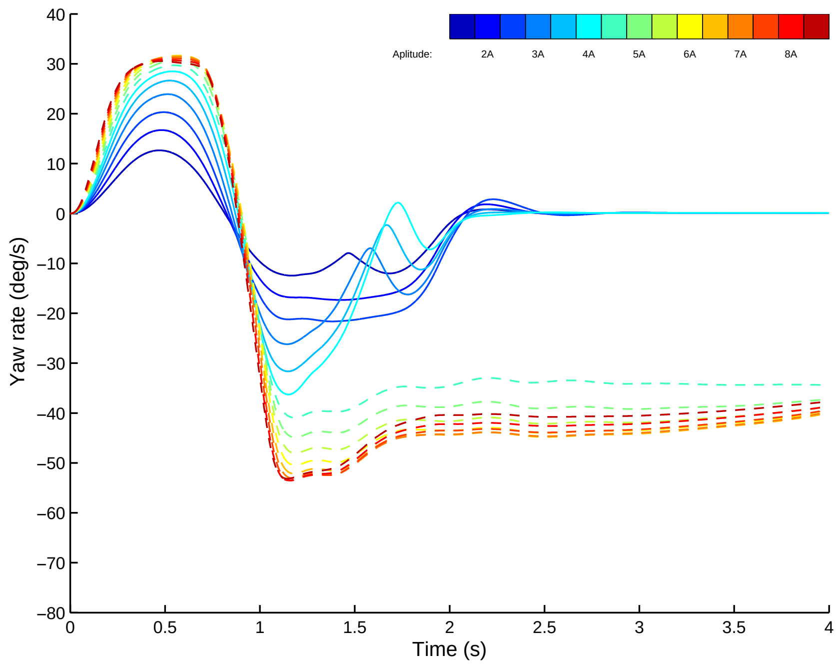


Fig. 6.16: Yaw rate during sine with dwell test for Bosch front wheel drive model (with ESC)

The dynamic response of the RWD model with ESC was then compared to an ESC equipped 4-door sedan vehicle that had been tested by the US National Highway Traffic Safety Administration (NHTSA). The comparison vehicle was a 2013 Hyundai Genesis and the sine with dwell test results for the vehicle are shown in Figure 6.17. It can be seen that the dynamic response of the RWD vehicle model with ESC is similar to that of the comparison vehicle.

In summary, the RWD vehicle model has been shown to display a dynamic response that is as expected both with and without ESC and also meets the minimum ESC effectiveness criteria. Based on this, it was concluded that the RWD model did indeed represent a family sized, 4-door sedan vehicle, with an appropriately tuned ESC system, and could be used with confidence for this investigation.

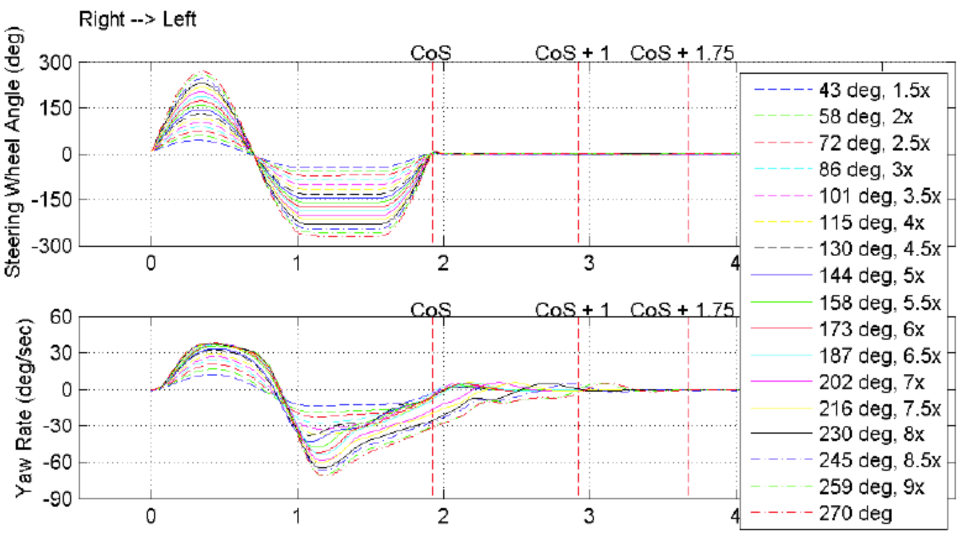


Fig. 6.17: Sine with dwell test for the 2013 Hyundai Genesis [reproduced from Lenkeit & Kebschull (2013)]

6.3 Development of loss of control scenarios

To conduct an investigation that was representative of the real world, a set of loss of control scenarios that were typical of high speed rural roads in Australia and could be simulated with CarSim were required. Each scenario needed to describe the environment where the loss of control takes place (road layout, coefficient of friction, roadside objects, etc), the circumstances leading to the loss of control, and the trajectory of the vehicle during the loss of control. It would then be possible to construct simulations with the same environment, circumstances, and trajectory as that described in each scenario. These initial simulations, that seek to mimic the loss of control scenarios, use the RWD vehicle model without ESC. Subsequent simulations of each scenario can then be run with the same conditions but using the RWD vehicle model with ESC so that the effects of ESC can be investigated.

Obtaining a set of representative loss of control scenarios for this investigation was achieved by developing a random set of crashes from the CASR in-depth database (described in Chapter 5). The database contains detailed information about 238 rural road crashes that occurred in South Australia but not all were relevant to the current investigation. Only those crashes involving a loss of control by a passenger vehicle on a high speed road were required, and the following exclusion criteria were applied:

- Crashes which were not sensitive to the effects of ESC (e.g. rear end, right angle, side swipe)
- Crashes in which a driver was unconscious or asleep prior to the crash

- Crashes where there was a suspicion of suicide
- Crashes on roads with a speed limit below 80 km/h
- Crashes not involving a passenger vehicle or derivative (e.g. motorcycles, trucks, buses)

Additionally, crashes that involved complex interactions with terrain that could not be simulated within CarSim, such as colliding with embankments or striking kerbs, were also excluded. A subset of ninety four loss of control crashes remained, from which ten were selected at random to represent typical loss of control scenarios.

During this process, ten crashes involving front wheel drive vehicles were selected but could not be simulated and had to be discarded due to problems with the front wheel drive vehicle model (explained in Section 6.2).

The ten crashes that were chosen to represent typical loss of control scenarios are described in the subsections below. For each scenario, a crash description is presented along with a table listing the prevailing environmental conditions of weather, lighting, road type, and speed limit. Also presented for each scenario are photographs from the crash and a site diagram of the crash scene that shows the layout of the road, final positions of the vehicle(s) involved, collision impact points, and any associated tyre marks.

The development of simulations (using the RWD vehicle model without ESC) to emulate these loss of control scenarios is described in the following sections.

6.3.1 Scenario 1

On a Friday at approximately 9:30 pm, a utility was travelling in the right of two lanes at a speed in excess of 100 km/h. The driver was travelling their normal route home after consuming alcohol (BAC of 0.206). The vehicle was seen by a witness to suddenly veer left, crossing both lanes of the carriageway with the left wheels travelling onto the unsealed shoulder. The driver of the utility overcorrected the vehicle sharply to the right, travelling across both lanes before overcorrecting back to the left. The utility then yawed in an anticlockwise direction across the carriageway and onto the unsealed shoulder for the second time. The front right side collided with a utility pole four metres from the sealed carriageway. The prevailing environmental conditions at the crash site are given in Table 6.3. Photographs showing the roadway and shoulder as well as the damage to the utility are shown in Figures 6.18 and 6.19. The site diagram for the crash is shown in Figure 6.20.

Tab. 6.3: Environmental conditions prevalent in scenario 1

Condition	**Status**
Weather	Fine
Lighting	Dark, no artificial lighting
Road type	National Highway, sealed, multi-laned divided, dry
Speed limit	90 km/h

Fig. 6.18: The roadway, roadside shoulder, and Stobie pole (far right) involved in scenario 1

Fig. 6.19: The damaged to the utility involved in scenario 1

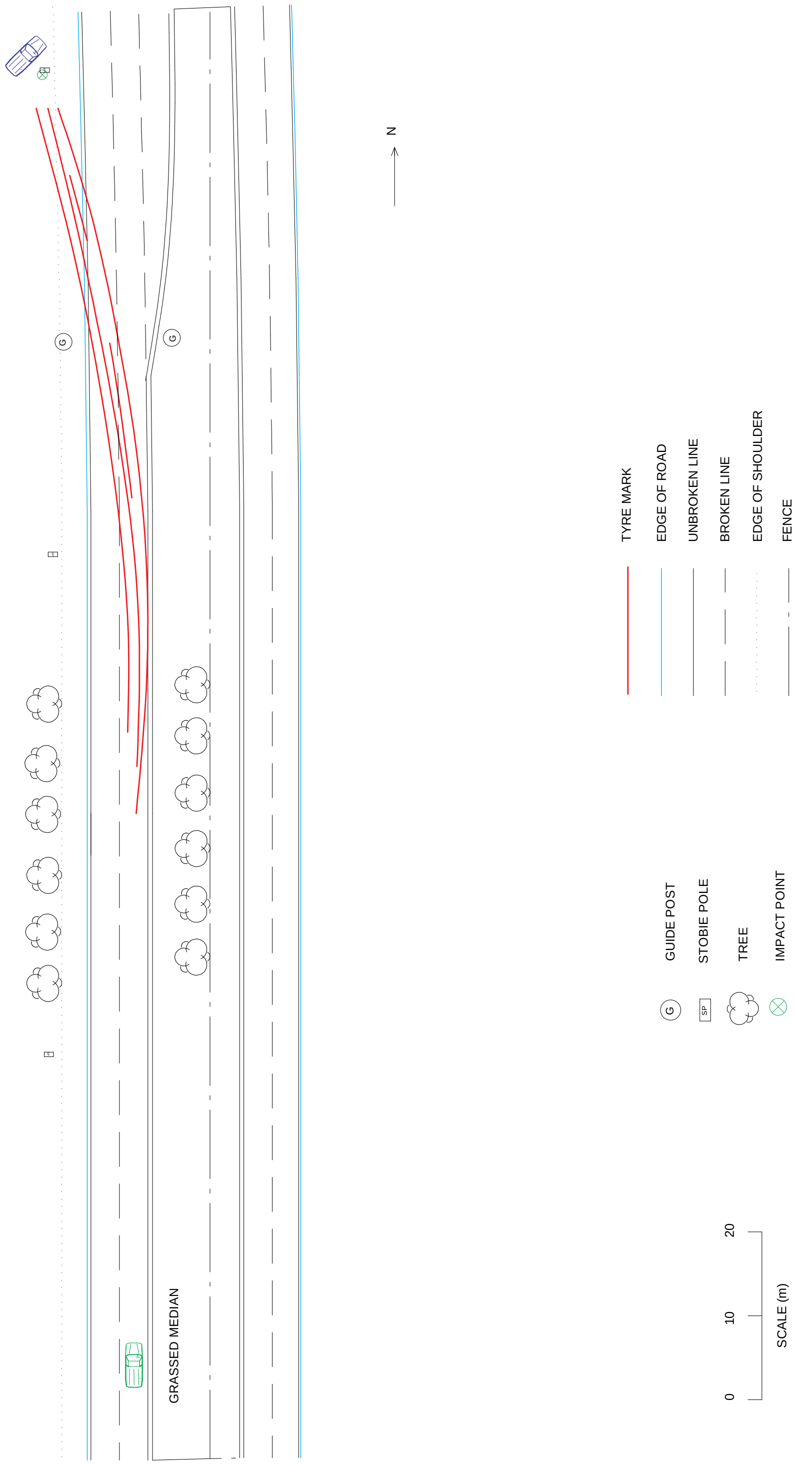


Fig. 6.20: Site diagram for scenario 1

6.3.2 Scenario 2

On a Tuesday at approximately 7:50 am, a car was travelling down a narrow carriageway at a speed in excess of 130 km/h. As the vehicle came over the top of a crest, the driver was confronted with a truck straddling the centre of the carriageway. The truck was travelling in the opposite direction at a self reported speed of 15 km/h. The truck driver attempted to veer left to allow room for the car to pass. The driver of the car braked and veered right. The car yawed in a clockwise direction across the carriageway and onto the right hand side verge, narrowly missing the front of truck. The left front corner of the car struck a large tree, 4.5 metres from the carriageway. The prevailing environmental conditions at the crash site are given in Table 6.4. Photographs showing the roadway and the damage to the car are shown in Figures 6.21 and 6.22. The site diagram for the crash is shown in Figure 6.23.

Tab. 6.4: Environmental conditions prevalent in scenario 2

Condition	**Status**
Weather	Fine
Lighting	Daylight
Road type	Unsealed, two way, dry
Speed limit	100 km/h

Fig. 6.21: The unsealed roadway involved in scenario 2 (note the crest in the road)

Fig. 6.22: The damage to the car involved in scenario 2

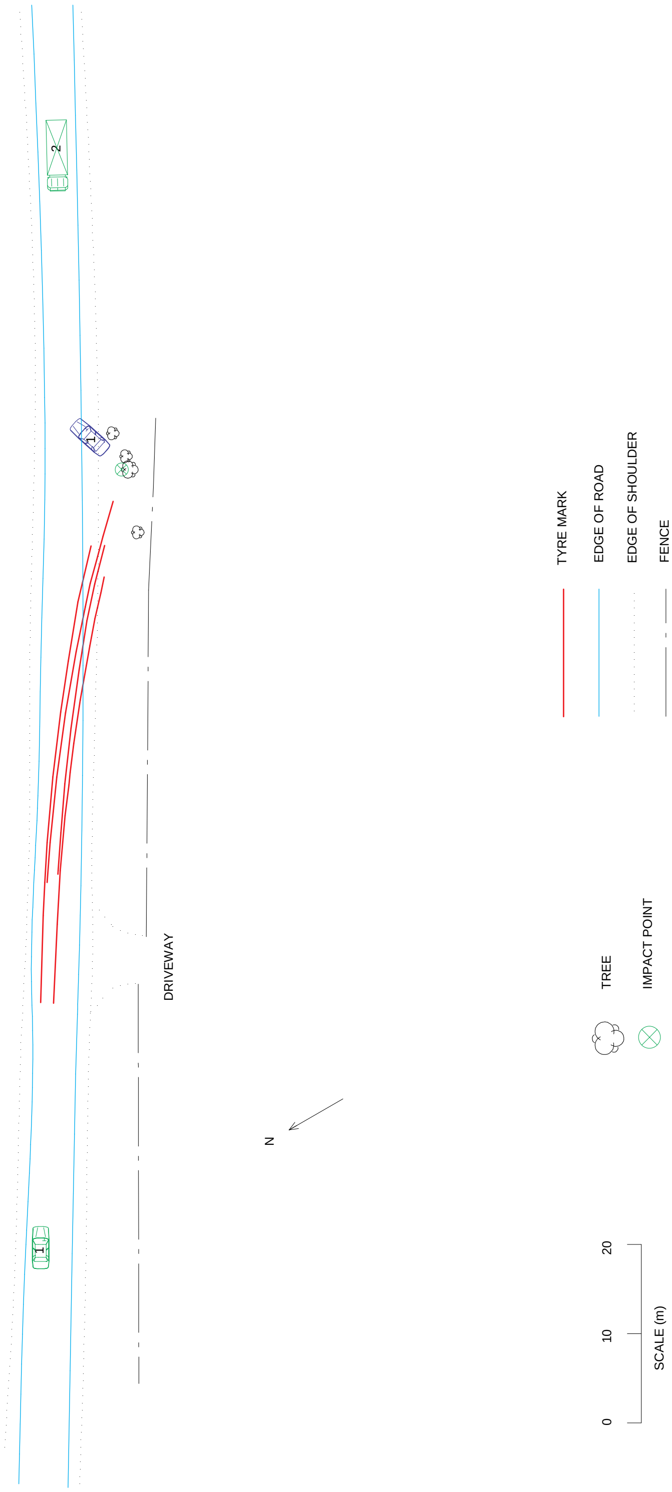


Fig. 6.23: Site diagram for scenario 2

6.3.3 Scenario 3

On a Thursday at approximately 3:00 pm, a car was travelling at an estimated speed of 85 km/h, negotiating a left bend with an advisory speed of 55 km/h. While negotiating the bend, the right hand wheels of the vehicle travelled over the double centre lines. The driver overcorrected the vehicle to the left to avoid a collision with an oncoming vehicle. The vehicle yawed in an anticlockwise direction across the left lane and onto the unsealed shoulder where the left front corner of the car clipped a large tree 3 metres south of the carriageway. The prevailing environmental conditions at the crash site are given in Table 6.5. Photographs showing the roadway and the damage to the car are shown in Figures 6.24 and 6.25. The site diagram for the crash is shown in Figure 6.26.

Tab. 6.5: Environmental conditions prevalent in scenario 3

Condition	**Status**
Weather	Fine
Lighting	Daylight
Road type	Rural Highway, sealed, two way, dry
Speed limit	80 km/h (55 km/h advisory)

Fig. 6.24: The roadway involved in scenario 3

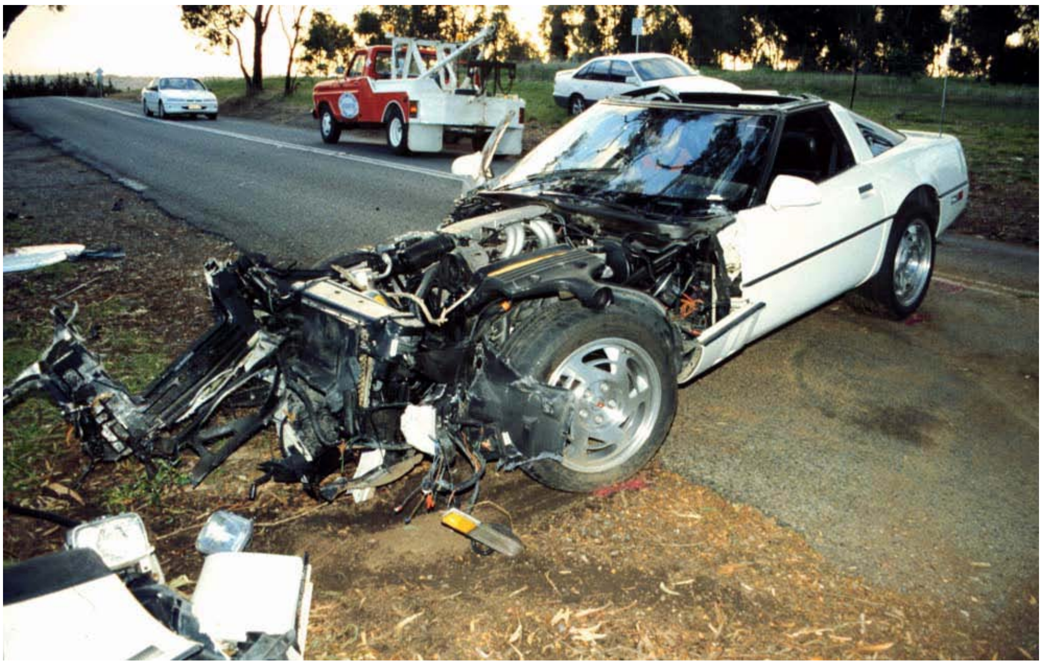


Fig. 6.25: The damage to the vehicle involved in scenario 3

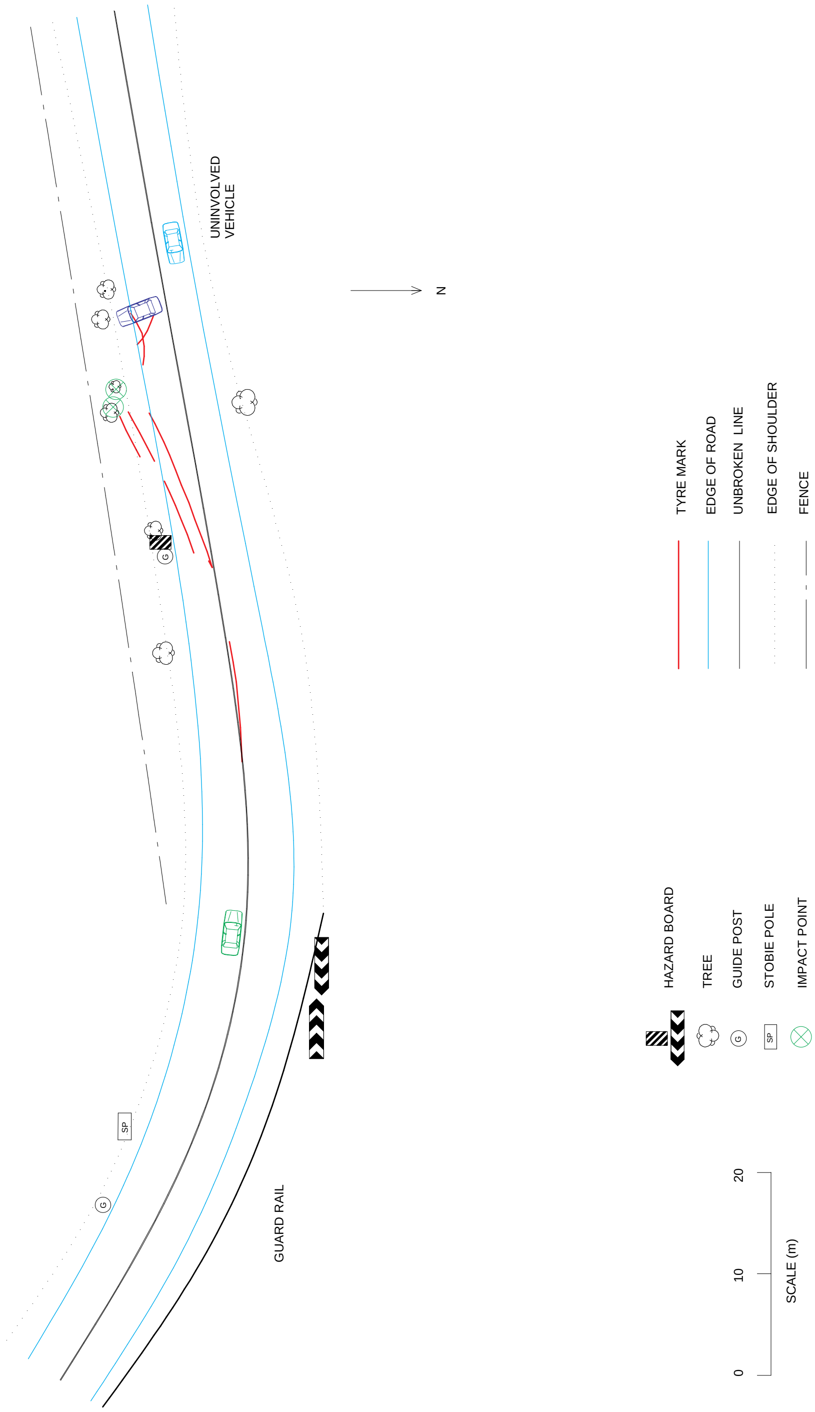


Fig. 6.26: Site diagram for scenario 3

6.3.4 Scenario 4

On a Friday at approximately 8:25 pm, a van was negotiating a slight right bend at a self reported speed of 115 km/h. It was raining heavily and the road was extremely wet. While negotiating the bend the van began to aquaplane across the smooth wet surface. The driver attempted to regain control of the vehicle but was unsuccessful. The vehicle yawed in a clockwise direction across both lanes of the carriageway and ran onto the right side unsealed shoulder. The left front wheel and door of the vehicle collided with a tree 6 metres from the edge of the carriageway. The prevailing environmental conditions at the crash site are given in Table 6.6. Photographs showing the roadway, roadside shoulder, and the damage to the van are shown in Figures 6.27 and 6.28. The site diagram for the crash is shown in Figure 6.29.

Tab. 6.6: Environmental conditions prevalent in scenario 4

Condition	**Status**
Weather	Heavy rain and strong winds
Lighting	Dark, no artificial lighting
Road type	National Highway, sealed, two way, wet
Speed limit	110 km/h

Fig. 6.27: The roadway and roadside shoulder involved in scenario 4

Fig. 6.28: The damage to the van involved in scenario 4

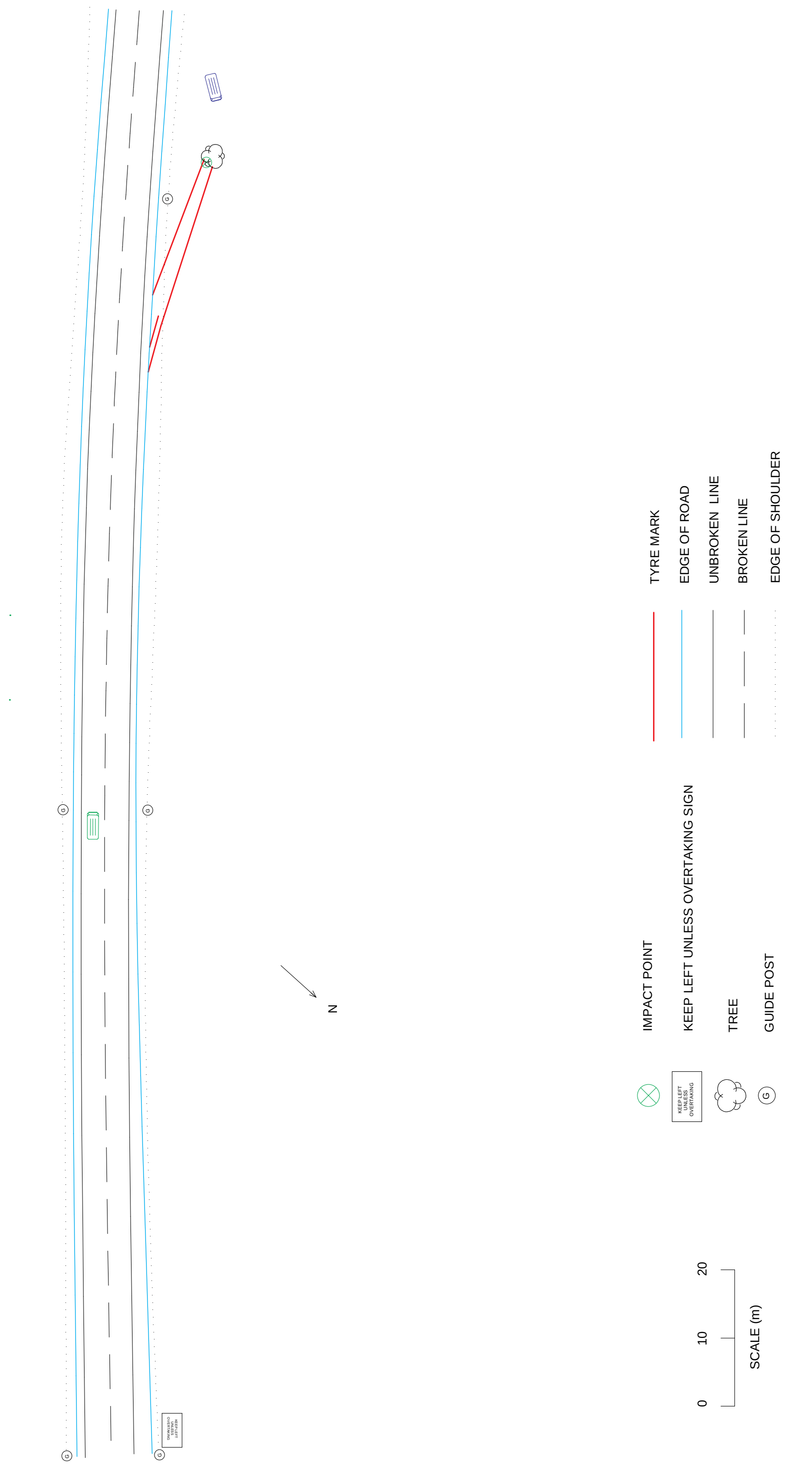


Fig. 6.29: Site diagram for scenario 4

6.3.5 Scenario 5

On a Thursday at approximately 7:35 am, a 4WD was negotiating a sweeping left bend at an estimated speed of 70 km/h. As the 4WD came over a crest the left front wheel ran onto the unsealed left shoulder. The driver overcorrected the 4WD to the right, crossing the centre line before overcorrecting back to the left. The 4WD yawed in an anticlockwise direction across the carriageway and an unsealed driveway. The right rear of the 4WD collided with a large tree located 4 metres from the carriageway and rolled onto it's roof. The prevailing environmental conditions at the crash site are given in Table 6.7. Photographs showing the crash site, the tree, and the damage to the 4WD are shown in Figures 6.30 and 6.31. The site diagram for the crash is shown in Figure 6.32.

Tab. 6.7: Environmental conditions prevalent in scenario 5

Condition	**Status**
Weather	Fine
Lighting	Daylight
Road type	Sealed, two way, dry
Speed limit	100 km/h

Fig. 6.30: The impacted tree and site of the final position for the 4WD involved in scenario 5

Fig. 6.31: The damage to the 4WD involved in scenario 5

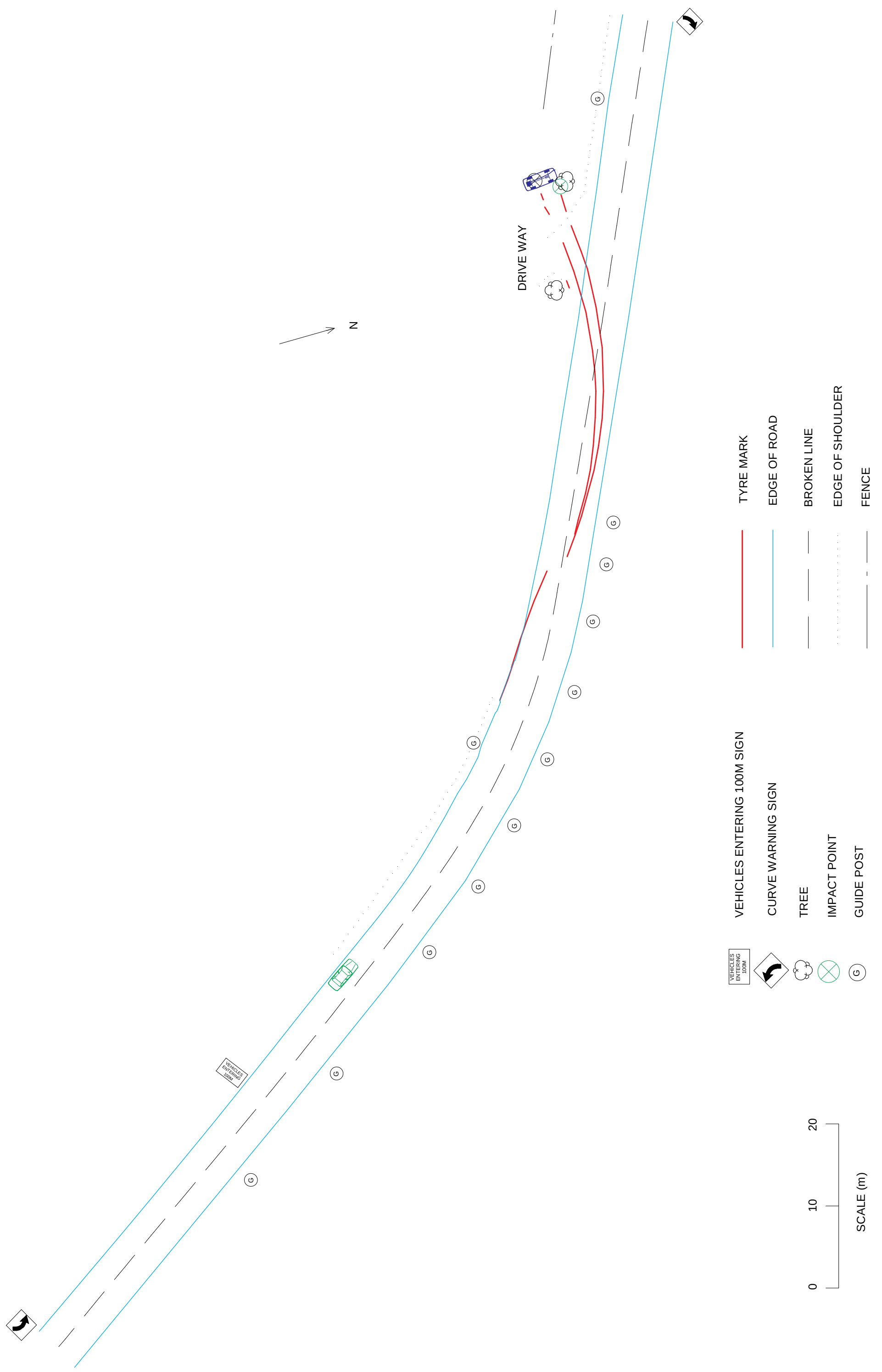


Fig. 6.32: Site diagram for scenario 5

6.3.6 Scenario 6

On a Wednesday at approximately 9:10 am, a car was travelling north and negotiating a slight right bend at an estimated speed of 95 km/h. While negotiating the bend, the left wheels ran onto the left side unsealed shoulder. The young driver, who was on a provisional licence but was familiar with the road, overcorrected the vehicle to the right and yawed in a clockwise direction across both lanes of the carriageway and onto the right side unsealed shoulder. The right front corner of the vehicle collided with a tree as it crossed onto the verge. The vehicle continued to rotate in a clockwise direction before the right side of the vehicle collided with a second tree 10 metres north of the first. The vehicle wrapped clockwise around the trunk of the tree on impact, coming to rest against the tree, facing north. The prevailing environmental conditions at the crash site are given in Table 6.8. Photographs showing the roadway, the tree, and the damage to the car are shown in Figures 6.33 and 6.34. The site diagram for the crash is shown in Figure 6.35.

Tab. 6.8: Environmental conditions prevalent in scenario 6

Condition	**Status**
Weather	Overcast
Lighting	Daylight
Road type	Rural highway, sealed, two way, dry
Speed limit	100 km/h

Fig. 6.33: The roadway involved in scenario 6

Fig. 6.34: The impacted tree and the damage to the car involved in scenario 6

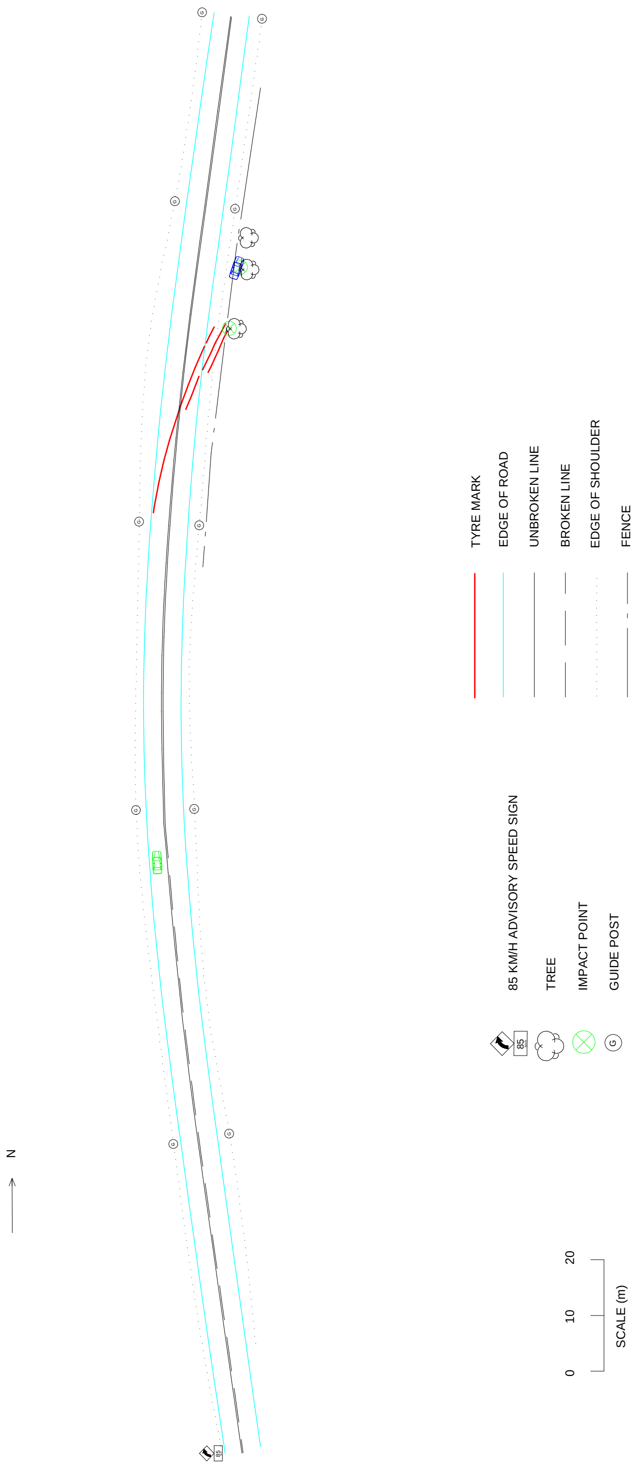


Fig. 6.35: Site diagram for scenario 6

6.3.7 Scenario 7

On a Wednesday at approximately 4:05 pm, a car was travelling along a straight section of sealed highway at an estimated speed of 85 km/h. As the car approached a side road on the left, the driver noticed a second vehicle travelling towards the intersection. Believing that the second vehicle was attempting to enter the carriageway, the driver veered sharply right to avoid a collision. The car travelled across both lanes of the carriageway where the right wheels travelled onto the right side unsealed shoulder. The driver overcorrected to the left and lost control of the vehicle. The vehicle yawed in an anticlockwise direction across both lanes of the carriageway and ran onto the left side unsealed shoulder. The front of the vehicle collided with a large tree 2 metres east of the carriageway. The vehicle rotated anticlockwise around the tree following the collision, coming to rest over the edge of the carriageway, facing the wrong way. The prevailing environmental conditions at the crash site are given in Table 6.9. Photographs showing the roadway, roadside shoulder, and the damage to the car are shown in Figures 6.36 and 6.37. The site diagram for the crash is shown in Figure 6.38.

Tab. 6.9: Environmental conditions prevalent in scenario 7

Condition	**Status**
Weather	Fine
Lighting	Daylight
Road type	Rural highway, sealed, two way, dry
Speed limit	100 km/h

Fig. 6.36: The roadway and roadside shoulder involved in scenario 7

Fig. 6.37: The damage to the car involved in scenario 7

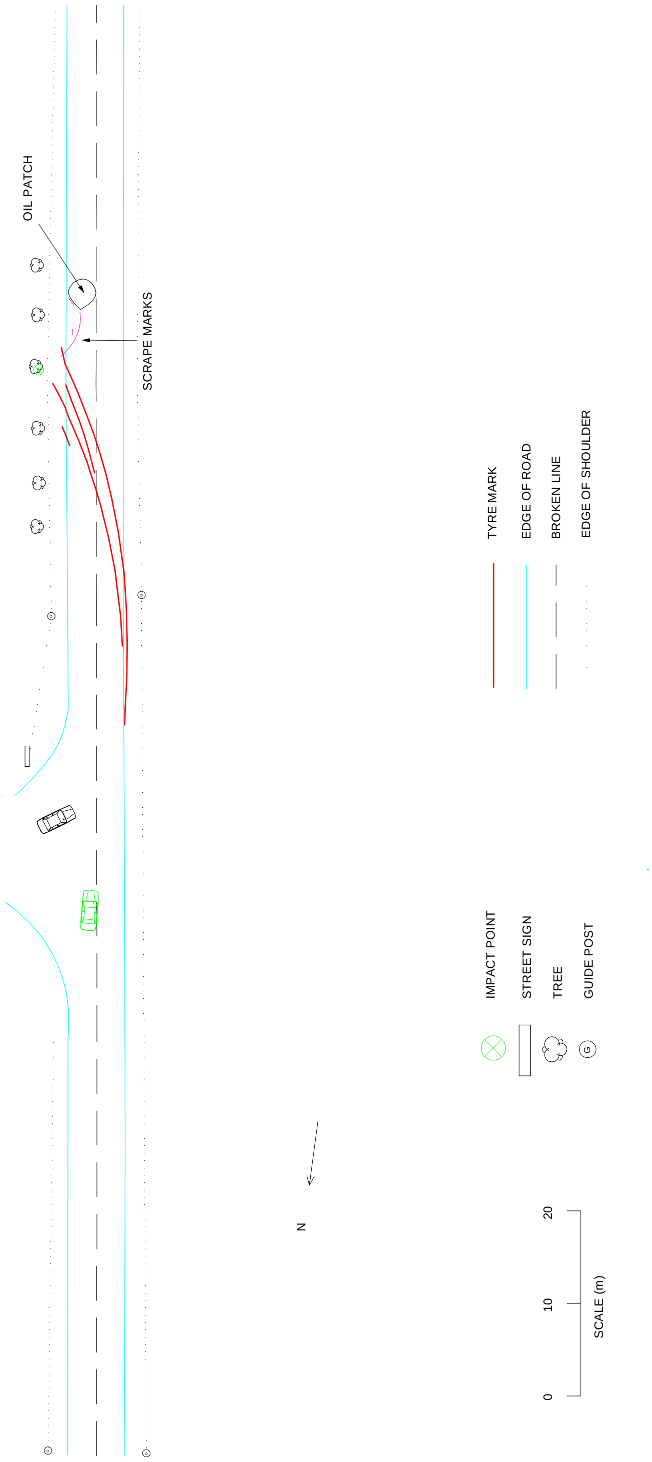


Fig. 6.38: Site diagram for scenario 7

6.3.8 Scenario 8

On a Saturday at approximately 4:30 pm, a car was travelling along a straight section of sealed carriageway at a speed greater than 100 km/h. The vehicle drifted onto the left unsealed shoulder for over 80 metres before the driver, who had a BAC of 0.256, swerved back to the right. The vehicle yawed in a clockwise direction across the carriageway and onto the right side unsealed shoulder where it travelled over a low embankment and through a wire fence. The vehicle then rolled onto its left side and roof before coming to rest on its right side 8 metres beyond the fence line. The prevailing environmental conditions at the crash site are given in Table 6.10. Photographs showing the roadway, roadside shoulder, and the damage to the car are shown in Figures 6.39 and 6.40. The site diagram for the crash is shown in Figure 6.41.

Tab. 6.10: Environmental conditions prevalent in scenario 8

Condition	**Status**
Weather	Fine
Lighting	Daylight
Road type	Sealed, two way, dry
Speed limit	100 km/h

Fig. 6.39: The roadway and roadside shoulder involved in scenario 8

Fig. 6.40: The damage to the car involved in scenario 8

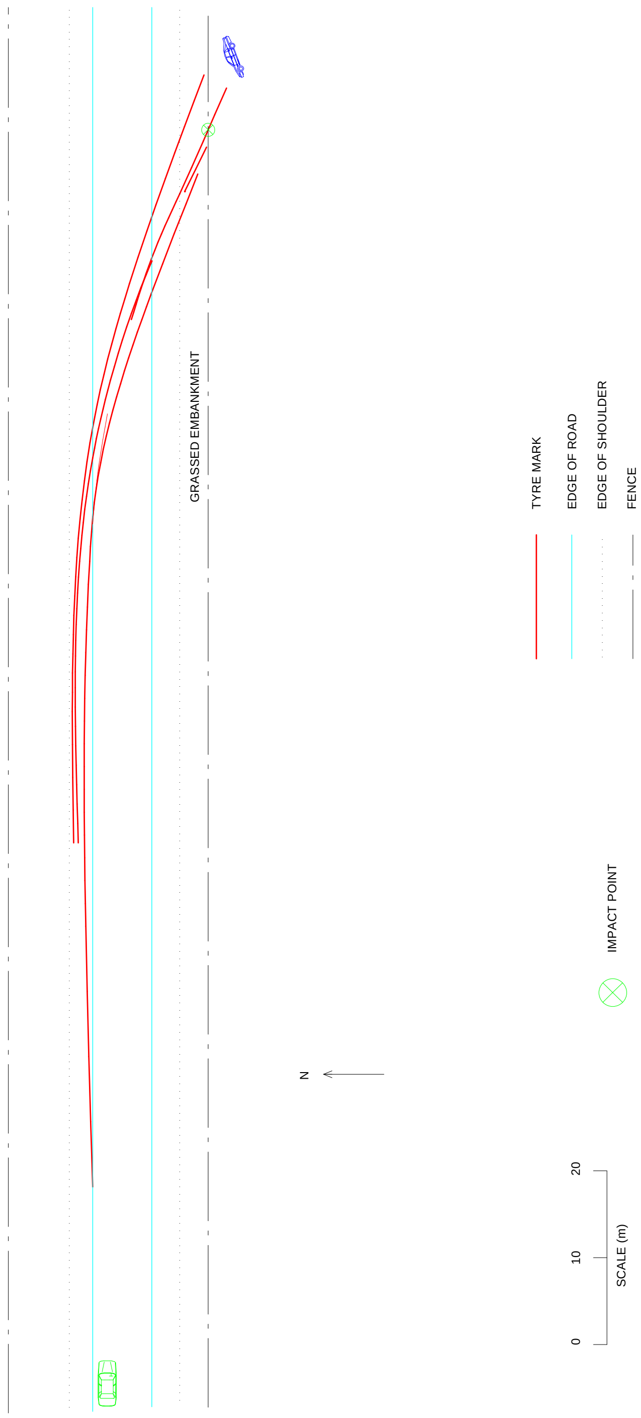


Fig. 6.41: Site diagram for scenario 8

6.3.9 Scenario 9

On a Thursday at approximately 11:25 am, a car was travelling along a straight section of sealed highway at an estimated speed in excess of 120 km/h. The vehicle was then seen to unexpectedly travel onto the left unsealed shoulder. The driver overcorrected the vehicle to the right, yawing in a clockwise direction across both lanes of the carriageway and onto the grassed median. The left side of the vehicle collided with a large tree 9.5 metres from the carriageway. The vehicle then rolled over and came to rest on its roof 7 metres from the tree. The prevailing environmental conditions at the crash site are given in Table 6.11. Photographs showing the roadway, roadside shoulder, and the damage to the car are shown in Figures 6.42 and 6.43. The site diagram for the crash is shown in Figure 6.44.

Tab. 6.11: Environmental conditions prevalent in scenario 9

Condition	**Status**
Weather	Fine
Lighting	Daylight
Road type	Rural highway, sealed, multi-laned divided, dry
Speed limit	110 km/h

Fig. 6.42: The roadway and roadside shoulder involved in scenario 9

Fig. 6.43: The damage to the car involved in scenario 9

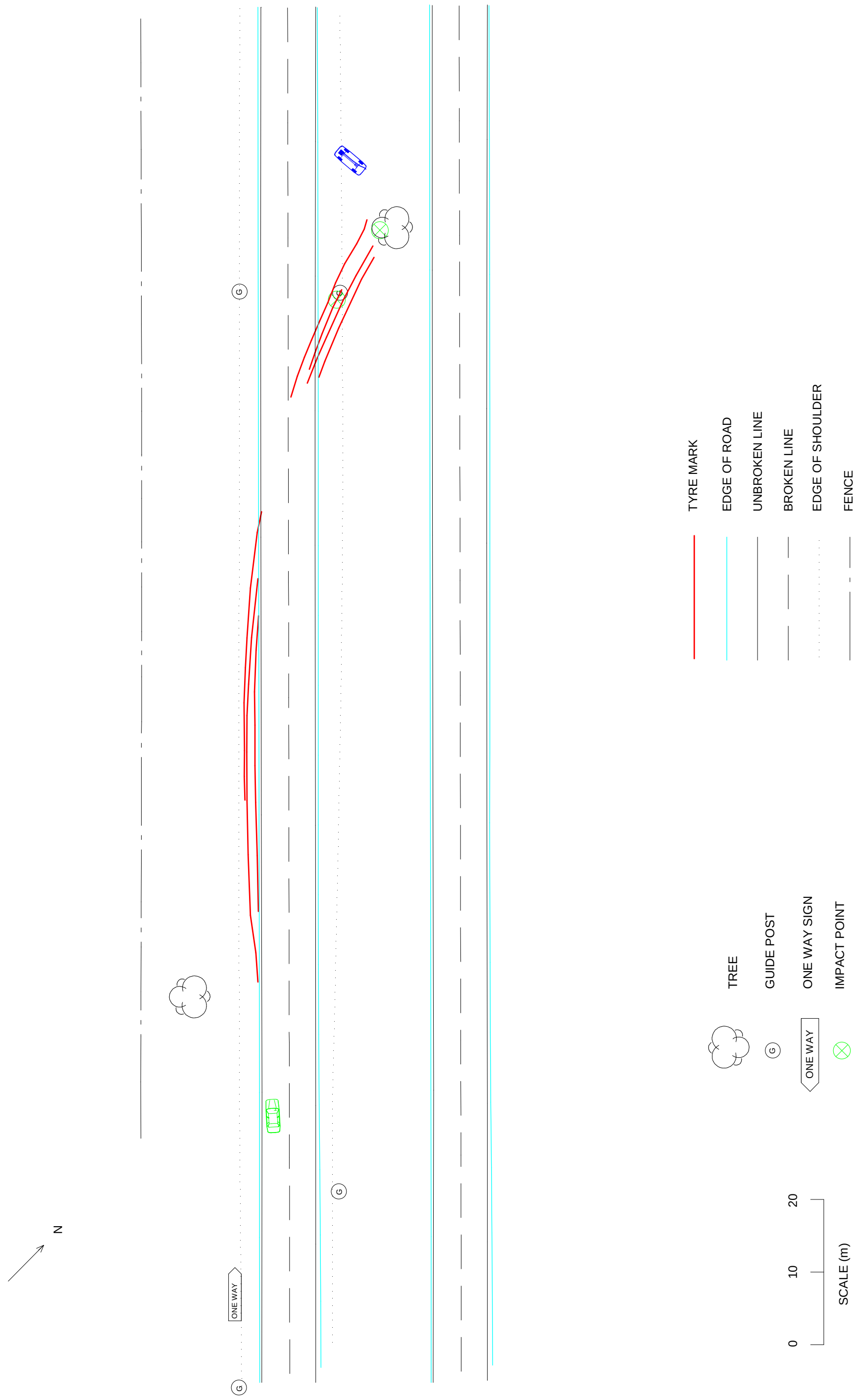


Fig. 6.44: Site diagram for scenario 9

6.3.10 Scenario 10

On a Thursday at approximately 6:55 am, a car was travelling along a straight section of sealed carriageway at an estimated speed of 115 km/h. The drivers attention was diverted when they leant down to retrieve their watch from the centre console. The vehicle drifted to the left of the carriageway with the left front wheel travelling onto the unsealed shoulder. The driver overcorrected the vehicle to the right and yawed in a clockwise direction across the carriageway and onto the right side shoulder. The vehicle collided with a wire fence and post 6 metres from the carriageway and was seen to somersault towards several large trees immediately beyond the fence line. The left side of the vehicle collided with a large tree. The vehicle then pivoted around the tree 180 degrees in a clockwise direction before coming to rest against another tree. The prevailing environmental conditions at the crash site are given in Table 6.12. Photographs showing the roadway, the roadside shoulder, and the tree are shown in Figures 6.45 and 6.46. The site diagram for the crash is shown in Figure 6.47.

Tab. 6.12: Environmental conditions prevalent in scenario 10

Condition	**Status**
Weather	Overcast
Lighting	Daylight
Road type	Sealed, two way, dry
Speed limit	100 km/h

Fig. 6.45: The roadway and roadside shoulder involved in scenario 10

Fig. 6.46: The impacted tree involved in scenario 10

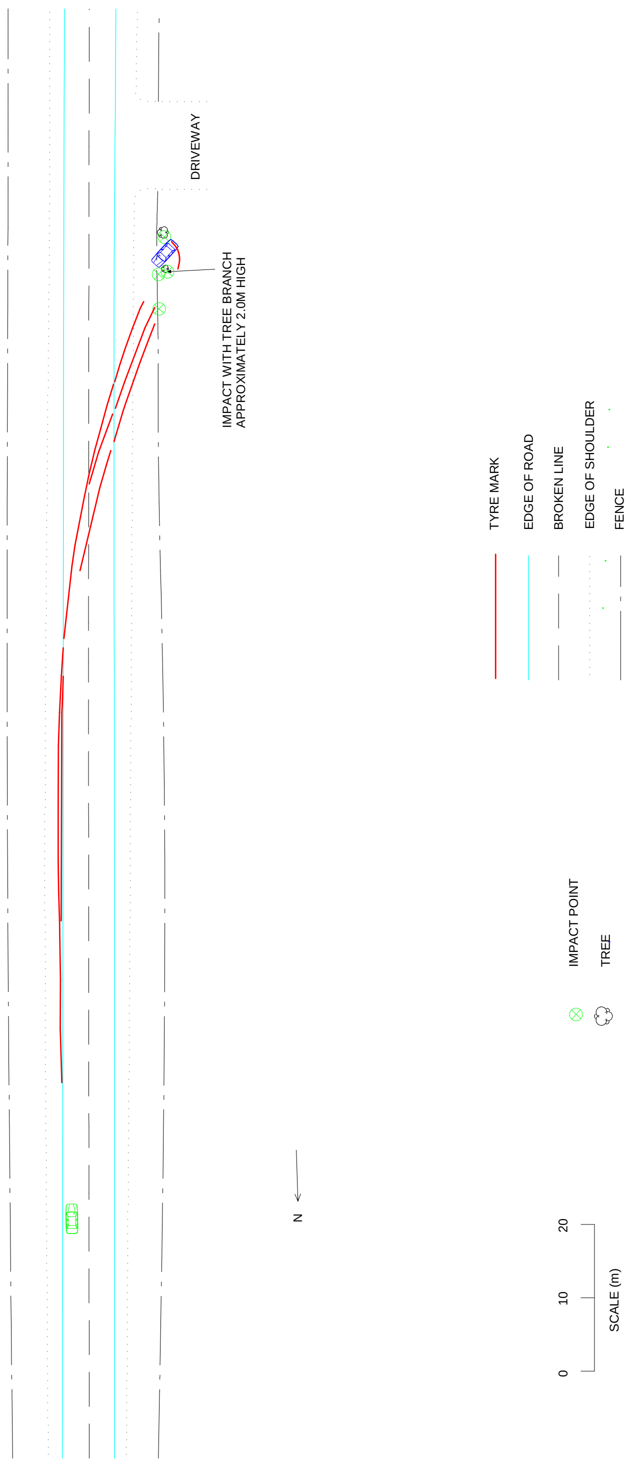


Fig. 6.47: Site diagram for scenario 10

6.4 Simulation of the environment

The environment data required by CarSim consists of a roadway model along with coefficient of friction values for the road, roadside shoulder, and any areas of low friction.

The method used to define the roadway model and select coefficient of friction values in the simulation of each of the loss of control scenarios is presented below.

6.4.1 Roadway model

The roadway is modelled by a set of three-dimensional points that define the centreline of the road. A surface is then created by defining the width of the road and roadside shoulder (which map along the centreline). Road camber/superelevation, which describes the cross sectional rise or fall of the road, is not able to be modelled within CarSim.

The site diagram associated with each scenario was developed from points measured using three-dimensional survey equipment during the in-depth crash investigations. Several points were measured along the centreline of the road and along both road edges as standard procedure during all of the investigations. It was therefore possible to use these points to directly define the centreline and to calculate a road width. The roadside shoulder width was defined as appropriate to allow space for any off road loss of control to occur. The roadway model was then checked against photographs of the crash site for accuracy.

6.4.2 Coefficient of friction

Measuring the coefficient of friction of the road surface at the crash scene was not a part of the crash investigation process. It would not have been appropriate to return to the crash scenes to measure the coefficient of friction as the value may have changed considerably over time (Mackey, 1999; Wilson & Dunn, 2005; Wilson & Kirk, 2005). Instead, values reported in literature were investigated and checked for appropriateness against real data collected on South Australian rural roads. Nominal values for the coefficient of friction on different surfaces are shown in Table 6.13 (Rivers, 1981).

Tab. 6.13: Nominal values for the coefficient of friction on various surface types (Rivers, 1981)

Surface type	**Coefficient of friction**	
	Dry	**Wet**
Travelled asphalt	0.55 - 0.70	0.40 - 0.65
Packed, oiled gravel	0.50 - 0.80	0.40 - 0.60
Loose gravel	0.40 - 0.70	0.45 - 0.75

The South Australia Police (Major Crash Investigation Unit) and the South Australian Department for Transport, Energy and Infrastructure (Pavements and Structures) were able to provide real data on typical coefficient of friction values for South Australian rural roads for this study.

In the event of a fatal crash on a South Australian road, the Major Crash Investigation Unit are often required to conduct an investigation which includes determining the coefficient of friction of the road. This is achieved through the use of commercial equipment which calculates a value based on the measured deceleration of a vehicle during full lock braking. At each fatal crash site a minimum of two values are calculated. Several years of data, numbering over 200 tests, indicated that an average coefficient for a dry sealed rural road is 0.72. A smaller number of tests were available for other surface types and conditions. These indicated that the average coefficient of friction for a dry unsealed rural road is 0.54, and for a wet sealed rural road is 0.62.

Using a machine called a grip tester, DTEI check large lengths of the South Australian rural road network for areas of low friction which may require maintenance. Based on three years of data in which 2,150 km of rural road was tested (representing almost 10% of the total network), an average coefficient of friction value of 0.67 was found. Since the purpose of testing was to identify road lengths with low coefficients of friction, it is likely that this value is an underestimate of the true average.

The real-world data from South Australian rural roads provided by SAPOL and DTEI corresponded well with the nominal values from literature. As no further accuracy could be gained for the specific roads on which the crash scenarios occurred, the dry/wet sealed roadway and dry unsealed roadside shoulder coefficient of friction vales shown in Table 6.14 were used for this investigation. No data could be found on typical values for the coefficient of friction of a gravel roadway, or a wet unsealed roadside shoulder in South Australia and so the values shown in Table 6.14 are based on the nominal range in Table 6.13.

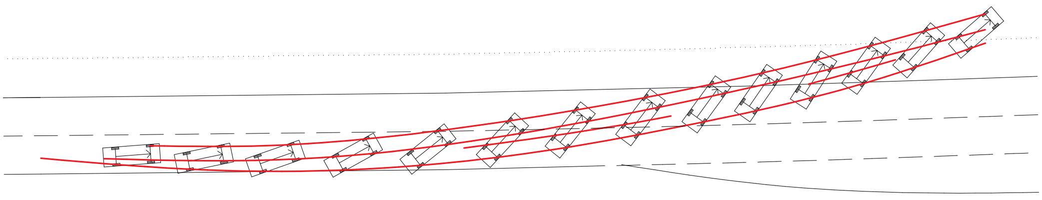
Loss of control scenario 4 involves a vehicle that aquaplanes over a shallow body of water on the roadway. CarSim cannot model aquaplaning explicitly and so a suitable coefficient of friction value was used as a proxy. Literature suggested that a suitable equivalent coefficient of friction for a fully aquaplaning tyre on a bitumen road was 0.05 (Horne & Dreher, 1963). Because aquaplaning will alter the vehicle trajectory, the location and refinement of the specific coefficient of friction value to use are explained in the following section.

Tab. 6.14: Coefficients of friction for various surface types used for simulations in this investigation

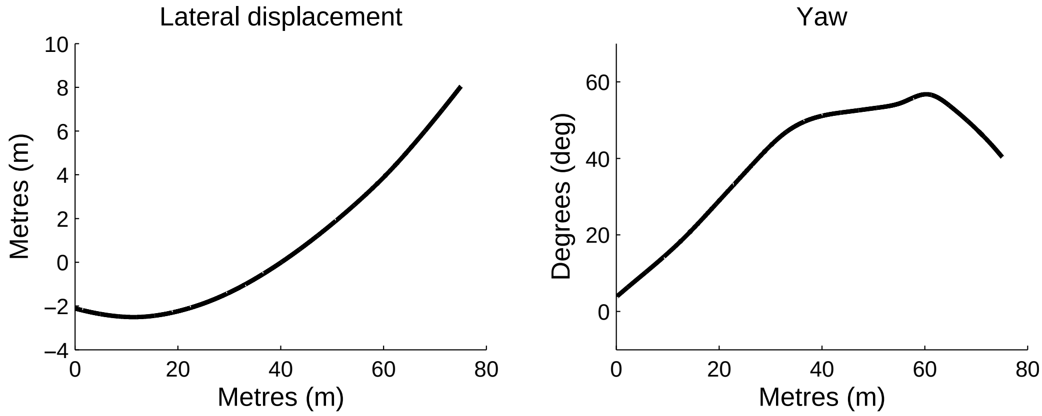
Surface type	**Coefficient of friction**
Dry sealed roadway	0.70
Wet sealed roadway	0.60
Dry unsealed roadside shoulder	0.60
Wet unsealed roadside shoulder	0.50
Dry gravel roadway	0.65
Aquaplane on sealed roadway	0.05

6.5 Simulation of the loss of control trajectory

For each loss of control scenario, the desired vehicle trajectory was determined using the site diagram that was generated as part of the crash investigation process. A series of dimensionally accurate vehicle templates were placed over the drawing of the tyre/yaw marks and the position and yaw of the template at several points along the vehicle trajectory were recorded. An example of this process is shown in Figure 6.48, along with the resulting trajectory data. The trajectory data consists of two components; lateral displacement and yaw. The lateral displacement is the lateral distance of the vehicle's centre of mass relative to the centreline of the road. The yaw is the angle of the vehicle relative to the centreline of the road or relative to the tangent of the centreline in the case of a curved road. Both trajectory components are measured relative to the longitudinal distance along the



(a)



(b)

Fig. 6.48: Example of using a dimensionally accurate vehicle template overlay to determine the scenario trajectory (a) and the resulting lateral displacement and yaw vs longitudinal distance data (b)

centreline of the road.

One additional aspect to be defined is the speed of the vehicle through the scenario trajectory. Unfortunately, it is not possible to accurately determine the speed of the vehicle over the course of the loss of control trajectory. However, it is possible to calculate the speed of the vehicle at the moment it first began to yaw based on the tyre marks left on the road. Speed calculations based on tyre marks have been used for many years and are an accepted way of estimating vehicle speed. Rivers (1981) states that the speed of a vehicle entering a yaw can be calculated from the curved yaw marks left by the tyres using the following equation:

$$S = 11.27\sqrt{c.R}$$

Where S is the calculated vehicle speed (in km/h) at the beginning of yaw, c is the roadway coefficient of friction, and R is the radius of the curved yaw mark (in metres).

The yaw marks in the site diagram of each loss of control scenario were used again to calculate the speed of the vehicle at the moment it began to yaw. By selecting three arbitrary points along the yaw mark path it was possible to generate a circle that provided a radius and, in turn, a vehicle speed. For each yaw mark, several speeds were calculated based on the radius generated from unique sets of three points. All the calculations were then averaged to define a final speed for that scenario trajectory.

A simulated vehicle trajectory is defined by CarSim events data which consists of parameters that describe the vehicle's initial speed (i.e. speed at the start of the simulation) along with any driver braking and steering actions. For one scenario the trajectory of the vehicle was additionally affected by aquaplaning.

The simulated vehicle's initial speed was set to be similar to the speed of the scenario trajectory calculated above. Each of the remaining events data parameters then interact dynamically to define the simulated trajectory. Because of this dynamic interaction, it is difficult to develop a simulated trajectory that accurately matches the scenario trajectory through manipulation of the parameter values by hand. As such, an optimisation method was used to isolate a set (or sets) of parameter values that define a simulated trajectory which matches well with the scenario trajectory. The full operation of this optimisation method is presented in the next section. However, one important aspect is that suitable initial parameter values are required in order for the optimisation method to operate effectively. That is, initial parameter values which define a simulated trajectory that, at least somewhat, resembles the scenario trajectory.

The method used to select initial values for the braking parameters, steering parameters, and the aquaplaning parameters for the loss of control scenarios is presented below.

6.5.1 Braking

Braking is defined by three parameters; the time at which braking was applied, the power of the brakes, and the time taken for the brake force to increase from zero to fully developed braking.

Braking details were not required for all of the scenarios that were simulated. Unless there was strong evidence that the driver had applied the brakes, the crash scenario was assumed to occur with an absence of braking. Supporting evidence for this assumption was provided by Yamamoto & Kimura (1996) and Langwieder et al. (2003) who found that in around 50 per cent of loss of control type crashes there was no braking applied. In a further 20 per cent of the crashes, only partial braking was applied.

In those scenarios where braking was obvious, it was assumed that full lock braking was applied at a certain point and maintained until the vehicle came to rest. Thus, the power of the brakes was set to full lock in all simulations. The braking start time was identified based on tyre mark evidence collected during the in-depth investigations. Locked wheel braking is known to occur 0.4 - 0.6 seconds before the appearance of skid marks, and the braking start time was selected to conform to this (Reed & Keskin, 1987). Reed & Keskin (1987) also suggested that an appropriate time from the start of braking to maximum brake force was 0.5 seconds and this value was used in all simulations where braking occurred.

6.5.2 Steering

The steering actions of a driver were simulated through the use of a driver model. The concept of modelling human steering behaviour was first explored by Sheridan et al. (1964). Sheridan (1966) developed the concept further and theorised a driver model that consists of a path following control system incorporating four human-like features. The first feature is a preview time which models the disposition of a driver to 'look ahead' when considering the steering actions required to maintain a desired vehicle trajectory. When the desired trajectory is simple (e.g. when navigating a straight stretch of road) a driver will base their steering actions on a long preview time. However, as a vehicle approaches a bend or other road feature that requires navigation the driver's preview time will reduce as the complexity of adjusting the steering to keep the vehicle travelling along the desired trajectory increases. Visual obstructions will also force a reduction in preview time.

The second human-like feature is an internal vehicle model that simulates the good understanding that a typical driver has of the steering response of their vehicle. This internal model allows the driver to predict how their steering inputs will alter the course of their vehicle. Note, however, that this understanding only relates to the vehicle's steering response during normal driving conditions and does not encompass the changes in steering response during extreme driving conditions when a vehicle approaches the limit of lateral stability.

Thirdly, a lag time models the well known time lapse between sensory input, mental interpretation, and physical response for all human actions. During driving, this manifests as the time between the driver observing the road (through the preview time), interpreting what response is required (via the internal vehicle model), and taking appropriate steering action.

Finally, the physiological/ergonomic constraints to the ability of a driver to effectively turn the steering wheel are modelled through restrictions on the speed at which the steering wheel can be rotated.

A driver model based on the theories of Sheridan (1966) was developed by MacAdam (1980, 1981) and has been implemented within CarSim. The operation of this model (henceforth refereed to as the UMTRI driver model) is shown in Figure 6.49. A previewed path is developed based on the section of the driver path currently encapsulated by the preview time. Concurrently, a predicted path is determined based on the current motion of the vehicle and the internal vehicle model. The steering control required to minimise the difference between the previewed path and the predicted path is then calculated. Finally, the steering control is applied to the vehicle via the driver physiological/ergonomic constraints which are defined by a maximum steering angle and a maximum steering rate.

The UMTRI driver model was shown by MacAdam (1981) to be able to successfully emulate the actions of a human driver. Most notably, (relevant

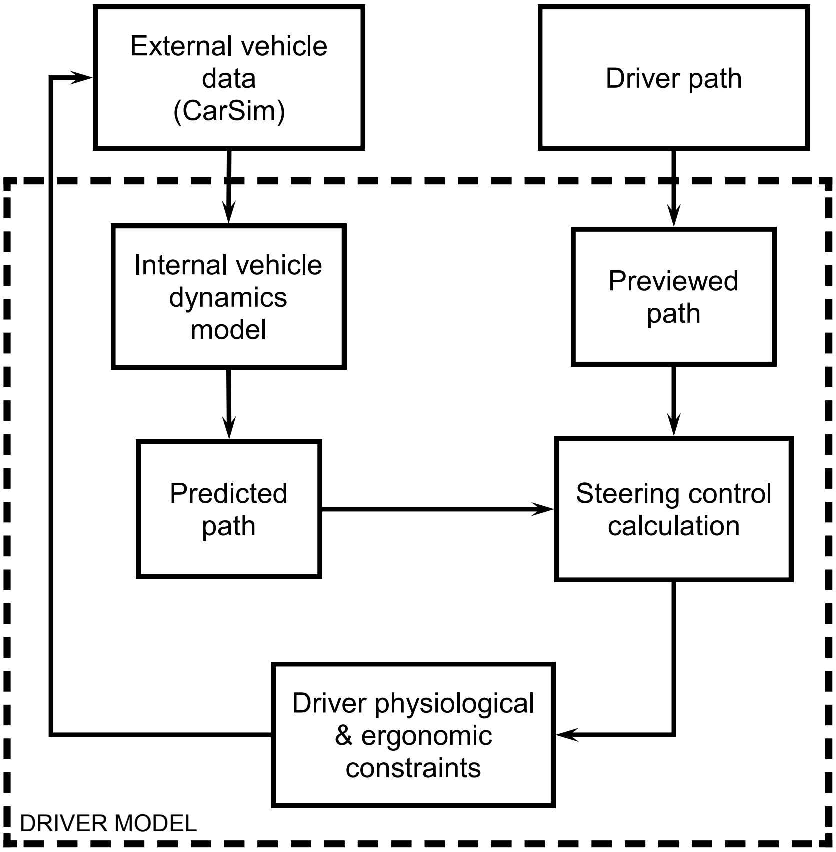


Fig. 6.49: UMTRI driver model flow [adapted from MacAdam (2003)]

to the current investigation of high speed loss of control scenarios) the driver model showed a good match to the steering actions of human drivers during a single lane change test manoeuvre at a speed of approximately 95 km/h.

However, it should also be noted that MacAdam later improved upon the UMTRI driver model by adding or improving several features; a variable preview time, driver speed control based on upcoming road curvature changes, sensory input limitations, advanced path selection, and situational awareness along with a more accurate 4 degree of freedom, non-linear, internal vehicle model (MacAdam, 2001). The improvements allowed the new driver model to mimic human steering behaviour better than the UMTRI driver model.

These improvements were most obvious in situations where the dynamic response of a vehicle becomes increasingly non-linear such as during loss of control emergency manoeuvres. This updated model (the GM driver model) would therefore have proved advantageous but was not implemented within CarSim at the time of this investigation.

The CarSim implementation of the UMTRI driver model has five parameters that need to be specified; preview time, lag time, maximum steering angle, maximum steering rate, and the driver path. The methods used to select appropriate initial values for each of these driver model parameters is described here.

Maximum steer and maximum steer rate

The ability of the human driver to turn the steering wheel effectively is usually assumed and only one study was identified that investigated what the physiological and ergonomic limits of the human driver may be. Forkenbrock & Elsasser (2005) analysed the steering wheel actions of a set of drivers during a double lane change test manoeuvre. The analysis was secondary to the main study of investigating the effects of ESC during a double lane change and thus the testing procedure was not explicitly designed for the purpose of investigating driver ability. There is little doubt that a high speed, double lane change manoeuvre can precipitate drastic steering, but at no point were any of the participating drivers asked to steer excessively, quickly, or with great force. For this reason, Forkenbrock & Elsasser believed the results give a conservative estimate of the typical abilities of a normal driver. Note that all vehicles that were used in the study were equipped with power steering.

When considering the maximum (or peak) steering wheel angles achieved by the participating drivers, it was found that all could achieve steering lock (in either direction) if desired. The steering lock values for the vehicles used in the test manoeuvres ranged from 475 degrees to 599 degrees. Consequently, for all simulations the maximum steer value for the driver model was set to 500 degrees (i.e. the full lock value for a typical vehicle).

When interpreting the maximum rate of change to the steering wheel angle achieved by the participating drivers, Forkenbrock & Elsasser (2005) gave consideration to the amount of time that a certain rate could be sustained. The recorded steering wheel angle rates for the participating drivers during the double lane change manoeuvre were post processed using four different filters:

- 6 Hz phaseless digital Butterworth
- 500 ms running average, one-pass
- 750 ms running average, one-pass
- 1000 ms running average, one-pass

As expected, the more aggressive the filter that was applied the lower the maximum steering wheel angle rate achieved. The maximum steering wheel angle rate using the 6 Hz Butterworth filter was 1819 degrees per second. For the 500 ms, 750 ms and 1000 ms running average filters, the maximum steering wheel angle rates were 1340, 1189 and 963 degrees per second respectively. Because the UMTRI driver model is a linear model it governs the steer rate with no consideration to the duration of application.

That is, it will allow a steer rate up to the maximum specified value regardless of how long that steer rate is maintained. For this reason, the maximum steering wheel angle rate determined using the most aggressive filter (1000 ms running average) was deemed preferable to the others and the maximum steer rate for the driver model was set to 1000 degrees per second in all simulations.

Preview time and lag time

During the validation stage of the GM driver model a group of drivers of varying abilities participated in several test manoeuvres in a vehicle simulator (MacAdam, 2001). The steering behaviour of the GM driver model was matched to the steering behaviour of each of the participants by adjusting the preview time and lag time through trial and error. Despite the ability of the GM driver model to utilise a varying preview time, a fixed preview time (as is the case in the UMTRI driver model) was used during this matching process.

The results of this matching process presented an opportunity to analyse the relationship between preview time, lag time, driver ability, and the type of emergency manoeuvre being performed. MacAdam observed that a roughly linear relationship existed between the driver's preview times and lag times. Based on this observation MacAdam postulated that during a critical driving situation a driver's preview time and lag time change in a coordinated manner to operate in a specific critical driving region as shown in Figure 6.50. Also shown in Figure 6.50 is a stable region and an unstable region. The stable region indicates a driver who is not driving close to their

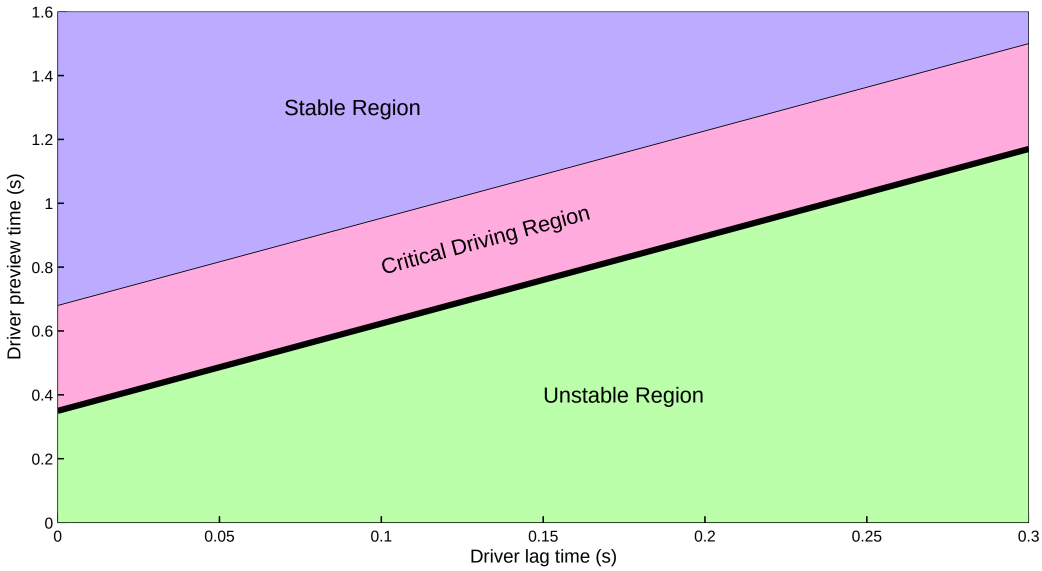


Fig. 6.50: Driver model parameter regions during critical driving [adapted from MacAdam (2003)]

limit and has capacity to spare. The unstable region represents a driver with an incompatible preview time and lag time that would likely result in poor path tracking and possibly a loss of vehicular control.

The vertical position of the line that separates the unstable region from the stable and critical driving regions is defined by the dynamics of the vehicle being driven. A vehicle with good lateral dynamics is able to respond to driver inputs faster and more effectively and is associated with a line that is lower while the opposite is true for a vehicle with bad dynamics. The critical driving region therefore represents the best driving performance achievable (i.e. with the most manoeuvrability) for a given vehicle without entering the unstable region.

The extent to which the test participant drivers' preview times and lag times varied within the critical driving region depended upon their driving ability and the type of manoeuvre being attempted. A more complex manoeuvre elicited a shorter preview time and lag time from all drivers. A less complex manoeuvre elicited a longer preview time and lag time.

Likewise, the drivers with a greater ability displayed a shorter preview time and lag time during all manoeuvre types while drivers with less ability displayed a longer preview time and lag time. Additionally, it was noted that drivers with greater ability were able to complete manoeuvres at higher speeds while the drivers with less ability reduced their speed to elicit an increased preview time and lag time.

Based on MacAdam's work it appears that, for the simulation of loss of control emergency manoeuvres, there are two important points to note. The first is that every driver has a minimum level to which they can reduce their lag time based on their driving ability. Secondly, the maximum preview time available for a specific manoeuvre is dictated by the speed and complexity of the manoeuvre. Consequently, it would be expected that a driver will control their vehicle speed to ensure they maintain a preview time which they are capable of complementing with their minimum lag time (as was the case in the validation testing for drivers who has less ability). A loss of control may therefore arise in a situation where a driver is forced to perform an emergency manoeuvre without the ability to dictate their vehicle speed or attempts a manoeuvre beyond their ability.

For each of the loss of control scenarios the speed and complexity of the manoeuvre being attempted as well as the ability of the driver are unique and unquantifiable. In addition, the fact that a loss of control occurred implies that there was a failure of coordination between the preview time and lag time. It is therefore impossible to select appropriate values for the driver model preview time and lag time prior to simulation empirically.

As such, multiple simulations were run for each scenario using several different initial preview time and lag time value pairs. The pair that resulted in the best trajectory match was then identified as the most appropriate (this process is explained further in section 6.6.5). A set of value pairs that spanned the range between the minimum and maximum likely values of preview time and lag time were developed for this purpose.

A lower limit for the preview time depends upon the lateral acceleration capability of the vehicle being driven. MacAdam (2001) estimated that the threshold value of preview time for the small truck type vehicle used in the simulator studies was around 0.6 seconds and suggested a sports car may have a value of around 0.3 seconds. The results of the sine with dwell test for the RWD vehicle model indicated that it responded in a similar way to a sedan or SUV. Therefore the lower limit of driver preview time in this study was set at 0.4 seconds.

During MacAdam's simulator validation, each driver completed each test manoeuvre several times. Only their fastest, successful run was recorded and matched to the driver model. The drivers with less ability elected lower entrance speeds in order to achieve a longer preview time. MacAdam did not explicitly discuss an upper limit of the preview time but a value of 1.5 seconds was never exceeded during any of the matched simulator tests. This value might represent an upper limit for drivers who know they are about to perform an emergency manoeuvre. During an unexpected emergency manoeuvre it is likely that an even lower preview time may be elicited as a driver has less time to prepare or visualise the required manoeuvre or to slow down to a speed that is appropriate for their driving ability. Therefore, the upper limit of driver preview time was set at 1.2 seconds.

It may seem appropriate to select the upper and lower values of lag time with some reference to the upper and lower values of preview time to produce combinations that lie in the critical driving region. However, it is reasonable to assume that during the loss of control scenarios, all of which resulted in a crash, there was some disparity in the preview time and lag time during the event. For example, to avoid a crash a driver may suddenly be called on to reduce their lag time (i.e. react very quickly) beyond their ability. As a result, their preview time and lag time combination may fall into the unstable region. Driver lag time was therefore treated independently of the preview time during the process of selecting the upper and lower values.

A lower limit for lag time is greatly influenced by driver ability and experience, along with the type of manoeuvre being attempted. During the simulator validation by MacAdam, the lowest lag time achieved was approximately 0.01 seconds. This lag time was achieved by a highly experienced test driver who may have performed the test manoeuvre numerous times. His low lag time may have been due to anticipation and a familiarity with the near limit response of the test vehicle. Conversely, the lowest lag times recorded by a 'normal' driver and a novice driver were 0.12 seconds and 0.25 seconds respectively. As it is expected that a surprise event would cause an increase in driver lag time, the lower limit was set at 0.15 seconds.

The highest lag times were all recorded by the novice driver and peaked at a value over 0.3 seconds. Despite the novice driver's lack of driving experience, the lag times were achieved while the driver was alert, sober and

Tab. 6.15: The 36 driver preview time and lag time value pairs that span the likely solution space (P, l)

1.2, 0.15	1.2, 0.20	1.2, 0.25	1.2, 0.30	1.2, 0.35	1.2, 0.40
1.1, 0.15	1.1, 0.20	1.1, 0.25	1.1, 0.30	1.1, 0.35	1.1, 0.40
1.0, 0.15	1.0, 0.20	1.0, 0.25	1.0, 0.30	1.0, 0.35	1.0, 0.40
0.9, 0.15	0.9, 0.20	0.9, 0.25	0.9, 0.30	0.9, 0.35	0.9, 0.40
0.8, 0.15	0.8, 0.20	0.8, 0.25	0.8, 0.30	0.8, 0.35	0.8, 0.40
0.7, 0.15	0.7, 0.20	0.7, 0.25	0.7, 0.30	0.7, 0.35	0.7, 0.40

aware of the upcoming steering requirements. It is expected that a typical or even an experienced driver would produce similar lag times for a sudden, unpractised manoeuvre. In addition, drivers may potentially be under the effects of alcohol and sleep deprivation which have also been shown to increase reaction time (Dinges & Kribbs, 1990). Therefore, the upper limit for the driver lag time was set at 0.4 seconds.

Table 6.15 shows the 36 pairs of preview time and lag time that were used as the initial values for each of the loss of control scenario simulations. Section 6.6 explains how each value pair was further refined and how the value pair that generated a simulation that was most representative of the scenario was chosen.

Driver path

Little attention has been given to the role of the driver path in previous literature. The reason for this may be that the driver model is typically used in situations where the driver path is obvious (e.g. the middle of a lane or through specific points of a test manoeuvre). However, for this investigation the path was used in a slightly unorthodox way to emulate the specific steering inputs prior to a crash. The general characteristics of the path in each loss of control scenario could be constructed based on the evidence at each crash scene, along with witness reports and logical reasoning.

The trajectory of the yaw/tyre marks at the crash scene do not represent the trajectory which the driver was attempting to travel. In fact, the presence of the yaw/tyre marks strongly suggests that the driver was attempting to resist the current trajectory of the vehicle. By realising this, it was possible to develop a theoretical path along which it is assumed the driver was attempting to travel. This theoretical path also takes into account other vehicles and obstacles that the driver would logically attempt to avoid and assumes that after any emergency manoeuvres have been made the driver would return the vehicle to the centre of the normal travelling lane.

It was noted that the driver path for all the scenarios could be parameterised as shown in Figure 6.51. In the figure, the station defines the linear distance along the centreline of the road. Thus, while the road may be curved, the driver path can be visualised along a normalised straight line. The lateral offset of the driver path is then shown relative to the centre of he road at each station. A driver path with no lateral offset would simply follow the centreline of the road. Initial values for the path sections a, b, c, d, and the path offsets e, f and g could be set according to what was known or suspected about the steering events during each scenario. This path definition allows any emergency manoeuvre which consists of up to two steering actions of varying levels of intensity and duration, bounded by periods of lateral lane keeping, to be simulated.

Note that while the driver path may appear to consist of abrupt steering changes it is not intended to be tracked literally by the driver model.

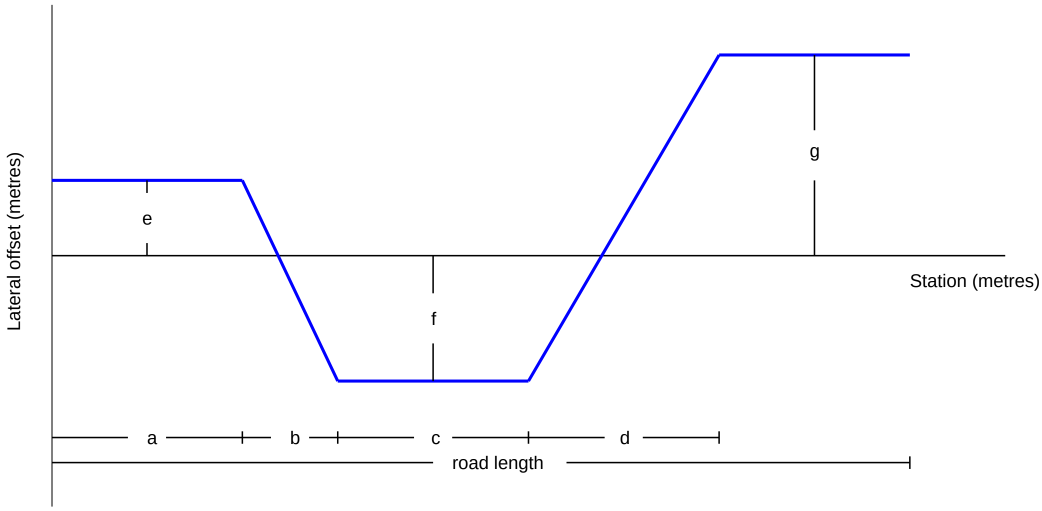


Fig. 6.51: Standard driver model path

The driver model views the upcoming changes in the path and attempts to transition from one offset to another. The smoothness of the transition depends upon the magnitude of the change along with the other driver model parameters of preview time, lag time, maximum steer, and maximum steer rate.

6.5.3 Aquaplaning

In the previous section a friction coefficient value of 0.05 was found to be an appropriate proxy for an aquaplaning vehicle. However, in one loss of control scenario the aquaplaning process caused the vehicle to begin yawing. This suggests there was a difference in the friction between the left and right wheels (i.e. a split mu situation) that must be simulated.

The area over which the aquaplane occurred was designated the 'low friction patch'. Four parameters were to describe the low friction patch; the beginning of the patch, the end of the patch, the friction coefficient on the left side, and the friction coefficient on the right side.

The beginning and end of the patch was determined based on evidence from the crash investigation. The patch was then given slightly different friction values for the left and right side. These friction values were varied on a trial and error basis to generate the desired loss of control trajectory.

6.6 Optimisation of simulation parameters

Several limitations of the GM driver model (implemented in CarSim) were mentioned in the previous section. These limitations mean that the behaviour of the driver model will not always correctly emulate the behaviour of a typical driver during loss of control situations. Additionally, for the scenarios where it is relevant, the characteristics of any braking or of the low friction patch associated with an aquaplane are not accurately known.

The objective of this section is to utilise the GM driver model to full potential (despite its limitations). At the heart of this endeavour is the use of optimisation to select the most appropriate driver model, braking, and low friction patch parameter values for each loss of control scenario. The most appropriate parameter values being those that produce a simulation where the trajectory of the non-ESC vehicle matches well with the scenario trajectory.

Some of the efforts, described below, to identify such parameter values may appear to be excessive and do not always result in a satisfactory match between the simulation and scenario trajectory. This may give the impression that a simulation which relies on parameters developed through these optimisation steps is not valid. However, this is not the case as whatever parameter values are selected will be used to run simulations both with and without ESC. As such, comparisons between simulations with and without ESC will be valid regardless of what parameter values are used.

The section is presented under five subsections. The first details the search for and ultimate selection of an appropriate optimisation technique. The second and third subsections discuss the method used to quantify how well a simulated trajectory matches a scenario trajectory and the criteria used to decide when the optimisation process should terminate. Some discussion regarding which parameters should and should not be optimised is presented in subsection four. Finally, in subsection five, some further discussion on choosing the best driver model preview time and lag time value pair is presented.

6.6.1 Selecting an optimisation technique

In order to generate the simulated trajectory associated with a specific set of parameter values a CarSim simulation must be run. This process takes a approximately 30 seconds and this must be taken into account when considering potential optimisation techniques.

Optimisation techniques can generally be separated into those that operate using gradient data and those that employ some kind of search pattern. Given the nature of the simulation process, it is only possible to determine gradient data through numerical methods by calculating the difference between consecutive data points (i.e. between two simulation runs). This is computationally intensive due to the time required to run a simulation for each data point and so optimisation techniques that use gradient data were not considered further.

Search pattern optimisation techniques can themselves be divided into two groups called iterative and heuristic. Iterative techniques proceed methodically and are designed to converge at each optimisation step towards a final optimal solution. Heuristic techniques utilise fewer function evaluations and seek only to improve upon the value of the previous optimisation step without any regard for the most optimal solution. Further detail concerning the convergence or non-convergence of search pattern techniques are discussed by Torczon (1997).

Because of the interaction between the simulation parameters, the optimisation solution space was predicted (and later confirmed through investigation) to be noisy and dynamic. That is, there may be no clear progression from the initial solution to a single optimal solution. Instead, several points may be found within the solution space that are equally favorable. It was therefore considered more appropriate to use a heuristic search pattern technique for the current optimisation task.

The Nelder Mead algorithm (Nelder & Mead, 1965) is a heuristic optimisation technique that is widely used in situations similar to the one described here. Lagarias et al. (1998) examined the convergence properties of the Nelder Mead algorithm and identified three key reasons for the algorithm's popularity. First, the Nelder Mead algorithm can be easily implemented with computational functions and can produce significant improvements over the first few iterations. Second, the algorithm is useful for functions that are expensive or time consuming to evaluate as it is frugal with the number of evaluations required during each iteration. Lastly, the algorithm is relatively easy to understand and to implement.

Given the selection of the Nelder Mead optimisation algorithm, the complete optimisation process proceeds as follows. An initial set of parameter values is passed through the Nelder Mead algorithm's initialisation routine and a new set of parameter values are generated for the first iteration step. The optimisation then continues to iterate until a termination criterion is met. During each iteration a simulation is run in CarSim using the current parameter values, the error between the resulting simulated trajectory and the scenario trajectory is calculated, and the Nelder Mead algorithm generates a new set of parameter values for the next iteration. Upon termination, the Nelder Mead algorithm generates the final set of optimised parameter values.

The next two subsections describe how the error between the simulated and scenario trajectories is calculated and what criteria cause the optimisation to terminate.

6.6.2 Quantifying an error term for optimisation

The objective of the optimisation technique was to find a set of parameter values that minimise the difference, or error, between the simulated and scenario trajectories. Thus, a quantitative method of determining the error between the trajectories was required.

Figure 6.52 shows an example of a simulated vehicle trajectory overlaid onto the scenario trajectory from Figure 6.48. Note that scenario trajectory data is only known where tyre/yaw marks are present (in this case between

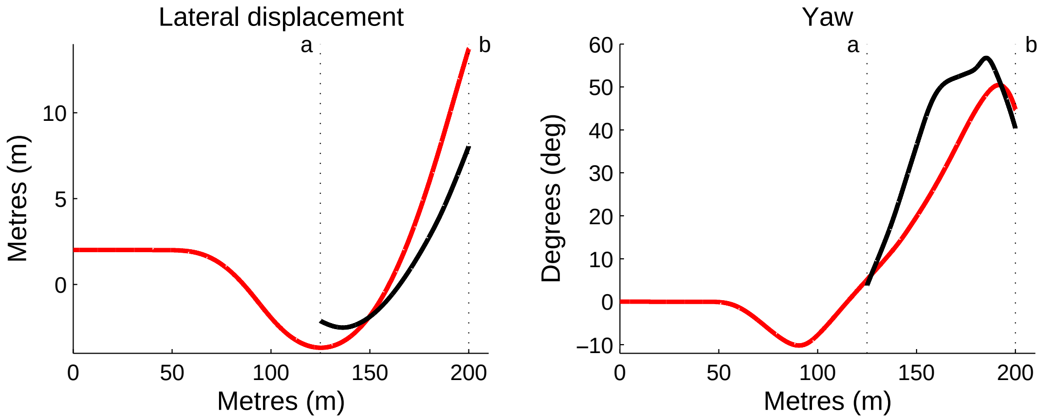


Fig. 6.52: Example of trajectory error calculation with the scenario trajectory shown in black and the simulated trajectory shown in red

approximately 125 metres and 200 metres from where the the simulation was started). The error between the scenario trajectory and the corresponding portion of the simulated trajectory (e.g. between point a and point b in Figure 6.52) was calculated using the following formula:

$$error = \alpha e_{lat} + e_{yaw}$$

$$e_{lat} = \sum_{x=a}^{b} W(x)|L_i(x) - L_s(x)|^2$$

$$e_{yaw} = \sum_{x=a}^{b} W(x)|Y_i(x) - Y_s(x)|^2$$

$$W(x) = x$$

Where e_{lat} and e_{yaw} are the lateral displacement error and the yaw error respectively, L_i and Y_i are the lateral displacement and yaw of the scenario trajectory, L_s and Y_s are the lateral displacement and yaw of the simulated trajectory, W is a weighting function, and α is a scaling factor.

Several weighting functions that emphasised particular portions of the scenario trajectory (e.g. the start, the end, or the points of highest change) during the error calculation were assessed based on how well they encouraged a reduction in the error. The best weighting function was found to be one that linearly increased the emphasis of the error over the length of the trajectory. This weighting meant that accurate matching was given increasingly more emphasis over the length of the trajectory.

Lateral offset and yaw have different units (metres and degrees respectively), and the value of α was used to give e_{lat} and e_{yaw} a degree of equal weighting. An appropriate value for α was selected for each loss of control scenario to ensure that there was no obvious bias in matching the lateral displacement of the trajectory while neglecting the yaw or vice versa. An initial value of α was calculated based on the ratio of the span of the lateral displacement to the span of the yaw in each scenario. For example, in Figure 6.52 the lateral displacement has a span of approximately 16 (a minimum of -3 to a maximum of 13) and the yaw has a span of approximately 52 (a minimum of 3 to a maximum of 55). As such, an initial choice for the value of α would be 3.25 (52 divided by 16). Further corrections to this initial value of α were then made, if required, through trial and error.

This use of α does not completely negate the issues of summing non-equivalent units but was considered satisfactory in this instance.

6.6.3 Selecting an optimisation termination criteria

As a heuristic optimisation technique, the Nelder Mead algorithm will iterate indefinitely until some termination criterion is reached. This usually consists of either reducing the error below a specific threshold or running through a specific number of iterations.

Since the error term is defined by the trajectory of each scenario (as well as the chosen value for α) it will be characteristically unique in each particular scenario. That is, the maximum size of the error term and the ease with which it can be reduced will be different for each scenario. Thus, it was not possible to select a threshold value that would be appropriate for all scenarios.

Instead, a certain number of iterations was used. After some experimentation using the Nelder Mead algorithm to minimise the error between a simulated and scenario trajectory, it was found that 100 iterations was sufficient for the error to stabilise to an acceptably low value. This is shown in Figure 6.53 where the average error (on a logarithmic scale) at each iteration step is plotted for 24 optimisations of various scenario and starting value combinations. It can be seen that as the number of iterations increases the error initially declines quickly then more slowly until it stabilises after approximately 90 iterations. As such, continuing beyond 100 iterations would produce no significant benefits.

A secondary termination criterion was also triggered in the case where one of more of the generated parameter values was found to be irrational (e.g. a negative driver model preview time or path section). Attempting to run a simulation using such parameter values would have resulted in an error. In this situation the optimisation was considered to have failed and no final optimised set of parameter values were generated.

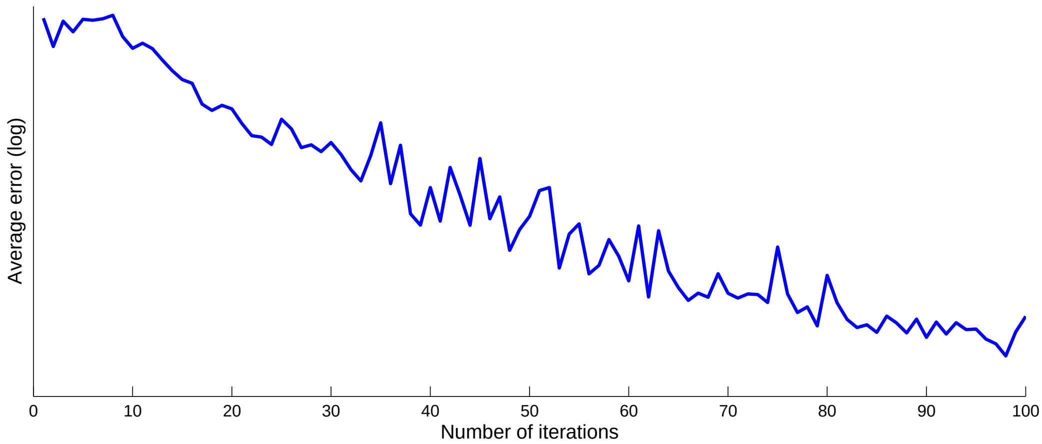


Fig. 6.53: Average error by number of optimisation iterations

6.6.4 Selecting which parameters to optimise

The ability of the Nelder Mead algorithm to effectively manage the optimisation of multiple variables is not without limitations. As the number of variables being optimised increases, the effectiveness of the algorithm is diluted (Torczon, 1997). It is therefore good practice to optimise only those variables that will contribute to the minimisation of the error. As such, only those parameters where it was suspected a value more suitable than the initial value might exist were optimised.

For the braking parameters, only the time at which braking was applied was ever optimised while the power of the brakes and the time taken for the brakes to increase from zero to full power were left at the values determined in Section 6.5.1. If the point at which braking began was well known and occurred before any steering manoeuvres, there was no need to optimise the time at which braking was applied. However, if the point at which braking began was ambiguous and there was a steering manoeuvre before the start of braking, then the time at which braking was applied was optimised. The reason for this was that once a steering manoeuvre has begun, the point at which braking occurs has a significant effect on the trajectory of the vehicle.

For the steering parameters, the maximum steer and maximum steer rate were left at the values determined in Section 6.5.2 while the driver preview time and driver lag time were always optimised. Deciding which of the driver path sections and offsets to optimise was made on a case by case basis depending on what was known about the intended path of the vehicle. In most cases, the parameters defining the start and end of the driver path (section a, offset e, and offset g) were not optimised. This was because it was usually assumed that the start and end sections of the driver path would travel the centre of the normal driving lane. Additionally, depending on the shape of the required trajectory, some of the driver path parameters were likely to be redundant and so did not require optimisation. For example, in the case of a trajectory that was the result of only a single steering input (i.e. a single lane change) the parameters that describe the second steering input (section c, section d, and offset f) would be ignored by the optimisation procedure.

Most of the values for the parameters that govern how an aquaplane affects the simulated trajectory were able to be determined with sufficient confidence that optimisation was deemed unnecessary. The coefficient of friction on one side of the low friction patch was optimised such that the exact effect of the aquaplane upon the trajectory was refined.

6.6.5 Selecting the best set of optimised parameter values

As was mentioned in the previous section, it was not possible to select appropriate initial values for the driver model preview time and lag time parameters. Instead, 36 different value pairs were each passed through the optimisation procedure in order to explore the likely solution space. As a result, there were potentially 36 sets of final parameter values produced along with their associated simulated trajectories. The single set of parameter values (including the preview time and lag time) that produced a simulated trajectory that best matched the scenario trajectory was then selected. This selection was based upon which simulated trajectory had the lowest associated error. However, the selection was also checked by hand.

The reason the final set was checked by hand is that multi-variable optimisation can produce results that, despite having a low error, may not be realistic. In some circumstances the optimisation procedure is able to successfully reduce the error through an unrealistic combination of parameter values and these results should be avoided. In addition, several combinations of parameter values may have a similar error but can be ranked further by hand. For example, Figure 6.54 shows two simulated trajectories that have a similar error value but it is clear that trajectory (a) is a superior match based on the curve in the yaw component.

The final selected set of optimised parameter values was then considered to generate a trajectory that best represents the loss of control scenario trajectory while using the RWD vehicle model and appropriate simulated environment conditions.

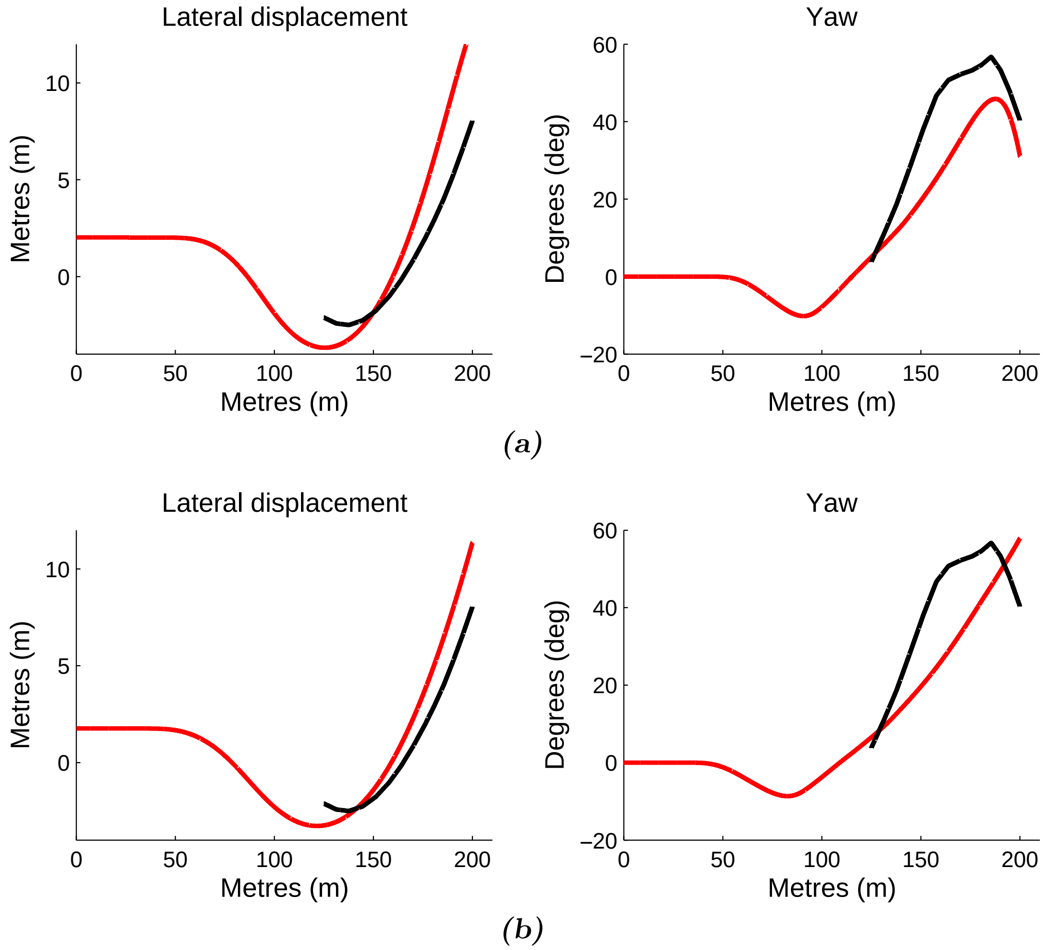


Fig. 6.54: Comparison of two optimised trajectories that have a similar error value

6.7 Summary

The modelling of loss of control crash scenarios through simulation for the purpose of investigating ESC braking interventions has been described above.

A suitable high fidelity vehicle dynamics simulation software package called CarSim was chosen with assistance from Bosch Australia. A pair of vehicle models and associated ESC models were supplied by Bosch that, coupled with CarSim, enabled the simulation of vehicles with and without

ESC.

The two vehicle models, a rear wheel drive (RWD) family sedan and a front wheel drive (FWD) small car, along with their ESC models were validated to ensure they were operating as expected and were suitable for the current investigation. The lateral stability of the vehicle models without ESC was investigated using the sine with dwell test manoeuvre. The responses of the Bosch vehicle models during the sine with dwell test were compared to the responses of several generic vehicle models representative of various market segments. This process indicated that the RWD model had a lateral stability that was similar to a SUV, while the lateral stability of the FWD model was not similar to any of the generic vehicle models.

The lateral stability of the Bosch vehicle models with ESC was then investigated using the sine with dwell test manoeuvre and evaluated using the minimum ESC effectiveness criteria. The RWD vehicle model and ESC model were found to be operating correctly and passed the minimum ESC effectiveness criteria. However, the FWD vehicle model and ESC model failed the minimum ESC effectiveness criteria and their use was subsequently discontinued.

The RWD vehicle model with ESC was further validated by comparing its lateral response during the sine with dwell test to the lateral response of ESC equipped family sedan type vehicles that had been tested using the sine with dwell test by NHTSA. The responses correlated well and it was concluded that the RWD vehicle model and ESC model were a valid representation of a family sized sedan with an appropriately tuned ESC system.

A set of representative loss of control crash scenarios was developed based on rural road crashes that occurred in South Australia and were subsequently investigated by the Centre for Automotive Safety Research. Ten loss of control scenarios were defined with sufficient detail regarding the environment, the circumstances preceding the loss of control, and the loss of control trajectory to enable a simulation with the RWD vehicle model.

The scenario environment was modelled as a three dimensional representation of the road on which the crash occurred along with values for the coefficient of friction on the roadway, roadside shoulder, and any areas of low friction. Data for the three dimensional representation of the road was available from the site survey conducted during the investigation of the crash. Values for the coefficient of friction on different surfaces were selected based upon what is suggested in literature and from measurements of coefficient of friction on similar types of rural road surfaces in South Australia.

The trajectory of the vehicle through the scenario was modelled through parameters that defined the braking and steering inputs from the driver as well as specific coefficient of friction values for an aquaplaning vehicle. It was discovered that selecting parameters to generate a simulated trajectory that emulated the scenario trajectory would require optimisation due to the dynamic interaction between parameters. Initial parameter values that generated a simulated trajectory that at least somewhat represented the scenario trajectory were required for use as the starting point in the optimisation procedure. Initial values for the braking and aquaplaning parameters were defined based on evidence collected during the crash investigations. Steering was modelled through the use of a driver model. Some of the initial steering parameter values were defined based on witness reports and evidence from the crash investigations but others (driver model preview time and lag time) were impossible to select empirically. Instead, a span of the likely parameter values were assessed to find those that generated a simulated trajectory that best matched the scenario trajectory.

The Nelder Mead algorithm was utilised to optimise the initial parameter values such that they produced a simulated trajectory that matched the scenario trajectory. A suitable method of quantifying the error between the simulated and scenario trajectories was developed along with a suitable optimisation termination criteria.

The outcome of this modelling process is presented in the next chapter where the ten typical loss of control scenarios are simulated with and without ESC. The change in vehicle trajectories as a result of ESC braking interventions are then explored and discussed.

7. INVESTIGATING THE EFFECTS OF ESC BRAKING INTERVENTIONS

This chapter uses simulations to investigate the effect that ESC braking interventions have on loss of control scenarios that are typical to high speed rural road crashes. The investigation is presented in three sections. In Section 7.1, the representative value sets for each of the loss of control scenarios described in Section 6.3 are identified based on the methods described in Sections 6.4 to 6.6.

Section 7.2 analyses the differences in vehicle trajectory for each scenario after using the representative value sets to run simulations with and without ESC. For each scenario the accuracy of the match between the measured at-scene trajectory and the trajectory generated by the simulation without ESC is discussed. The effects that the addition of ESC to the vehicle had on the simulated trajectory are highlighted along with how these effects would have altered the result of each scenario had the vehicle been fitted with ESC. A summary is then presented that analyses the overall effect that ESC interventions had on the the loss of control scenarios in general.

Finally, in Section 7.3 the scenarios were simulated again after altering the representative values sets to emulate specific rural road safety measures such as a slower travelling speed, a sealed road, or a sealed roadside shoulder.

A discussion of how these alterations may have effected the validity of the simulations is then provided.

7.1 Identifying representative value sets

Using the methods specified in the previous chapter, representative sets of parameter values were identified for each of the ten loss of control scenarios. The first step in this process was to develop sets of initial parameter values. In four scenarios there were multiple initial values chosen for certain parameters due to ambiguities in the evidence at the crash scene or in reports from witnesses. In such cases a representative set was sought for every combination of initial values.

In Scenario 1, the speed calculations based on the yaw marks left at the crash scene resulted in two different speeds depending on whether the inside wheel or the outside wheel yaw mark was measured. As such, two initial speeds were selected.

Two different driver paths were also selected for Scenario 1. While a witness states that they saw the vehicle initially veer from the right lane to the left, there is uncertainty as to how sharply this occurred or even if it occurred at all. There were no tyre marks to support this, although none would be expected unless a very sharp turn was made. Because the evidence was inconclusive, the possibility that the vehicle may have been initially travelling in either lane was considered. Two driver paths were therefore constructed; one starting in the left lane and steering into the right (single lane change), and the other starting in the right lane, steering left, and then back to the right (double lane change).

The tyre marks at the crash scene in Scenario 4 were the result of a linear slide that was caused by an aquaplane and not a yaw. Therefore, it was not possible to calculate an initial speed empirically. As there was no other evidence which could indicate an initial speed, the driver reported travelling speed was selected. In order to account for the possibility that the vehicle was travelling faster than the driver stated, a speed 10 km/h faster was also selected.

During Scenario 5 the vehicle was noted to have travelled a considerable distance (including an uphill section) before entering a yaw. To account for the speed that would have been lost during this travel two initial speeds, 15 km/h and 25 km/h higher than that calculated based on the yaw marks, were selected.

Calculations based on the inside wheel and the outside wheel yaw marks also resulted in two different speeds in Scenario 8 and thus two initial speeds were selected.

The roadway layout for each scenario are shown in Figures 7.1 to 7.10. Also shown are the initial driver paths and the coefficients of friction for the various roadway surfaces. These figures were constructed based on the site diagrams presented in Section 6.3 along with the information developed using the methods in Sections 6.4 and 6.5. Tables 7.1 and 7.2 show the chosen initial values for each of the simulation parameters in each scenario. A marker is used to indicate those parameters that were to be optimised.

Each set of initial parameter values were then run through the optimisation procedure in combination with each of the 36 likely preview time and lag time pairs. The resulting set of optimised trajectories and the identification of the representative trajectory are presented in Appendix B.

The representative value sets associated with the representative trajectory for each scenario are shown in Tables 7.3 and 7.4. Note that the accuracy of the match between the representative set trajectory and each scenario trajectory varied. Some scenarios were able to be simulated well, while others were less accurate (see Section 7.2). There were several reasons for this such as differences in the characteristics of the vehicle model and the vehicle involved in the loss of control scenario as well as environment conditions or circumstances that were not able to be fully modelled in CarSim. Despite these limitations to the accuracy, all of the representative value sets are considered to be generally representative of a loss of control scenario that would be typical on a high speed rural road.

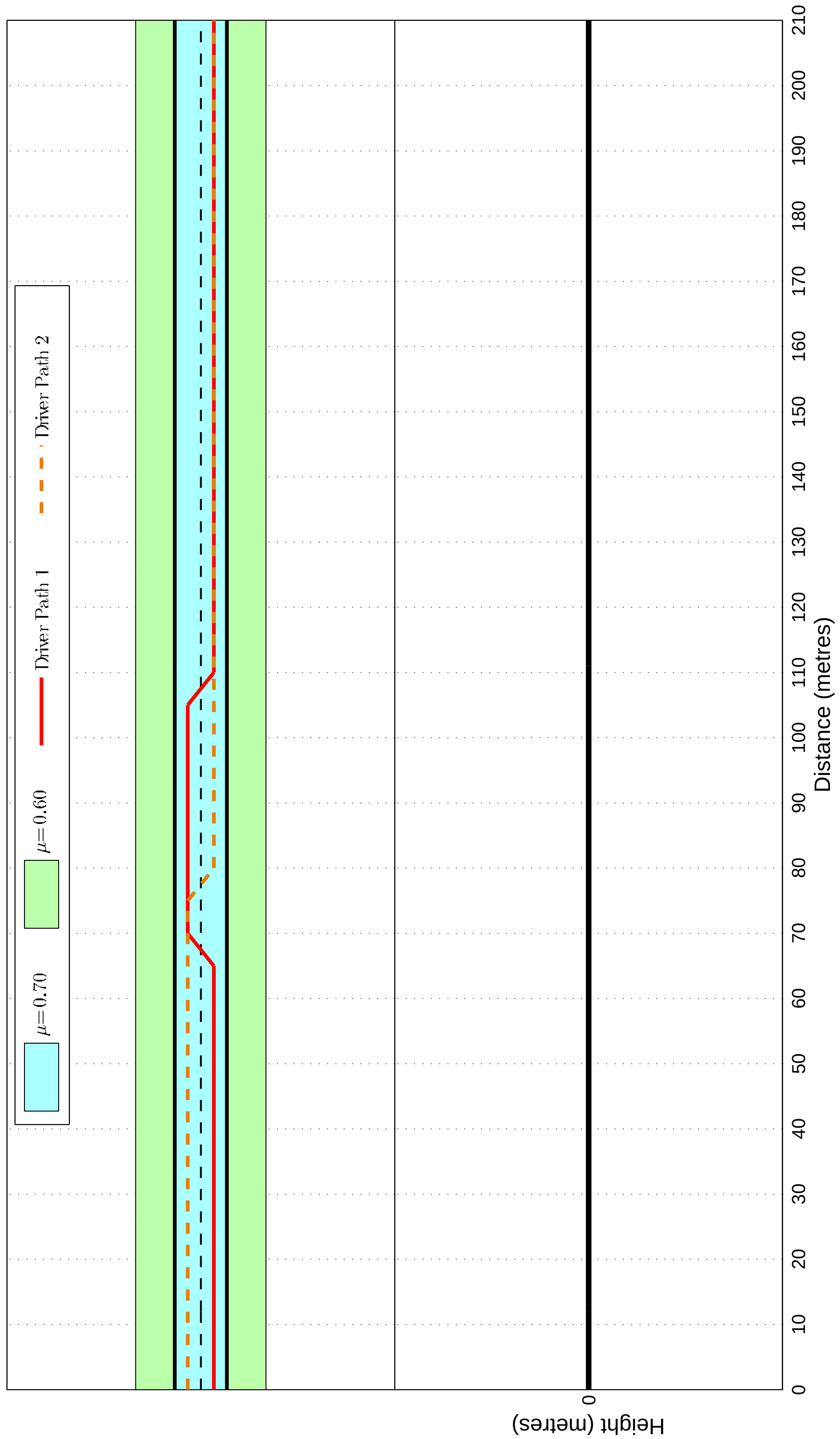


Fig. 7.1: Roadway layout, coefficient of friction values, and initial driver paths (Scenario 1)

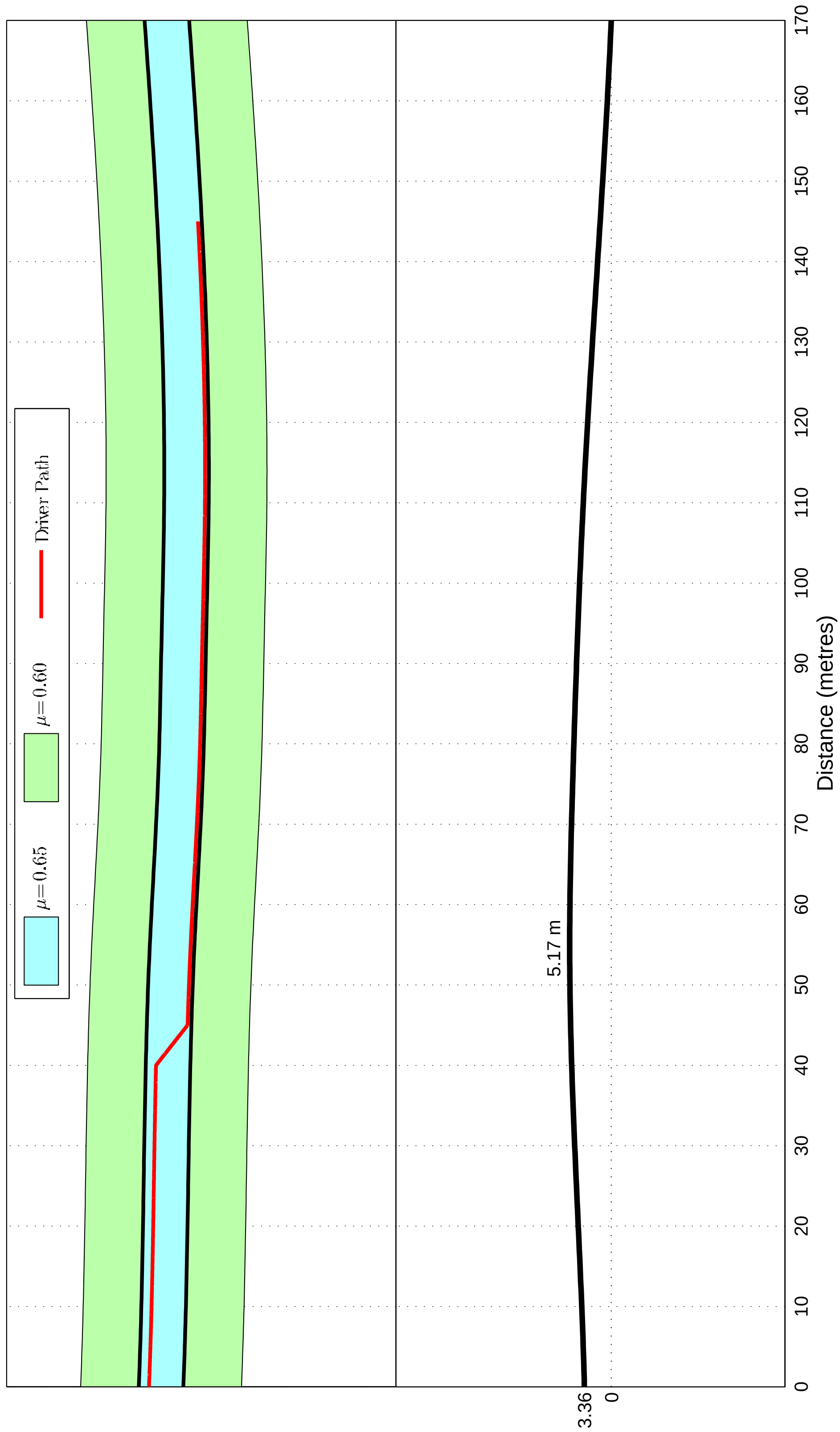


Fig. 7.2: Roadway layout, coefficient of friction values, and initial driver path (Scenario 2)

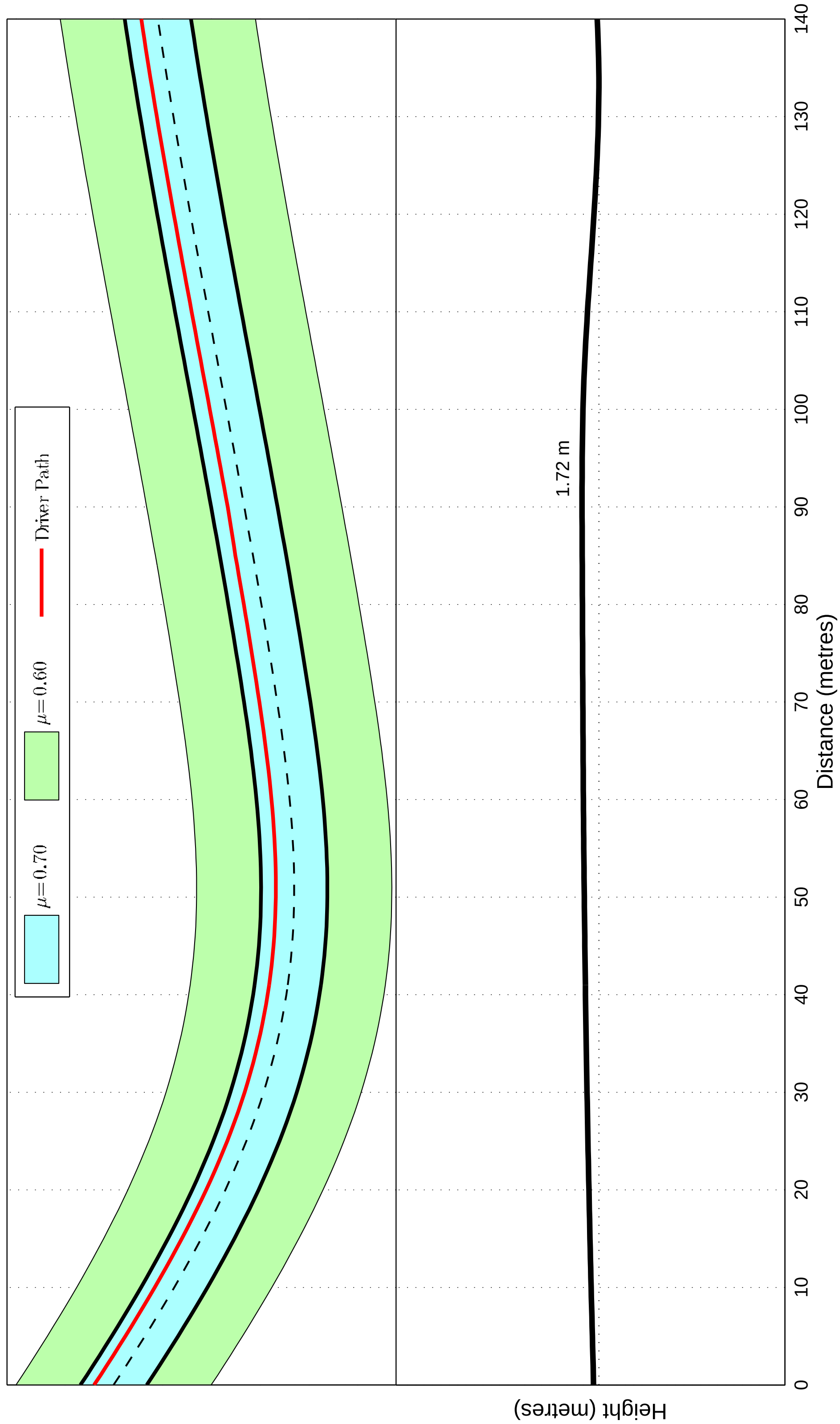


Fig. 7.3: Roadway layout, coefficient of friction values, and initial driver path (Scenario 3)

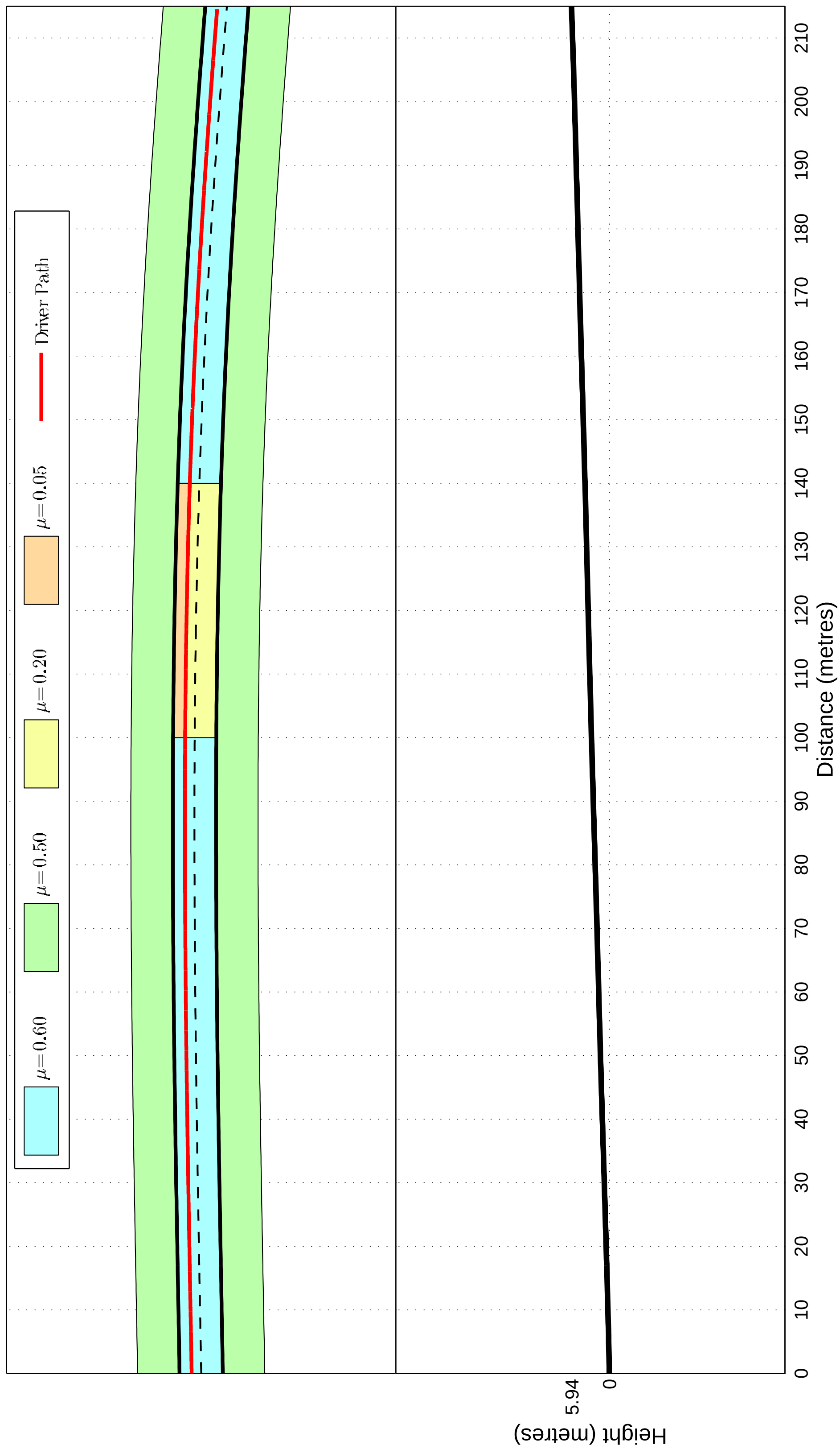


Fig. 7.4: Roadway layout, coefficient of friction values, initial position of low friction patch, and initial driver path (Scenario 4)

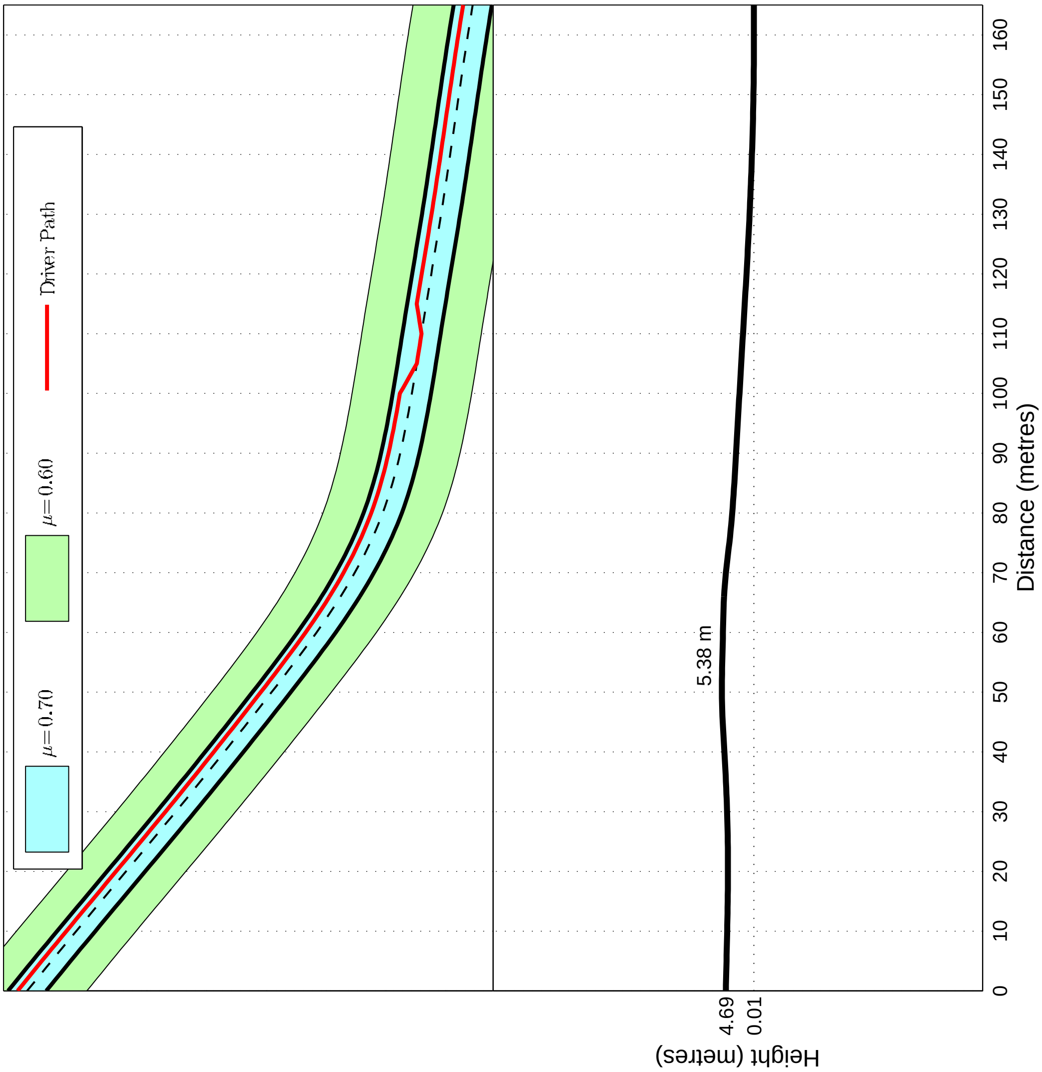


Fig. 7.5: Roadway layout, coefficient of friction values, and initial driver path (Scenario 5)

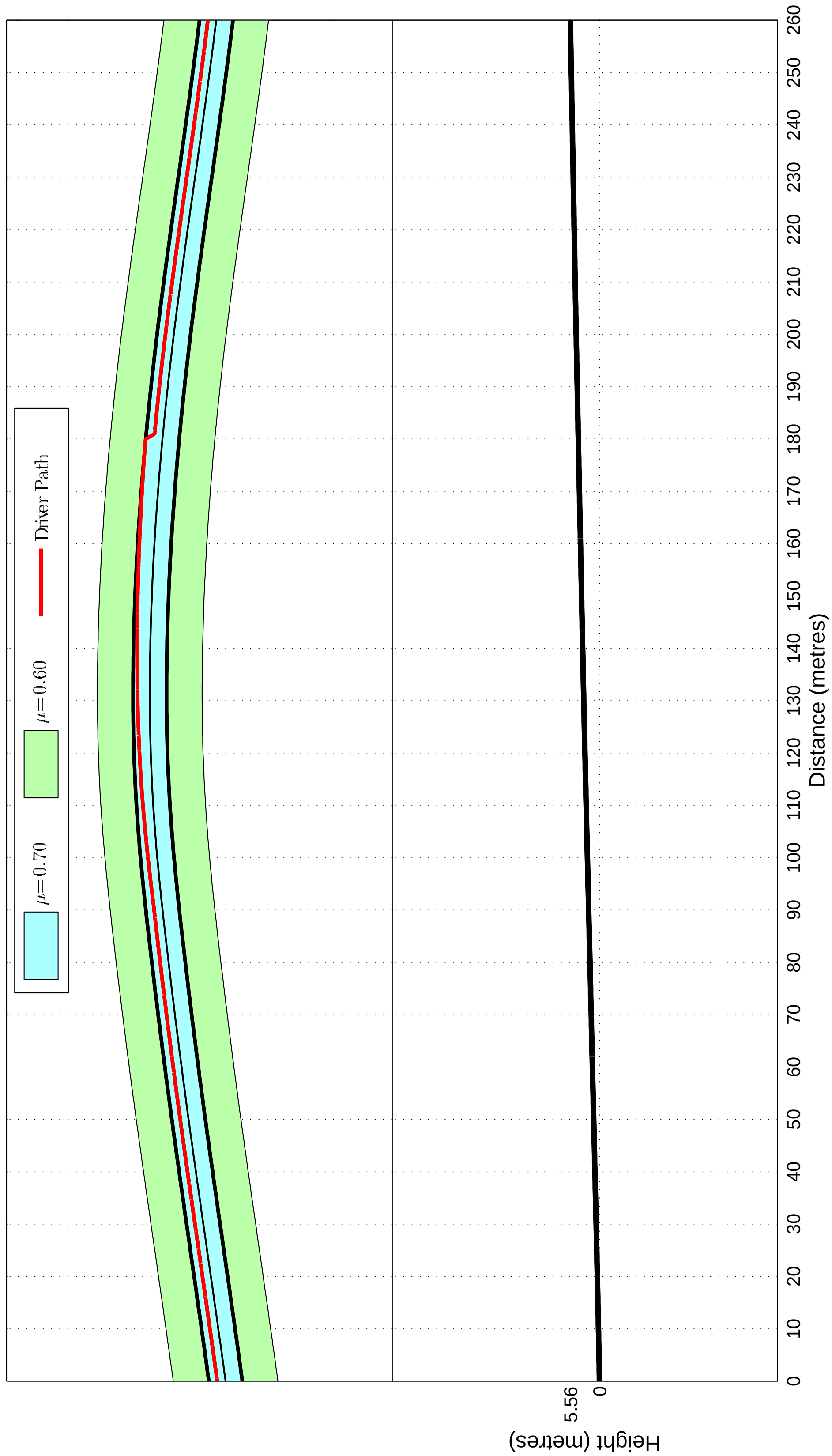


Fig. 7.6: Roadway layout, coefficient of friction values, and initial driver path (Scenario 6)

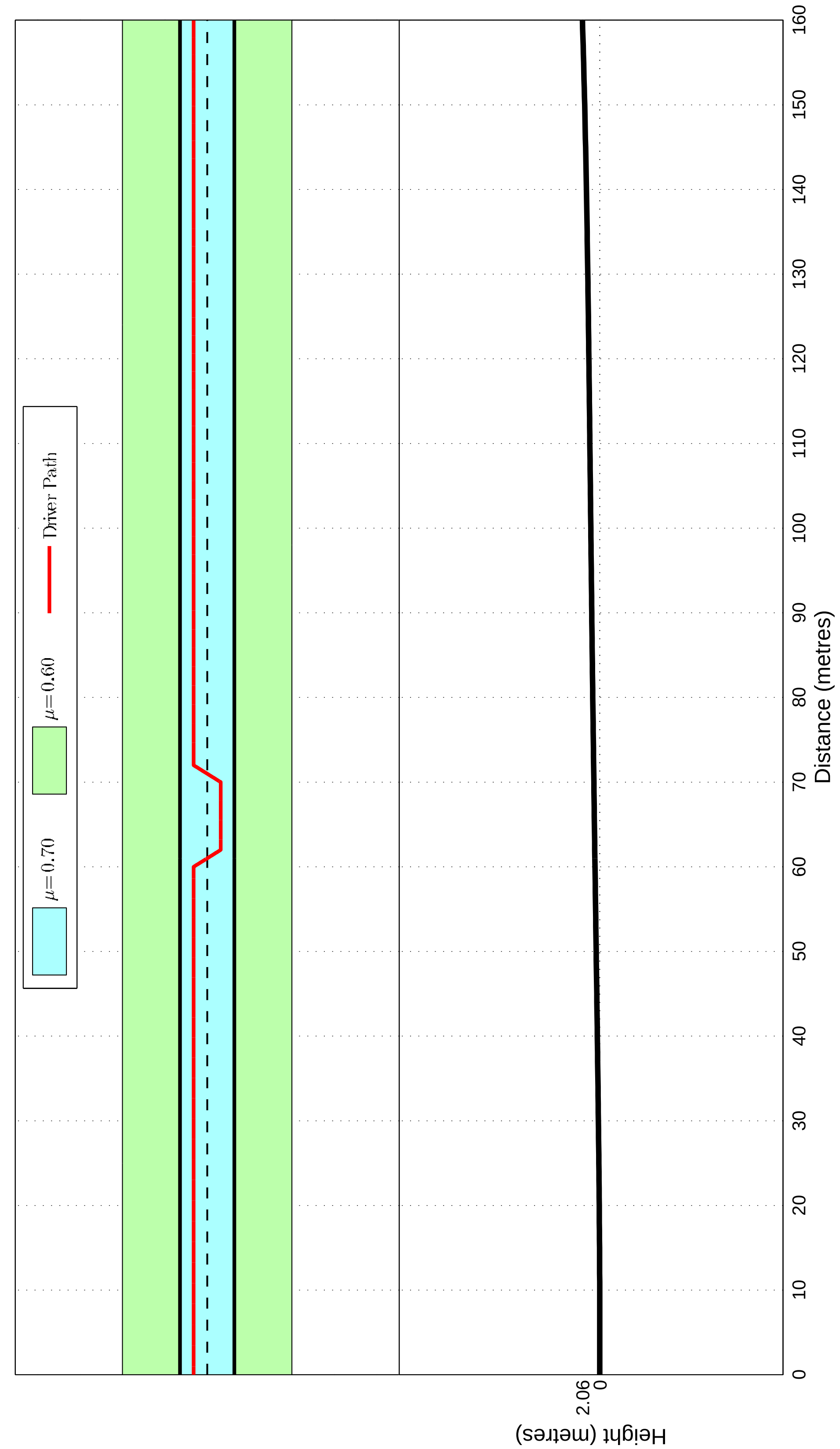


Fig. 7.7: Roadway layout, coefficient of friction values, and initial driver path (Scenario 7)

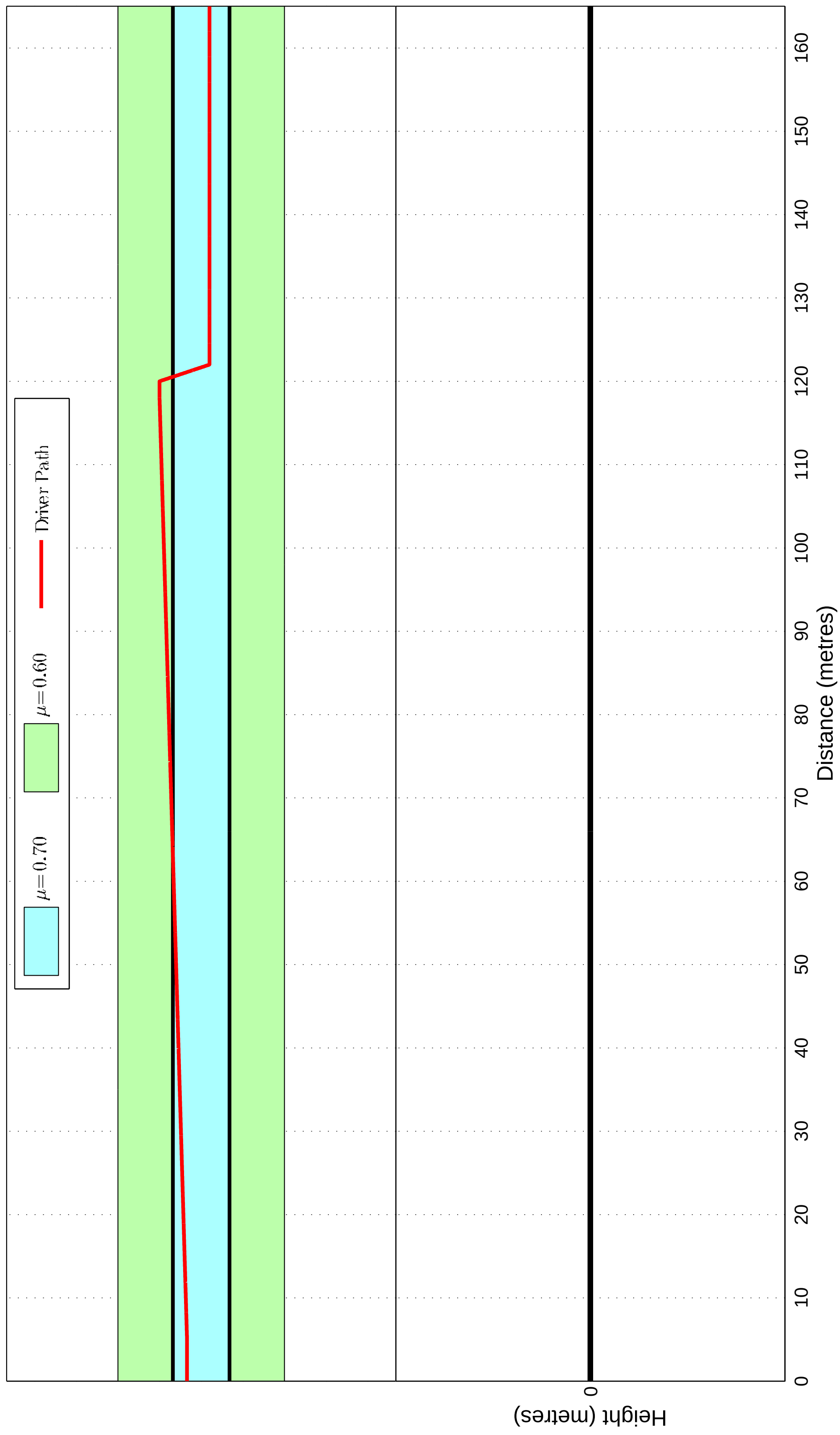


Fig. 7.8: Roadway layout, coefficient of friction values, and initial driver path (Scenario 8)

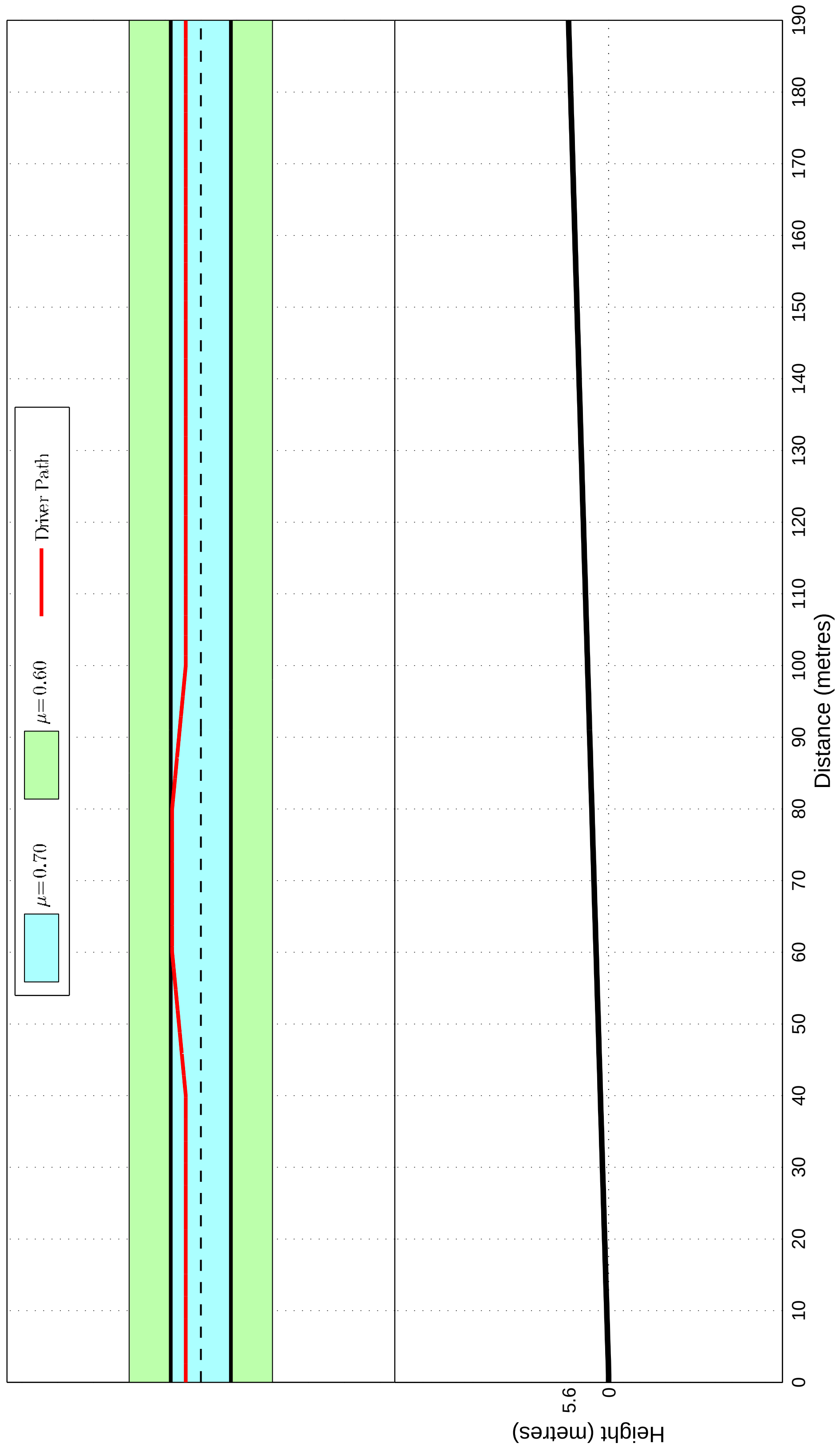


Fig. 7.9: Roadway layout, coefficient of friction values, and initial driver path (Scenario 9)

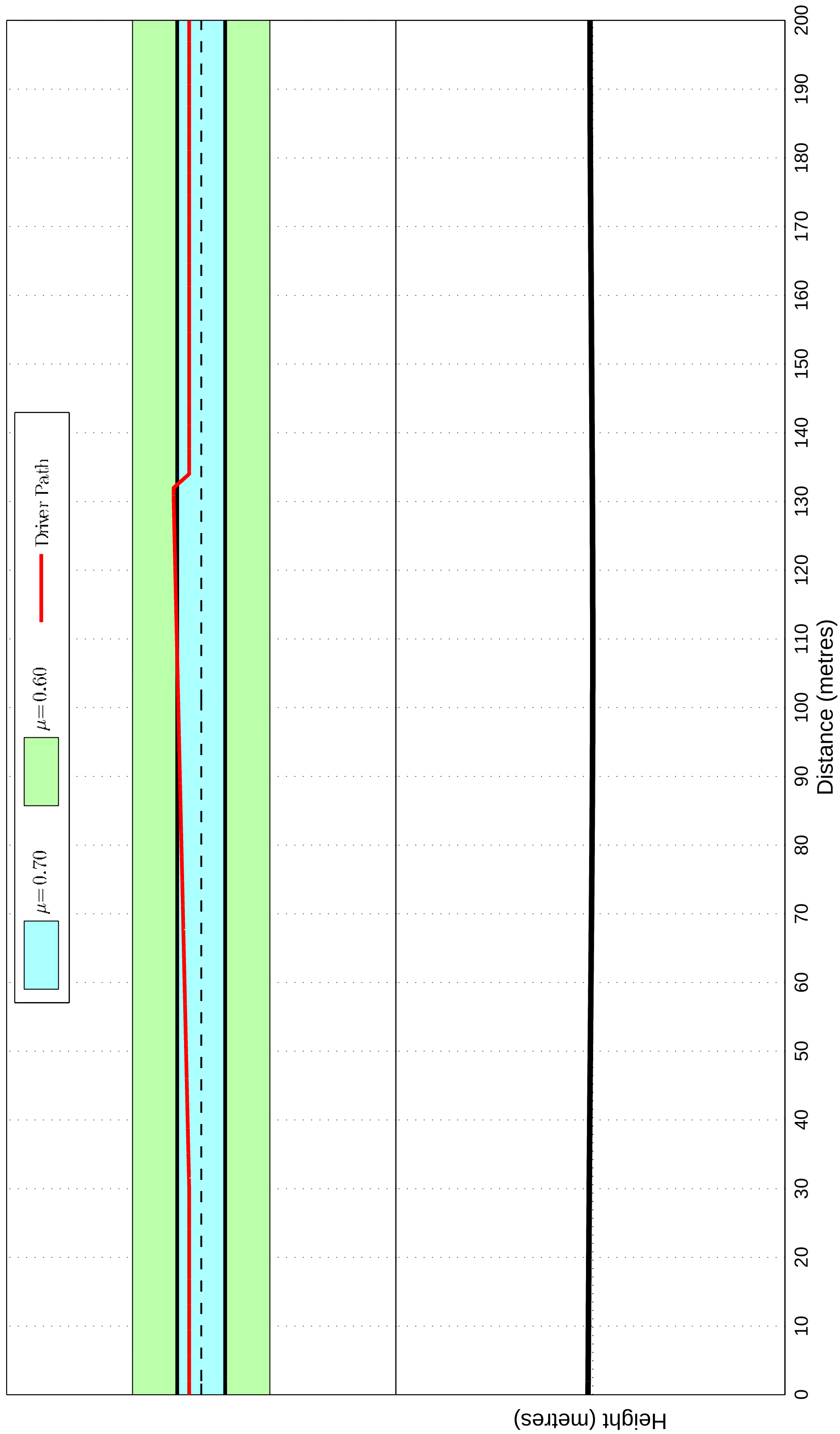


Fig. 7.10: Roadway layout, coefficient of friction values, and initial driver path (Scenario 10)

Tab. 7.1: Initial value sets (part 1)

Parameter	**Scenario 1**				**Scenario 2**	**Scenario 3**	**Scenario 4**	
	Set 1	**Set 2**	**Set 3**	**Set 4**			**Set 1**	**Set 2**
Preview time	0.7-1.2*	0.7-1.2*	0.7-1.2*	0.7-1.2*	0.7-1.2*	0.7-1.2*	0.7-1.2*	0.7-1.2*
Lag time	0.15-0.40*	0.15-0.40*	0.15-0.40*	0.15-0.40*	0.15-0.40*	0.15-0.40*	0.15-0.40*	0.15-0.40*
Initial speed	135	155	135	155	135	95	115	125
Road length	210	210	210	210	170	145	215	215
Path section a	75*	75*	65*	65*	40*	10*	10	10
Path section b	5*	5*	5*	5*	5*	70*	10	10
Path section c	15	15	25*	25*	45	5*	10	10
Path section d	5	5	5*	5*	10	5	10	10
Path offset e	2*	2*	-2	-2	1.5	2	1.5	1.5
Path offset f	-2	-2	2*	2*	-2.3	1.8*	1.5	1.5
Path offset g	-2	-2	-2	-2	-2.3	1.7	1.5	1.5
Brake start time	-	-	-	-	1.5*	-	-	-
Road friction	0.70	0.70	0.70	0.70	0.65	0.70	0.60	0.60
Shoulder friction	0.60	0.60	0.60	0.60	0.6	0.60	0.50	0.50
Low friction left	-	-	-	-	-	-	0.05*	0.05*
Low friction right	-	-	-	-	-	-	0.2*	0.2*
Low friction start	-	-	-	-	-	-	100*	100*
Low friction end	-	-	-	-	-	-	140	140

* parameters to be optimised

Tab. 7.2: Initial value sets (part 2)

Parameter	**Scenario 5**		**Scenario 6**	**Scenario 7**	**Scenario 8**		**Scenario 9**	**Scenario 10**
	Set 1	**Set 2**			**Set 1**	**Set 2**		
Preview time	0.7-1.2*	0.7-1.2*	0.7-1.2*	0.7-1.2*	0.7-1.2*	0.7-1.2*	0.7-1.2*	0.7-1.2*
Lag time	0.15-0.40*	0.15-0.40*	0.15-0.40*	0.15-0.40*	0.15-0.40*	0.15-0.40*	0.15-0.40*	0.15-0.40*
Initial speed	80	90	115	90	100	130	115	135
Road length	185	185	260	160	165	165	160	200
Path section a	100*	100*	90	60*	5	5	40*	30
Path section b	5*	5*	88*	2	113*	113*	20*	100*
Path section c	5*	5*	2*	8*	2	2	20*	2*
Path section d	5*	5*	1	2	2	2	20*	2
Path offset e	2*	2*	1.6	1.6	1.7	1.7	2.1	1.75
Path offset f	0*	0*	3.2*	-1.6*	5*	5*	4*	4*
Path offset g	1.6	1.6	1.6	1.6	-1*	-1*	2.1	1.75
Brake start time	-	-	-	-	-	-	-	-
Road friction	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Shoulder friction	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Low friction left	-	-	-	-	-	-	-	-
Low friction right	-	-	-	-	-	-	-	-
Low friction start	-	-	-	-	-	-	-	-
Low friction end	-	-	-	-	-	-	-	-

* parameters to be optimised

Tab. 7.3: Representative value sets (part 1)

Parameter	**Scenario 1**				**Scenario 2**	**Scenario 3**	**Scenario 4**	
	Set 1	**Set 2**	**Set 3**	**Set 4**			**Set 1**	**Set 2**
Preview time	1.1002	1.0608	1.1845	1.1723	0.9184	0.4588	0.7205	0.6955
Lag time	0.2189	0.1603	0.2022	0.1851	0.3627	0.2778	0.2964	0.3249
Initial speed	135	155	135	155	135	95	115	125
Road length	210	210	210	210	170	145	215	215
Path section a	75.2339	64.5733	44.4015	30.5366	52.1230	12.2102	10	10
Path section b	5.0041	3.7198	6.7369	5.6854	6.6200	66.5110	10	10
Path section c	15	15	29.5177	19.1262	45	6.0339	10	10
Path section d	5	5	5.0556	6.4389	10	5	10	10
Path offset e	2.0114	2.0340	-2	-2	1.5	2	1.5	1.5
Path offset f	-2	-2	1.0272	1.8547	-2.3	0.2514	1.5	1.5
Path offset g	-2	-2	-2	-2	-2.3	1.7	1.5	1.5
Brake start time	-	-	-	-	2.4846	-	-	-
Road friction	0.70	0.70	0.70	0.70	0.65	0.70	0.60	0.60
Shoulder friction	0.60	0.60	0.60	0.60	0.6	0.60	0.50	0.50
Low friction left	-	-	-	-	-	-	0.0513	0.0592
Low friction right	-	-	-	-	-	-	0.2071	0.2485
Low friction start	-	-	-	-	-	-	101.7778	98.2439
Low friction end	-	-	-	-	-	-	140	140

Tab. 7.4: Representative value sets (part 2)

Parameter	**Scenario 5**		**Scenario 6**	**Scenario 7**	**Scenario 8**		**Scenario 9**	**Scenario 10**
	Set 1	**Set 2**			**Set 1**	**Set 2**		
Preview time	0.7144	0.6788	0.7420	0.7312	0.9800	0.8025	0.7132	0.9874
Lag time	0.2447	0.2564	0.3160	0.3306	0.3748	0.4464	0.3379	0.4496
Initial speed	80	90	115	90	100	130	115	135
Road length	185	185	260	160	165	165	160	200
Path section a	107.0917	105.1557	90	55.8348	5	5	42.6645	30
Path section b	4.9174	5.4918	58.4751	2	88.2466	112.9168	24.3961	48.5384
Path section c	4.8474	5.4783	2.4920	8.2163	2	2	18.4739	2.2918
Path section d	4.8398	4.7027	1	2	2	2	18.3926	2
Path offset e	2.1058	2.3505	1.6	1.6	1.7	1.7	2.1	1.75
Path offset f	0.0005	-0.0011	4.0495	-1.6858	5.9801	4.8014	3.7159	3.7349
Path offset g	1.6	1.6	1.6	1.6	-0.9770	-0.9806	2.1	1.75
Brake start time	-	-	-	-	-	-	-	-
Road friction	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Shoulder friction	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Low friction left	-	-	-	-	-	-	-	-
Low friction right	-	-	-	-	-	-	-	-
Low friction start	-	-	-	-	-	-	-	-
Low friction end	-	-	-	-	-	-	-	-

7.2 Comparing loss of control scenarios with and without ESC

Each of the representative value sets were used to run simulations with the ESC equipped vehicle model. The differences in each scenario between the simulation with ESC and the simulation without ESC were then analysed.

In the subsections below an analysis is presented for each of the simulated scenarios. The accuracy of the match between the trajectory of the simulation without ESC and the scenario trajectory is discussed. The effect that the addition of ESC to the vehicle had on the simulation trajectory is then highlighted along with how this effect would have altered the result of the crash scenario had the vehicle been fitted with ESC.

These discussion points make reference to figures that compare the trajectory, sideslip angle, and the slip at each wheel for the ESC equipped and non-ESC equipped vehicle models over the course of each scenario simulation. Each figure consists of five graphs which share a common abscissa (longitudinal distance along the roadway). In all graphs, a blue line refers to the vehicle without ESC and a red line refers to the vehicle with ESC.

The top graph describes the lateral offset of the vehicle's centre of mass relative to the centre of the left lane of the road. A positive lateral offset is to the left and a negative lateral offset is to the right. A thin black line displays the driver path. A green line shows the lateral offset of the scenario trajectory for reference.

The second graph describes the yaw angle of the vehicle relative to the centre of the road. This can be thought of as the angle at which the vehicle is facing, relative to the centre line of the road. A positive yaw is an anti-clockwise angle and a negative yaw is a clockwise angle. A thin black line displays the zero point at which a vehicle is angled exactly longitudinal to the centre of the road. A green line shows the yaw of the scenario trajectory for reference.

The third graph describes the slide slip angle of the vehicle. A positive side slip angle indicates the vehicle has some component of velocity to the left and a negative side slip angle indicates some velocity to the right. A thin black line displays the zero point where the velocity of the vehicle is entirely in the forward, or longitudinal, direction.

The fourth and fifth graphs describe the wheel slip, due to braking, at the front and rear wheels respectively. In each graph the left wheel is shown as a solid line and the right wheel as a dashed line.

It is important to note here that the changes to the trajectory of the vehicle brought about through ESC braking interventions will affect the behaviour of the driver model. Before the first ESC braking intervention the same driver model steering behaviour will elicit the same vehicle trajectory (leading to a potential loss of control) during both the simulation with and without ESC. However, after the first intervention the driver model steering behaviour that resulted in a loss of control during the simulation without ESC may not be appropriate for the simulation with ESC when the vehicle is no longer in a situation that is considered to be an emergency. For example, driver model parameter values (preview time and lag time) that elicited panicked or sudden steering in response to a skidding vehicle would not be appropriate for a vehicle that is no longer in a skidding situation.

These inappropriate driver model parameter values can manifest as erratic path tracking for the ESC equipped vehicle beyond the first intervention. Indeed, some of the figures below appear to show that the addition of ESC resulted in a vehicle that avoided a loss of control at the point of interest (i.e. where the non-ESC vehicle lost control) but then became unstable such that a different collision would have occurred. Therefore, caution is advised in interpreting the results beyond the initial ESC braking intervention and associated change in trajectory when looking at the figures below.

As mentioned in Section 6.5.2, the use of the GM driver model, which includes a variable preview time, would have been able to mitigate such issues but was not available within the CarSim software at the time the simulations were run.

A final subsection presents a summary of the effects of ESC, including comparisons of the maximum lateral offset, maximum yaw, and maximum sideslip observed during the simulations with and the simulations without ESC.

7.2.1 Scenario 1

There were four different parameter sets simulated for Scenario 1. The trajectories of the simulated vehicles without ESC were generally similar to the scenario trajectory but none showed a particularly good match. In all simulations, the non-ESC vehicle had a lateral offset that peaked further to the right than in the scenario. This meant that in some of the simulations the vehicle may have travelled slightly off the right side of the road and onto the median. The yaw component of trajectory was noted to vary depending on whether the parameter set was simulating a single lane change (set 1 and set 2) or a double lane change (set 3 and set 4). For the double lane change simulations the amount of yaw increased during the second steering manoeuvre and continued to increase until the end of the simulation. On the other hand, the single lane change simulations displayed a yaw that was more like the scenario in that it peaked and then began to decrease.

The simulation based on parameter set 1 (135 km/h, single lane change) was considered to generate a non-ESC vehicle trajectory that best emulated the scenario trajectory (though not well enough to be considered particularly good as mentioned above). When the same parameter set was used to simulate an ESC equipped vehicle the trajectory changed considerably. The ESC equipped vehicle showed a lateral offset that successfully reentered the roadway (without travelling off the left side) after the initial excursion offto the right. Similarly, the ESC equipped vehicle did not display the excessive amounts of yaw and sideslip that were apparent with the non-ESC vehicle.

Given these results it is suggested that if Scenario 1 occurred with a vehicle equipped with ESC then a loss of control would have been avoided and, assuming no other vehicles were nearby, no collision would have occurred.

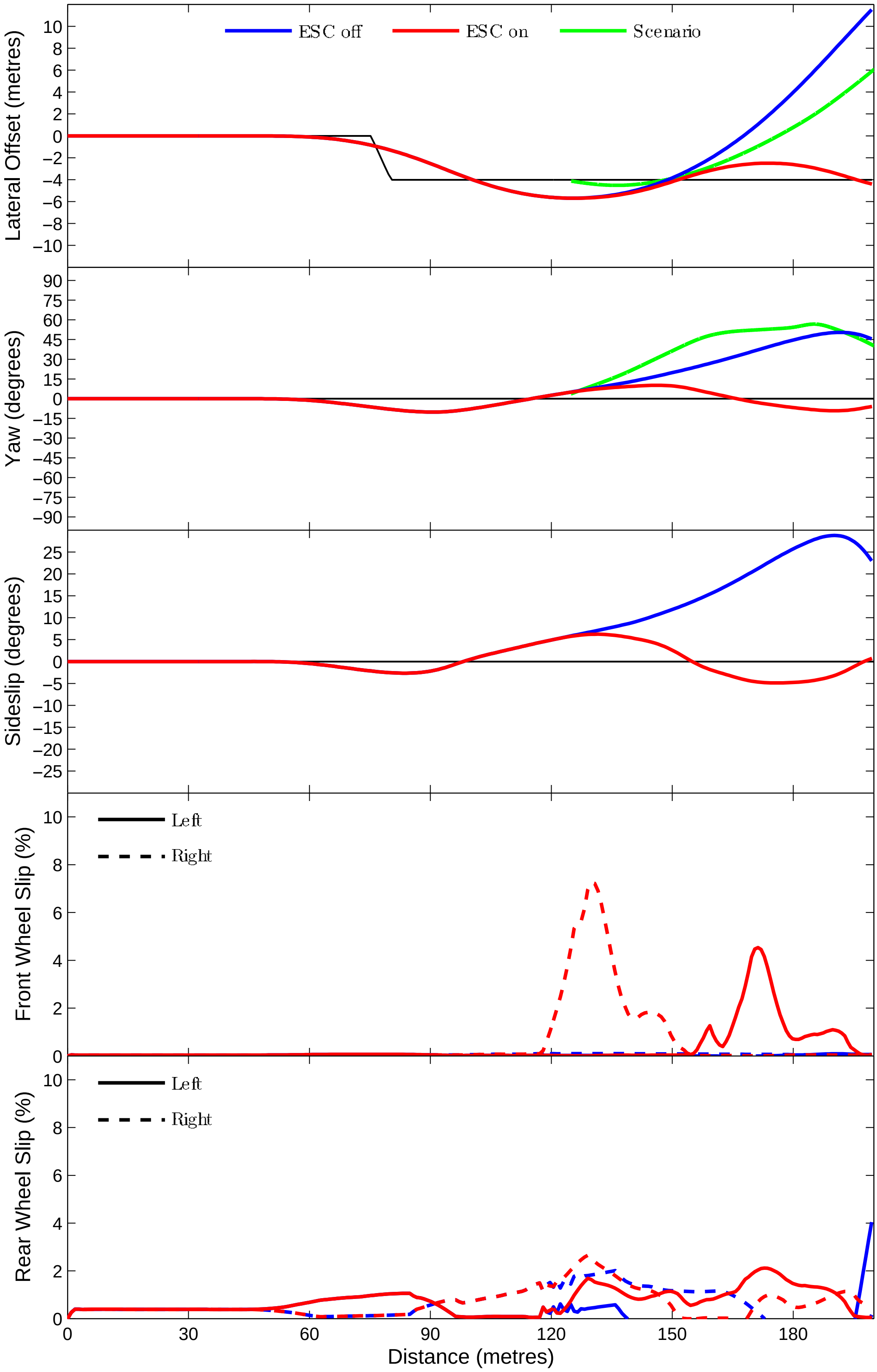


Fig. 7.11: Effect of ESC (representative value set 1, scenario 1)

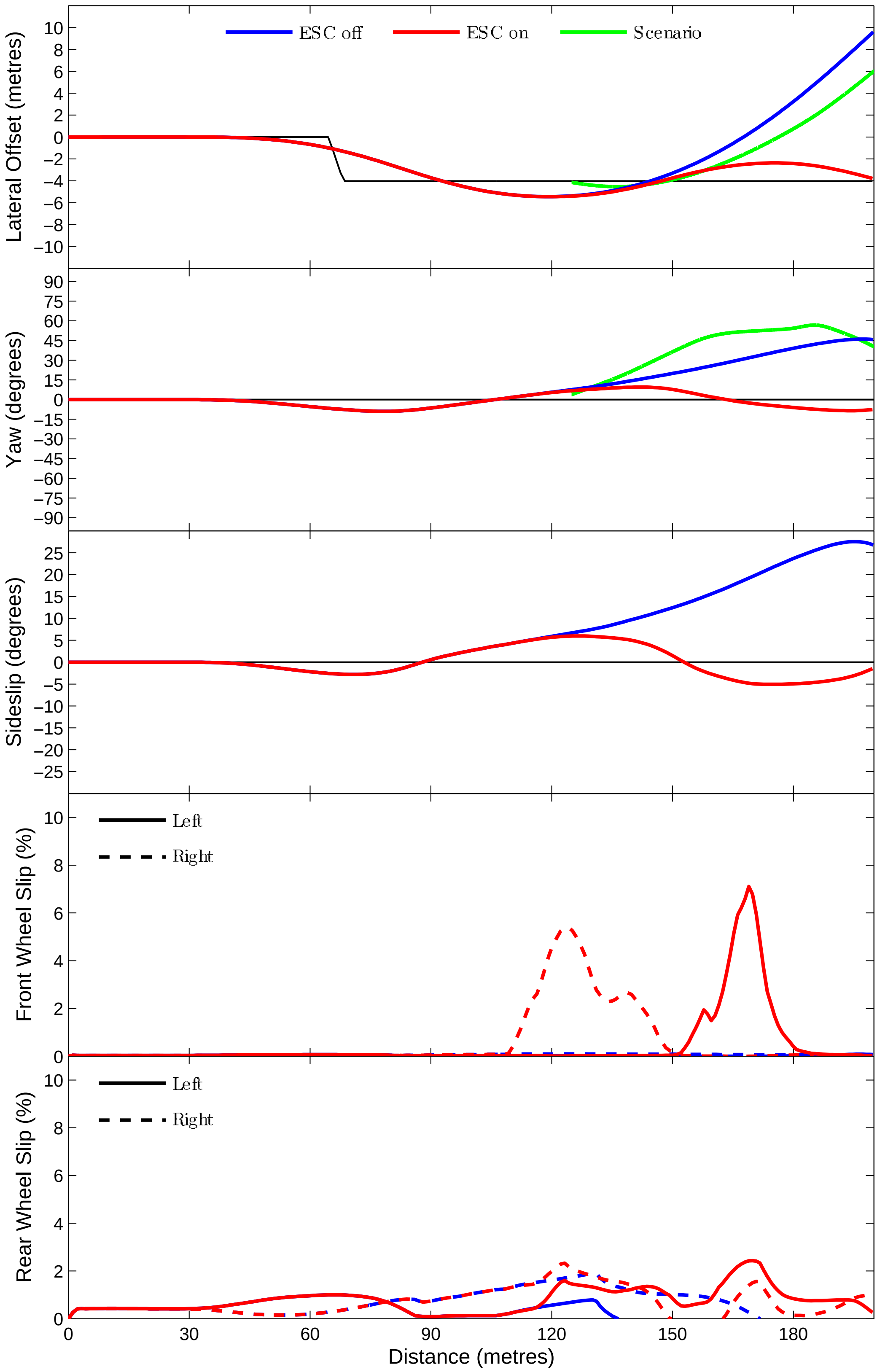


Fig. 7.12: Effect of ESC (representative value set 2, scenario 1)

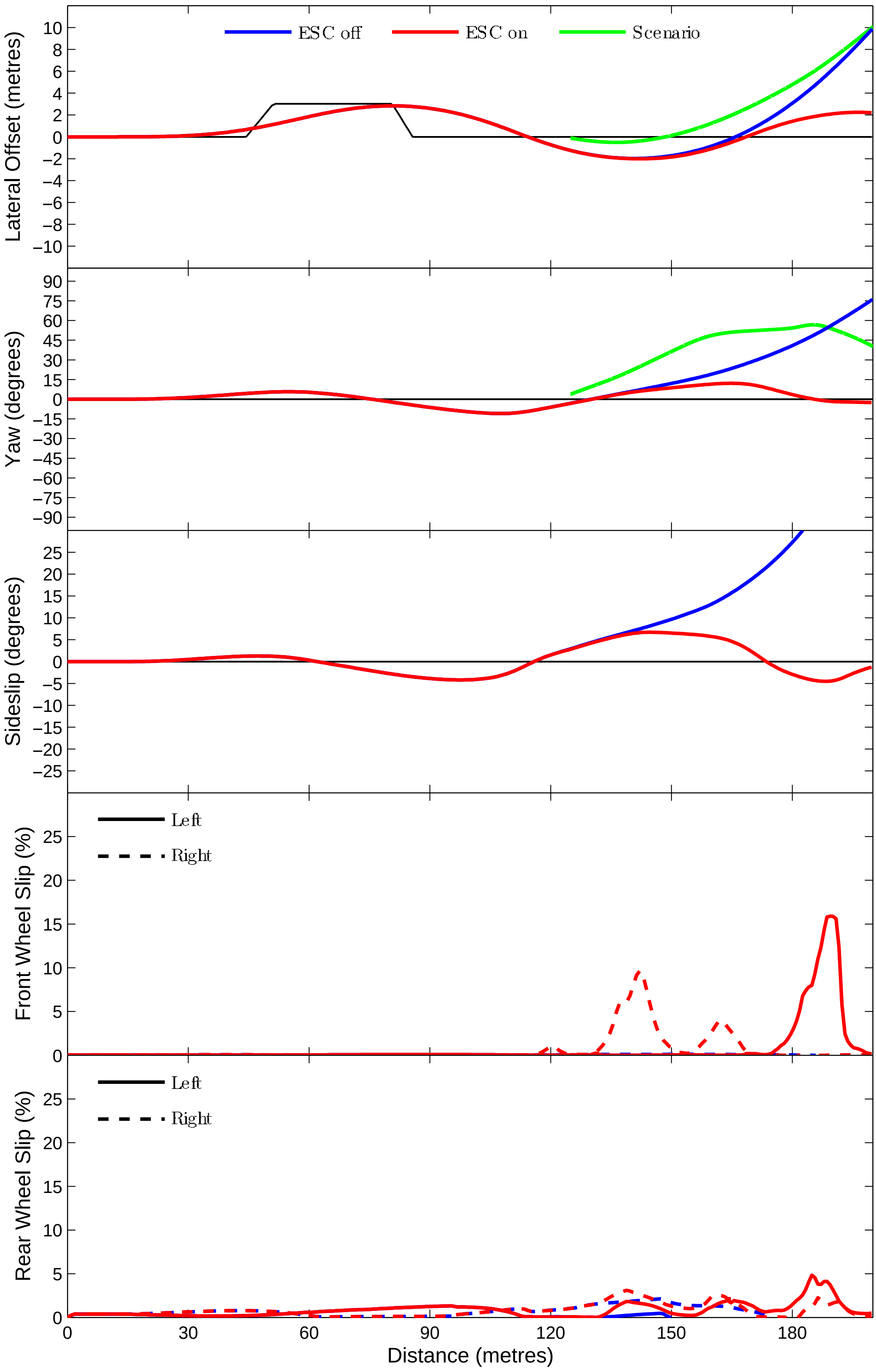


Fig. 7.13: Effect of ESC (representative value set 3, scenario 1)

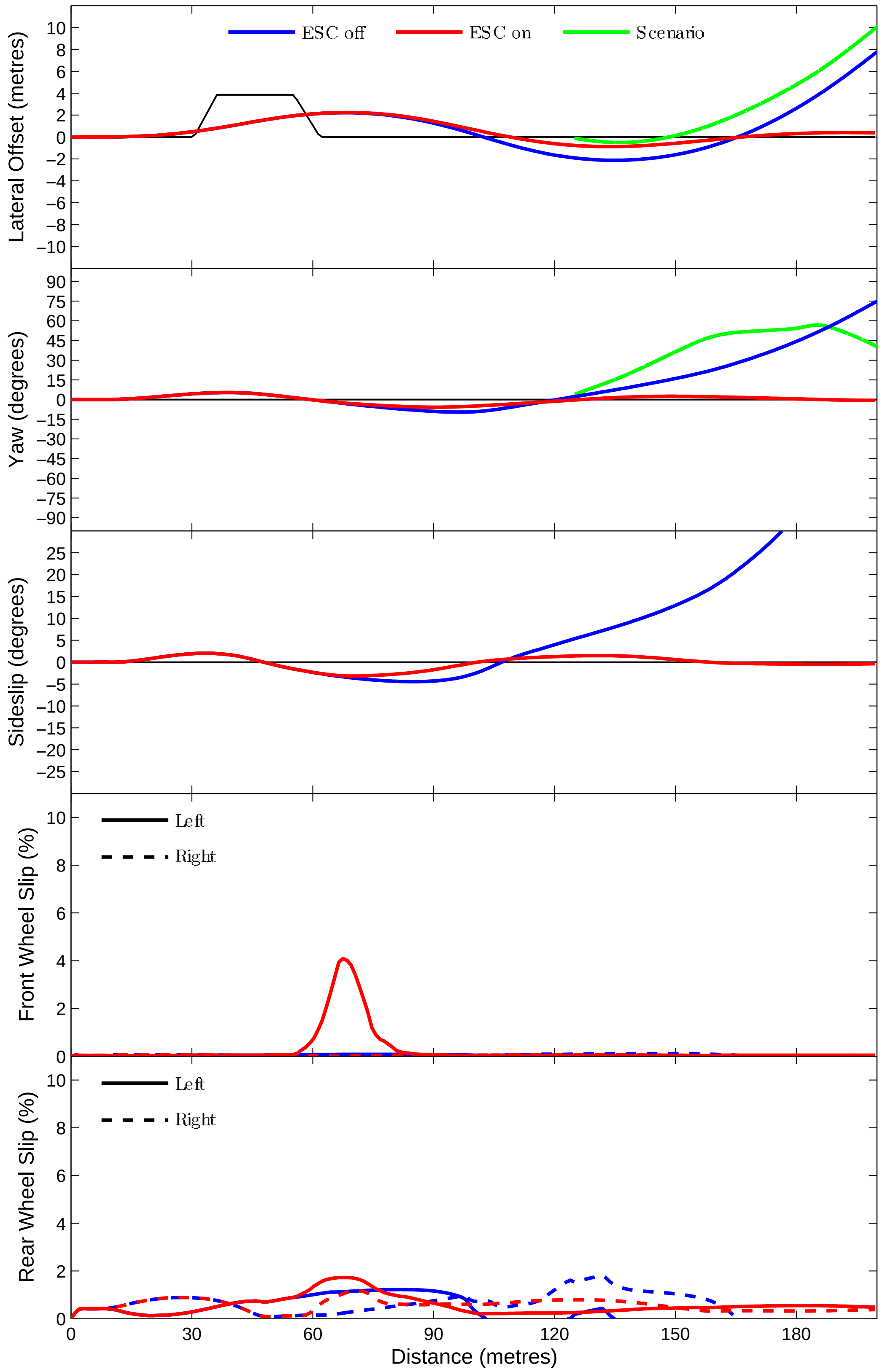


Fig. 7.14: Effect of ESC (representative value set 4, scenario 1)

7.2.2 Scenario 2

Only one parameter set was used in simulating Scenario 2. In this simulation the non-ESC vehicle had a trajectory that matched well with both the lateral offset and yaw components of the scenario trajectory.

When the parameter set was used to simulate a vehicle equipped with ESC the yaw angle of the trajectory was altered, although the lateral offset remained relatively unchanged. Thus, the ESC equipped vehicle would have travelled the same course but been angled more towards the direction of travel.

Given these trajectory changes it is concluded that if Scenario 2 occurred with an ESC equipped vehicle then a collision with a tree was still likely to have occurred but with the impact configuration altered from a side impact to a frontal impact. This is viewed as a more favorable outcome as a frontal impact facilitates a greater potential to mitigate occupant injury through passive safety features such as seat belts, airbags, and crumple zones that are ineffective during a side impact.

An in-depth investigation of 138 fatal crashes in Sweden by Lie (2012) found similar situations of crash non-avoidance by ESC equipped vehicles. Crashes that occurred from 2004 to 2010 and involved a fatality in a vehicle built post 2002 were reviewed and nine loss of control crashes by ESC equipped vehicles were identified. In three of these crashes the loss of control occurred on the road side shoulder, and in another three the loss of control was the result of extreme speed. The specific details of each crash were not provided so it is unknown whether the collisions were frontal or side impacts.

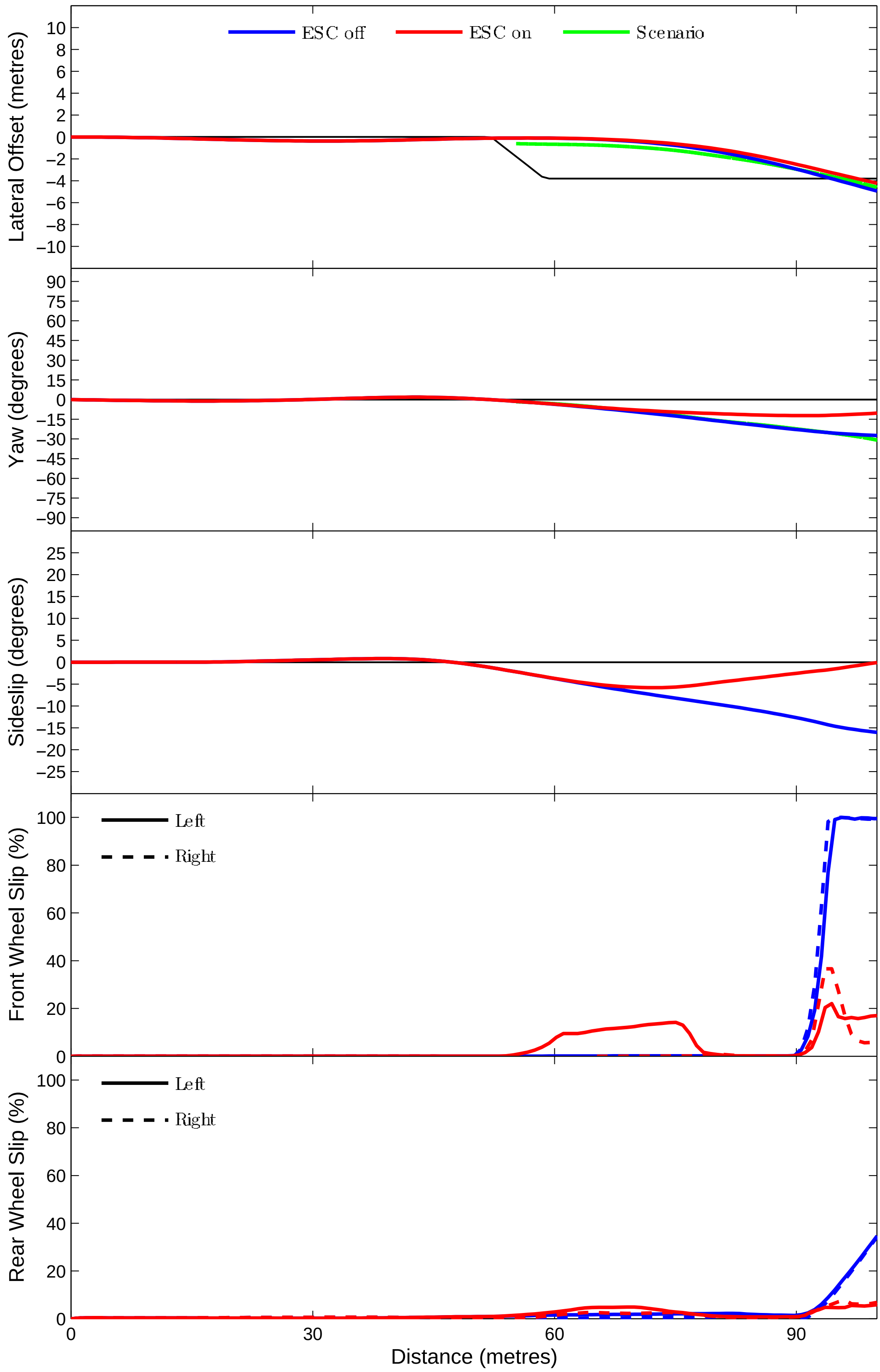


Fig. 7.15: Effect of ESC (scenario 2)

7.2.3 Scenario 3

A single parameter set was used to simulate Scenario 3. While the simulation of the vehicle without ESC was able to achieve a trajectory that somewhat resembled the scenario trajectory, it was not an accurate match. Compared with the scenario, the lateral offset of the non-ESC vehicle peaked further to the right while the yaw began increasing earlier and more gradually. The simulated trajectory thus shows a vehicle that loses control earlier in the curve and would have resulted in the vehicle travelling on the wrong side of the road.

When the same parameter set was used to run a simulation with an ESC equipped vehicle, this earlier loss of control resulted in an early ESC intervention. This intervention, as well as the subsequent interventions, prevented the sideslip and yaw angles from becoming excessive and thus avoided a loss of control. However, this intervention process appears to have caused the vehicle to understeer slightly and resulted in a greater lateral offset to the right which would have caused the vehicle to travel onto the wrong side of the road. The sudden and excessive travel back towards the correct side of the road that occurred just before the end of the simulation was likely caused by inappropriate driver model parameter values as discussed earlier.

While the simulated loss of control was slightly different to that during Scenario 3, the results suggest that an ESC equipped vehicle could have avoided a collision with a roadside object. However, the vehicle is indicated to have travelled onto the wrong side of the road for a short distance and so was thus exposed to a potential collision with the oncoming vehicle.

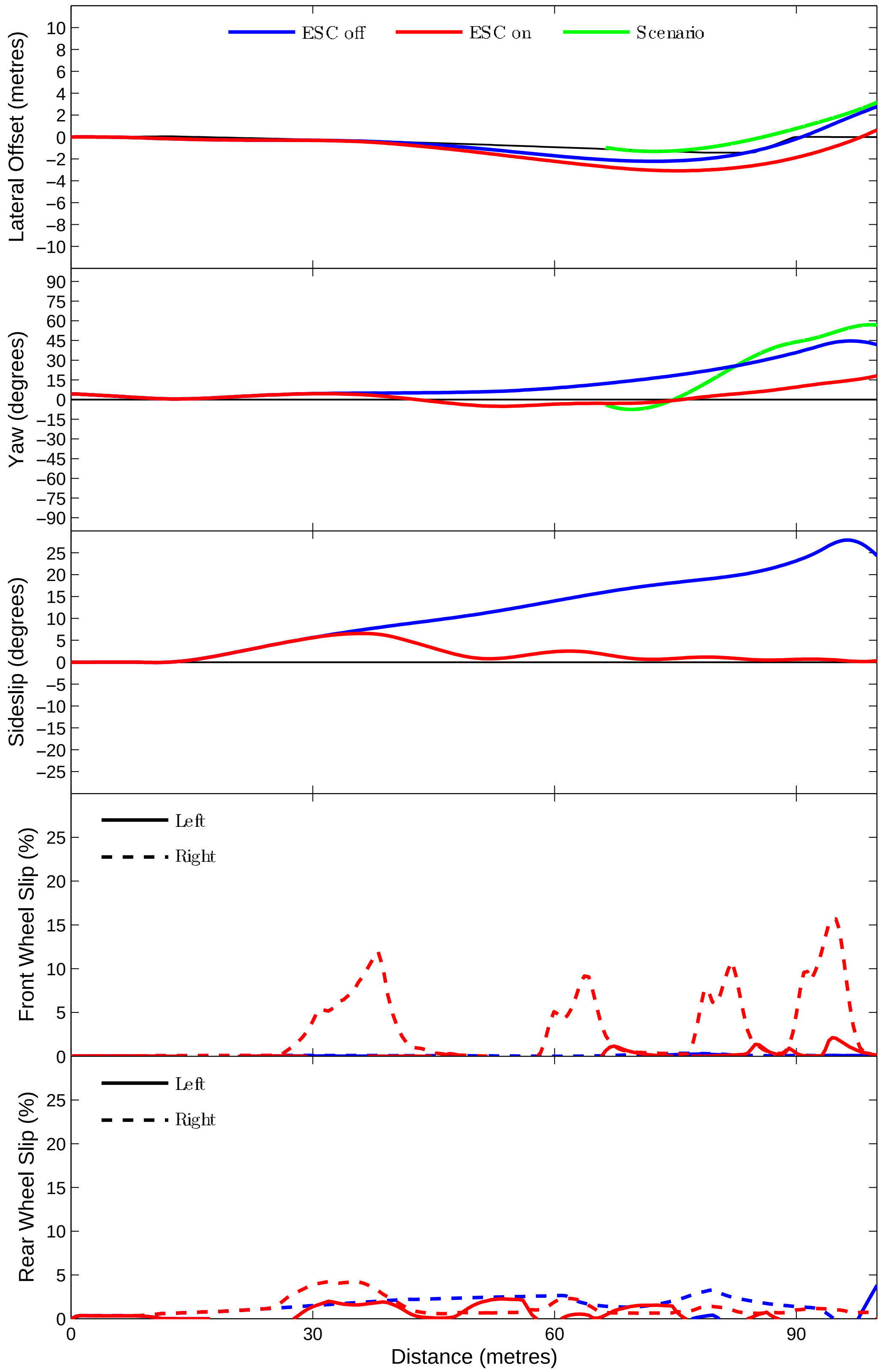


Fig. 7.16: Effect of ESC (scenario 3)

7.2.4 Scenario 4

Two parameter sets were used during the simulation of Scenario 4 and both produced similar non-ESC vehicle trajectories. These trajectories appeared to display the same type of loss of control mechanism as the scenario trajectory where there was a sudden increase in lateral offset to the right and a clockwise yaw. However, the non-ESC vehicle trajectories could not be said to match well with the scenario trajectory since they did not achieve the same high levels of lateral offset and yaw.

Using the same parameter sets to run simulations with the ESC equipped vehicle also resulted in two trajectories that were similar. Neither ESC equipped trajectory displayed any significant increase in lateral offset or yaw as a result of the vehicle travelling over the low friction patch. However, there did appear to have been some instability induced as the vehicle exited the low friction patch. Nevertheless, given the low level of sideslip at this point it is likely a typical driver would be able to correct for this easily.

From these results it is suggested that if Scenario 4 occurred with an ESC equipped vehicle then a loss of control and collision would have been avoided.

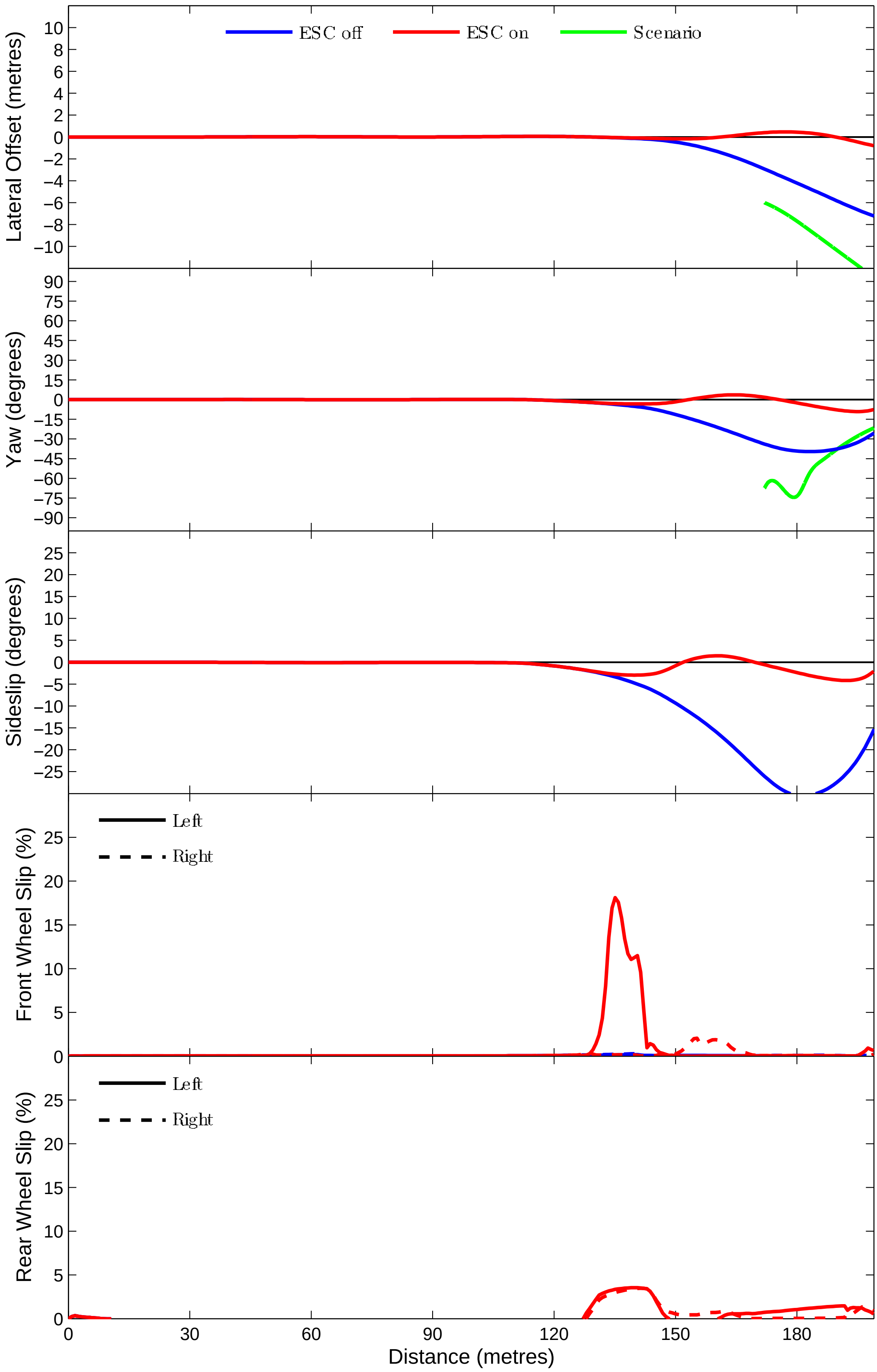


Fig. 7.17: Effect of ESC (representative value set 1, scenario 4)

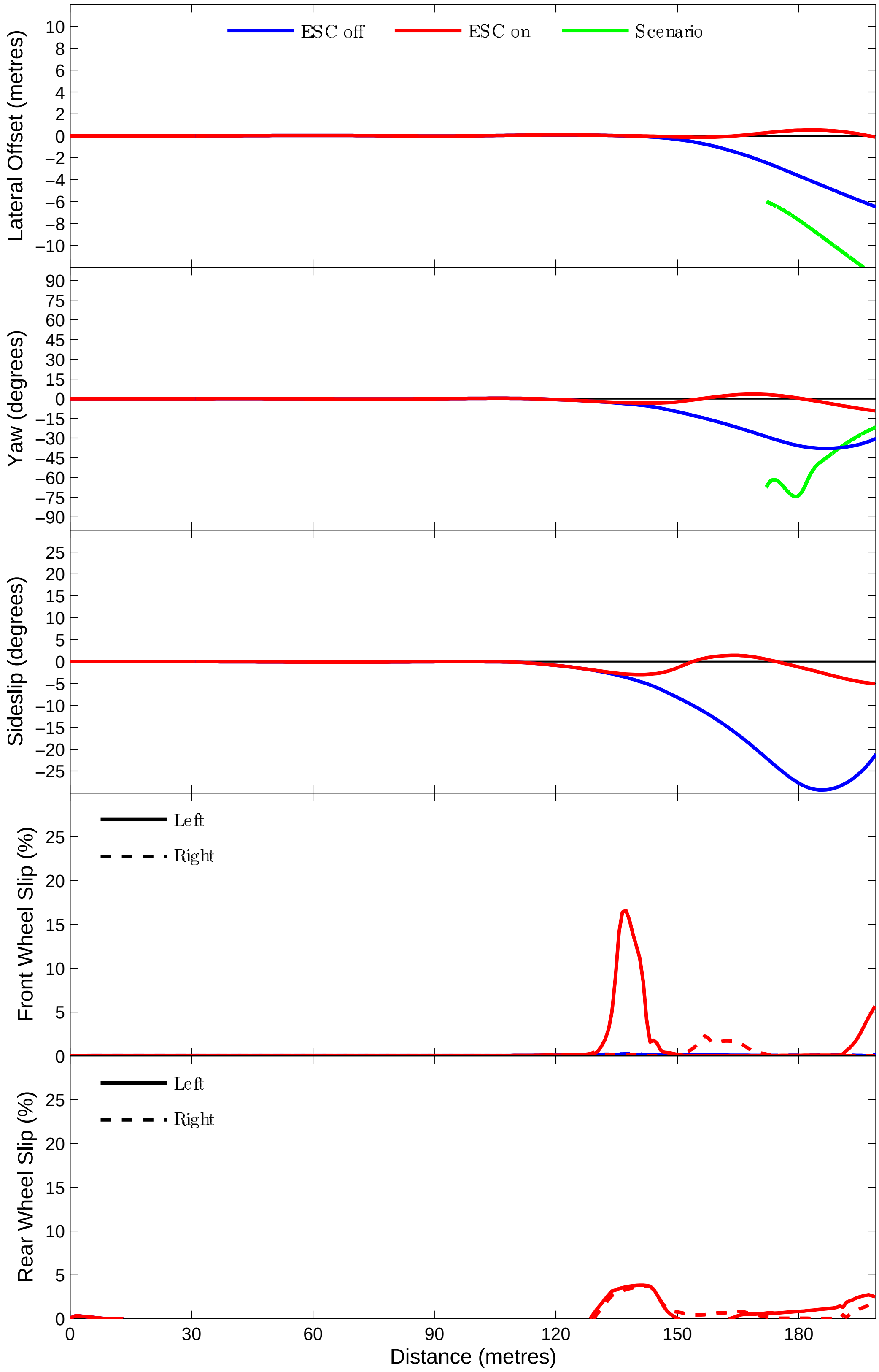


Fig. 7.18: Effect of ESC (representative value set 2, scenario 4)

7.2.5 Scenario 5

There were two different parameter sets simulated for Scenario 5. The trajectories of the simulated vehicles without ESC were similar, and were also similar to the scenario trajectory but with a slight positional offset. That is, the simulated loss of control occurred at an later point in the road compared to the scenario loss of control. Despite this, the lateral offset and yaw profiles of the simulated trajectories were approximately equivalent to the scenario trajectory. However, one feature that was not equivalent was that the scenario trajectory showed an initial lateral offset to the left which the simulated trajectories did not.

The simulation based on parameter set 1 (80 km/h) was considered to generate a non-ESC vehicle trajectory that best emulated the scenario trajectory (although with some positional offset as mentioned). When the same parameter set was used to simulate an ESC equipped vehicle there was a corresponding change in trajectory. The ESC equipped vehicle did not experience an excessive increase in yaw angle and had a lateral offset that did not continue to increase to the left at the end of the simulation. Despite the vehicle no longer having a lateral offset that increases at the end of the simulation, the trajectory showed that the vehicle would still have travelled some distance off the left side of the road. Some of this excursion to the left was likely caused by inappropriate driver model parameter values.

If Scenario 5 occurred with a vehicle equipped with ESC then these results suggest that a loss of control would have been avoided. The initial steer by the driver would still have caused the vehicle to travel onto the wrong side of the road but the driver would have maintained control and been able to steer back into the correct lane, possibly with some travel on the left roadside shoulder. Assuming there were no oncoming vehicles or object close to the left side of the road (as was the case in the scenario), no collision would have occurred.

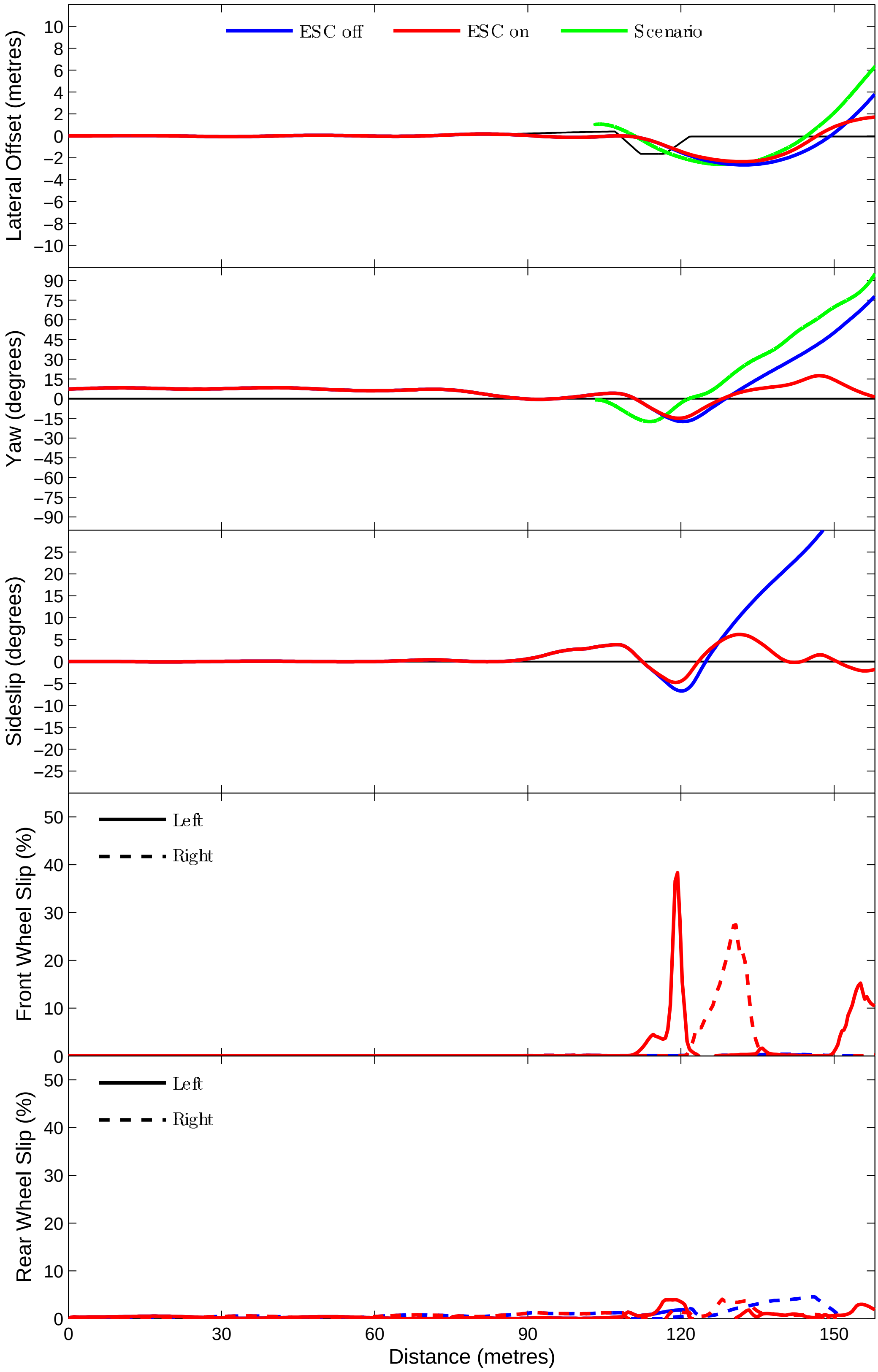


Fig. 7.19: Effect of ESC (representative value set 1, scenario 5)

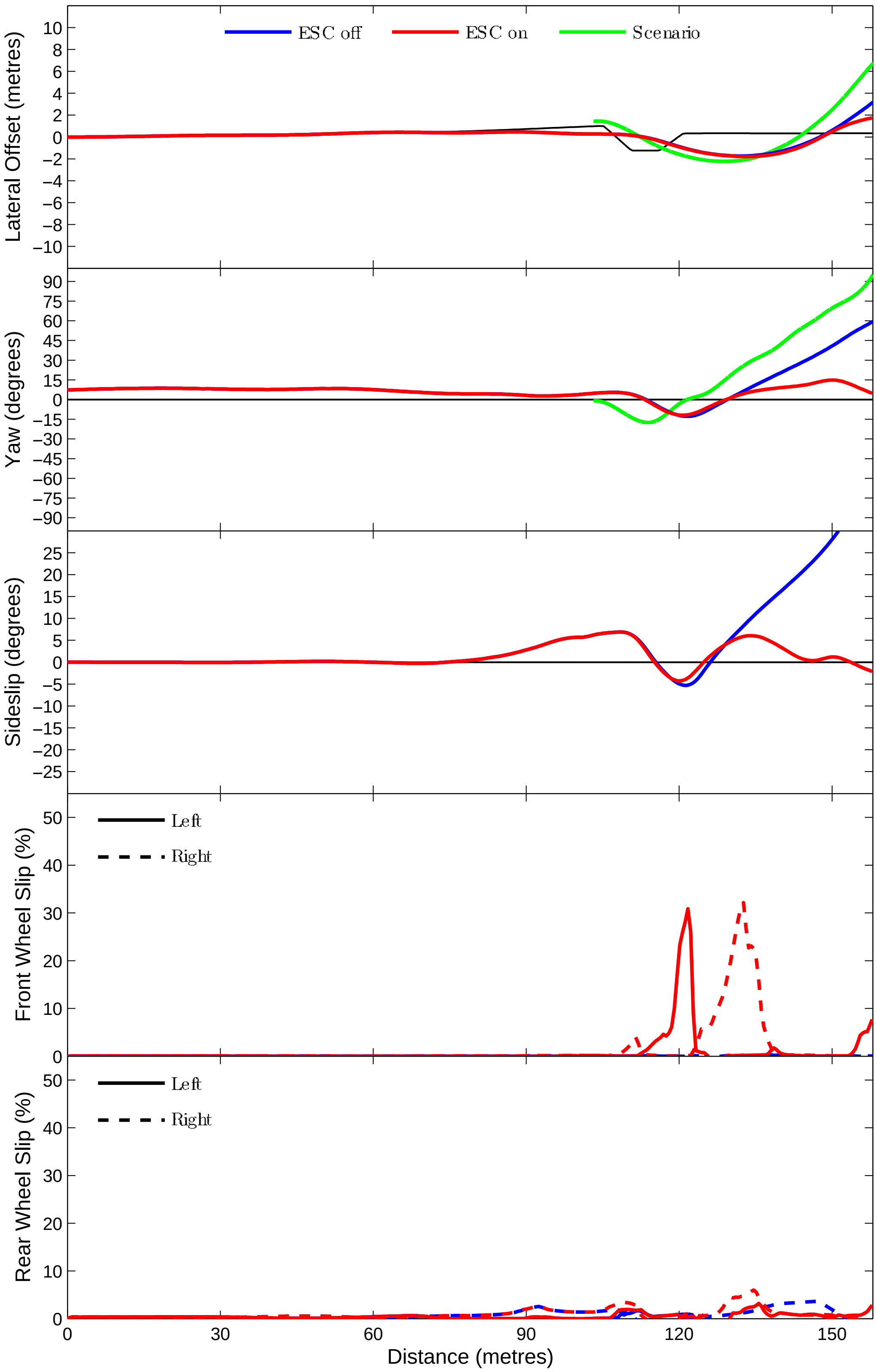


Fig. 7.20: Effect of ESC (representative value set 2, scenario 5)

7.2.6 Scenario 6

Scenario 6 was simulated with just one parameter set. The simulated trajectory of the vehicle without ESC was a little different to the scenario trajectory. The simulated trajectory consisted of two initial steering manoeuvres while there was just a single initial steering manoeuvre described in the scenario. Once the loss of control had occurred the simulated and scenario trajectories were generally similar, although there was slightly less lateral offset to the right in the simulated trajectory.

When the parameter set was used to simulate the ESC equipped vehicle the resulting trajectory was changed. The extreme levels of lateral offset and yaw were no longer observed. Similarly, the sideslip angle no longer increased to levels characteristic of a loss of control.

Given these changes it is suggested that no loss of control and no (or only very minor) deviation into the oncoming lane would have occurred if Scenario 6 involved a vehicle equipped with ESC. As such, a collision would have been avoided.

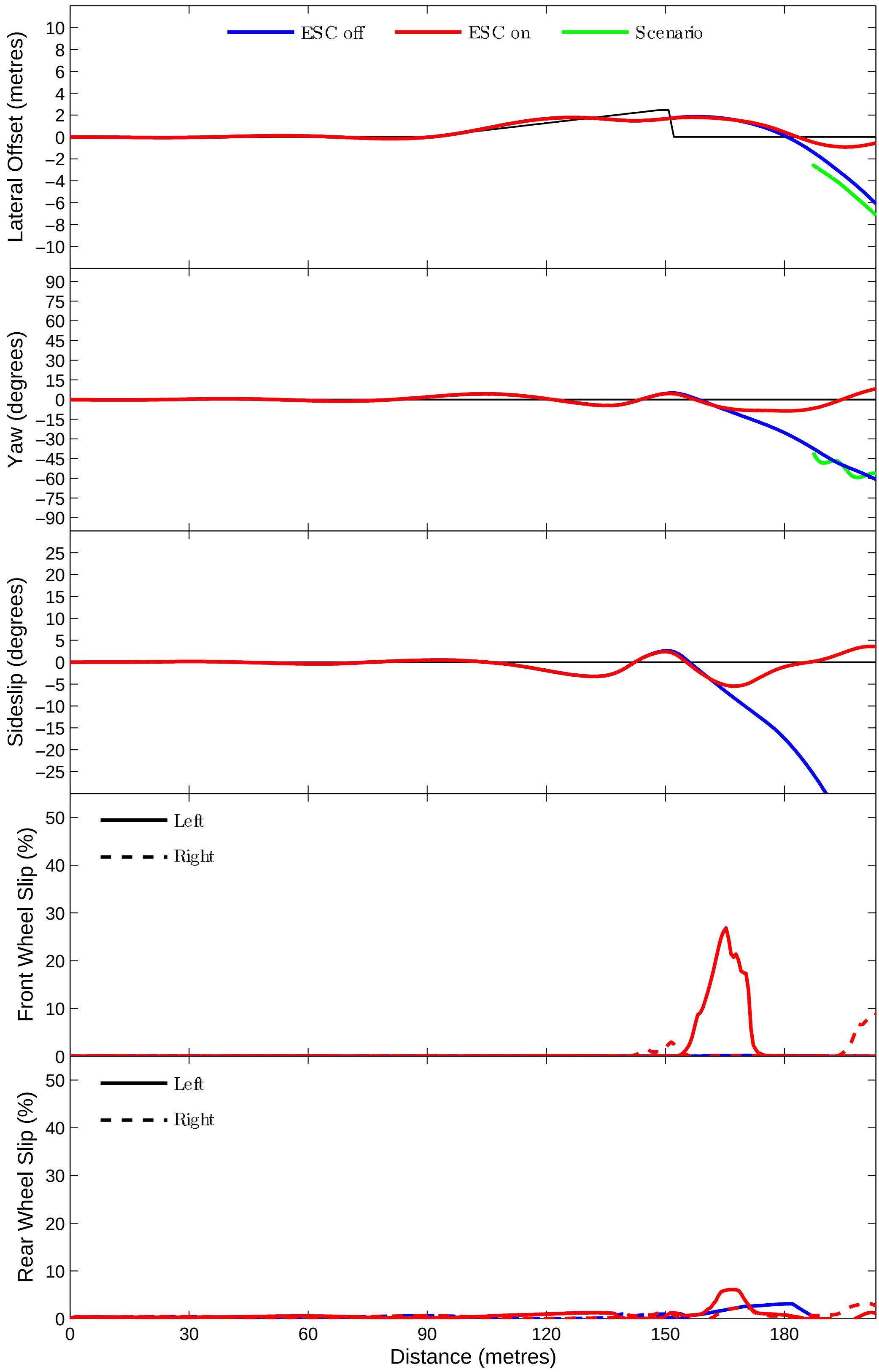


Fig. 7.21: Effect of ESC (scenario 6)

7.2.7 Scenario 7

Only one parameter set was used to simulated Scenario 7 and this generated a non-ESC equipped vehicle trajectory that matched well with the scenario trajectory.

After using the parameter set to simulate a vehicle with ESC a new trajectory was generated. The ESC equipped vehicle trajectory did not display the excessive increase in yaw and sideslip angle that was apparent in the non-ESC trajectory. Additionally, the lateral offset of the ESC equipped vehicle returned more quickly to the correct lane after the initial travel onto the wrong side of the road. Beyond the quick return to the correct lane there was some overshoot but this may have been due to inappropriate driver model parameter values.

It is expected from these results that if Scenario 7 had occurred with a vehicle equipped with ESC then there would have been no loss of control and no corresponding collision.

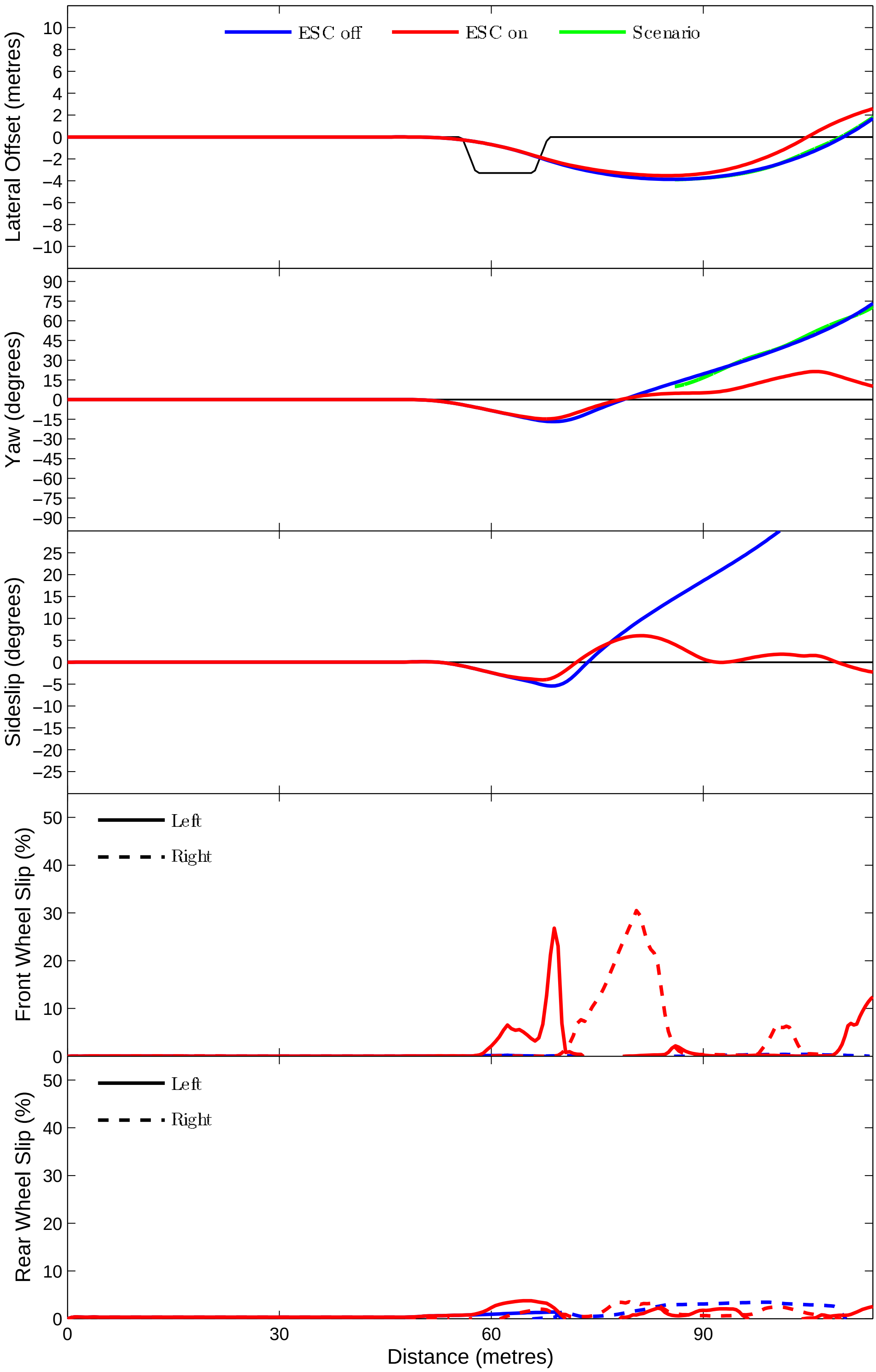


Fig. 7.22: Effect of ESC (scenario 7)

7.2.8 Scenario 8

Two parameter sets were used to simulate Scenario 8. The trajectory of the vehicle without ESC using the first parameter set (100 km/h) consisted of two initial steering manoeuvres before losing control through a third steering manoeuvre. Using the second parameter set (130 km/h), the trajectory of the vehicle without ESC consisted of only a single initial steering manoeuvre and had a lateral offset that matched well with the scenario trajectory. The match between the yaw angle was less accurate. The yaw angle in the scenario began to increase gradually and then changed to a more rapid increase while the simulated yaw angle from parameter set 2 simply showed a single constant increase.

The simulation based on parameter set 2 was considered to generate a non-ESC vehicle trajectory that best emulated the scenario trajectory (though with some defects with regards to yaw angle). When the same parameter set was used to simulate an ESC equipped vehicle the trajectory changed considerably. The sideslip and yaw angle no longer increased to excessive levels and the lateral offset showed a more gradual shift from left to right. This change in the lateral offset should have enabled a typical driver to return their vehicle to the road in a controlled manner.

Based on these results it is expected that had Scenario 8 occurred with a vehicle equipped with ESC then no loss of control would have occurred and there would no longer have been any type of collision.

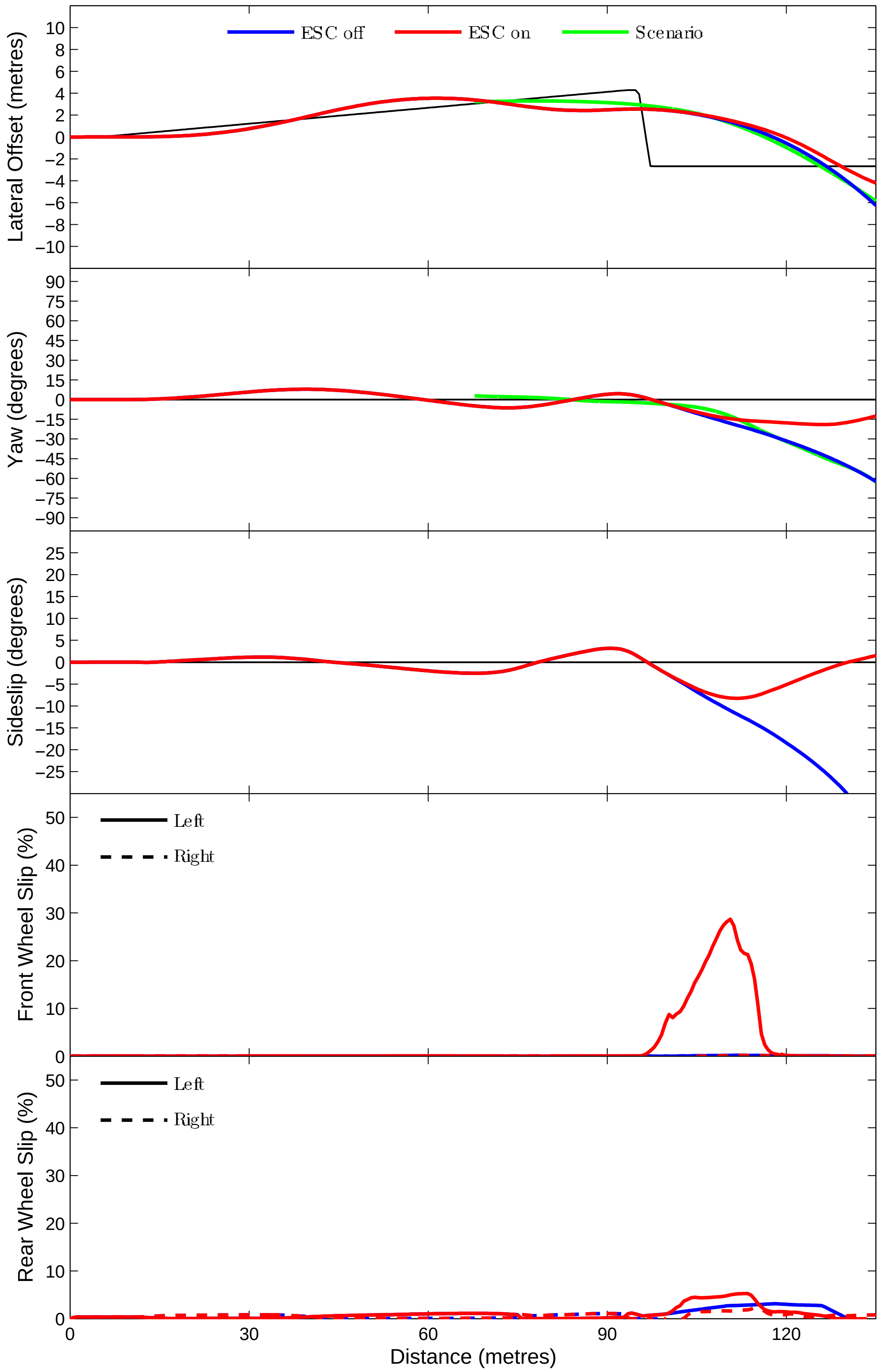


Fig. 7.23: Effect of ESC (representative value set 1, scenario 8)

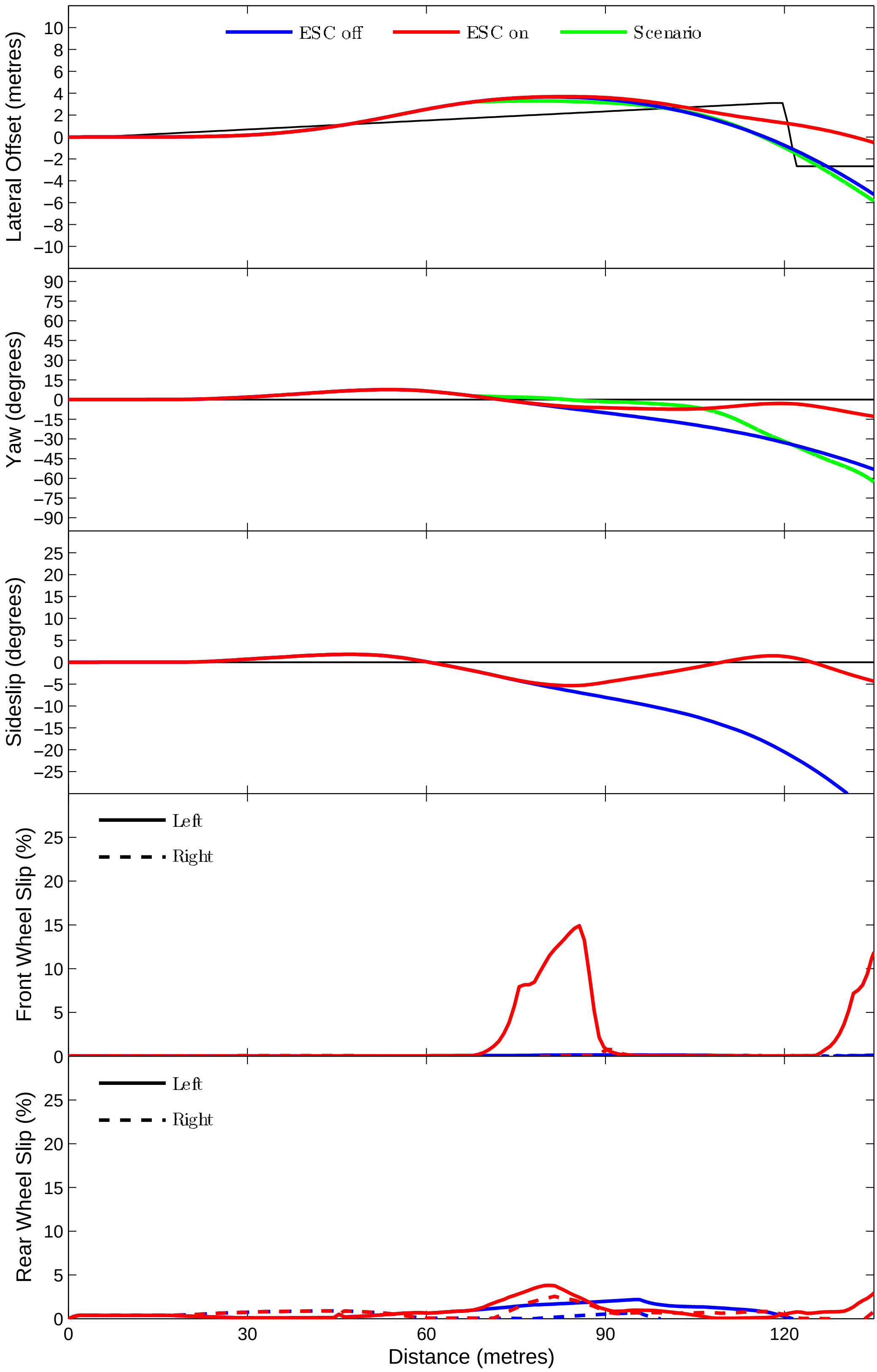


Fig. 7.24: Effect of ESC (representative value set 2, scenario 8)

7.2.9 Scenario 9

Just a single parameter set was used to simulate Scenario 9. The non-ESC trajectory generated from this parameter set displayed a yaw angle that matched well with the scenario but a lateral offset that peaked slightly more to the left. This would have resulted in the simulated vehicle spending more time on the unsealed shoulder.

When the parameter set was used to simulate a vehicle with ESC there was a definitive change in the trajectory. There was no longer an excessive increase in the sideslip and yaw angle. Additionally, the lateral offset showed a more gradual return to the road but then still continues past the original lane of travel and into the right lane (and even beyond onto the median). The size of this overshoot would likely be mitigated with more appropriate driver model parameter values. Regardless, the road was divided and so some controlled deviation into the right lane would not have put the vehicle into any significant danger of crashing (assuming the right lane was unoccupied, as was the case in the scenario).

From these results it would be expected that a vehicle fitted with ESC would not have lost control during Scenario 9. The vehicle may have travelled somewhat into the right lane but, in the absence of other errant vehicles, no collision would have occurred.

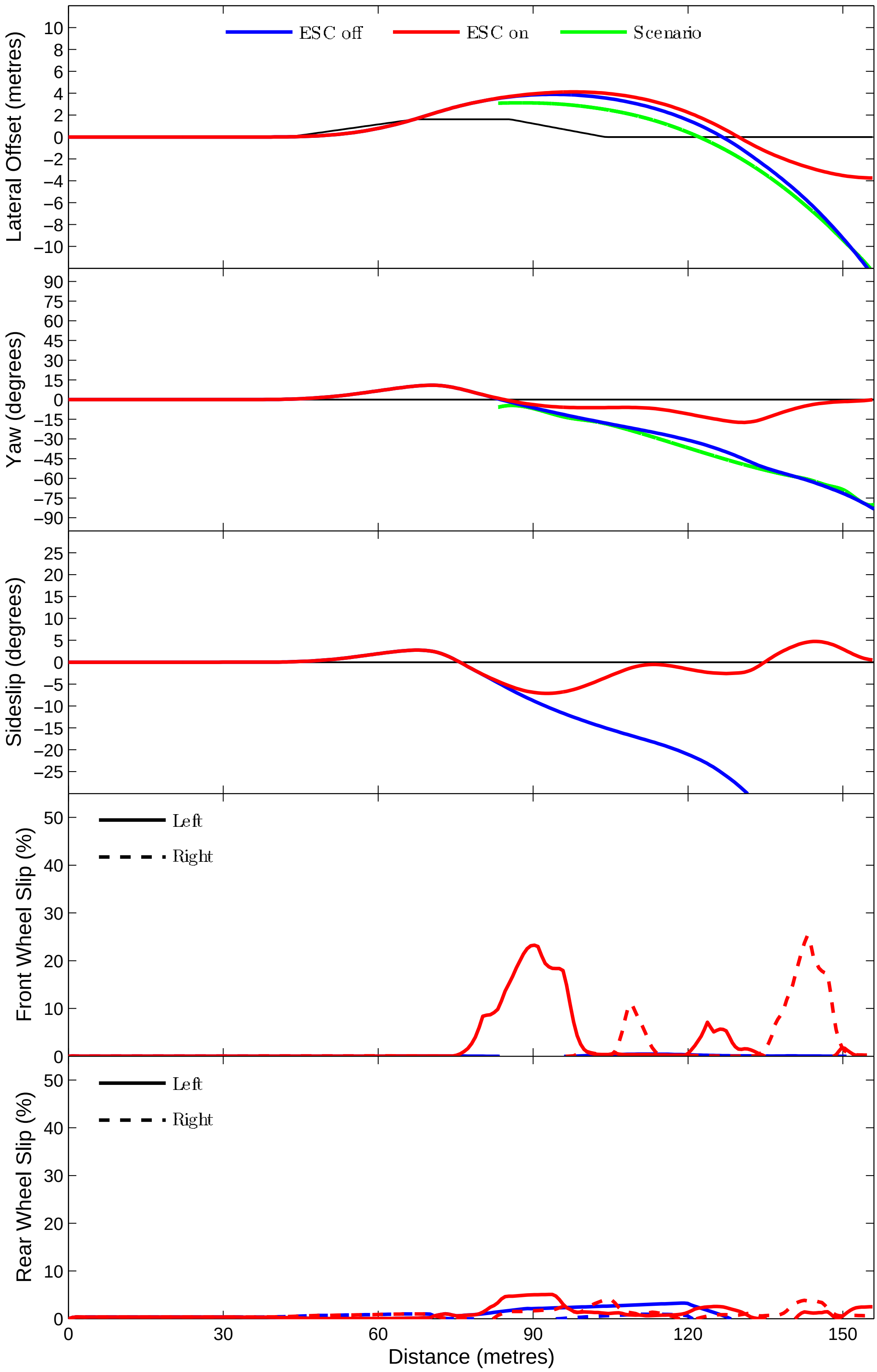


Fig. 7.25: Effect of ESC (scenario 9)

7.2.10 Scenario 10

The single parameter set that was used to simulated Scenario 10 generated a non-ESC trajectory that somewhat matched the scenario trajectory. The lateral offset of the simulated trajectory peaked further to the left than the scenario and this would have resulted in the non-ESC vehicle spending a greater amount of time on the roadside shoulder. There was also some differences in the yaw angle. As in Scenario 8, the yaw angle for the scenario showed a gradual increase which then changed to a more rapid increase. However, the simulated yaw angle simply showed a single constant increase.

After using the same parameter set to simulate a vehicle equipped with ESC the trajectory was different. The lateral offset shifted more quickly back towards the lane of travel, continued into the oncoming lane and then onto the right roadside shoulder. However, this overshoot was likely caused or at least exacerbated by inappropriate driver model parameter values. Both the sideslip and yaw angle were also altered and no longer increased to extreme levels.

Given the trajectory changes resulting from the addition of ESC to the vehicle, it is suggested that there would not have been a loss of control during Scenario 10 had an ESC equipped vehicle been involved. The possibility of some lateral deviation into the oncoming lane cannot be ruled out, but in the absence of an oncoming vehicle no collision would have occurred.

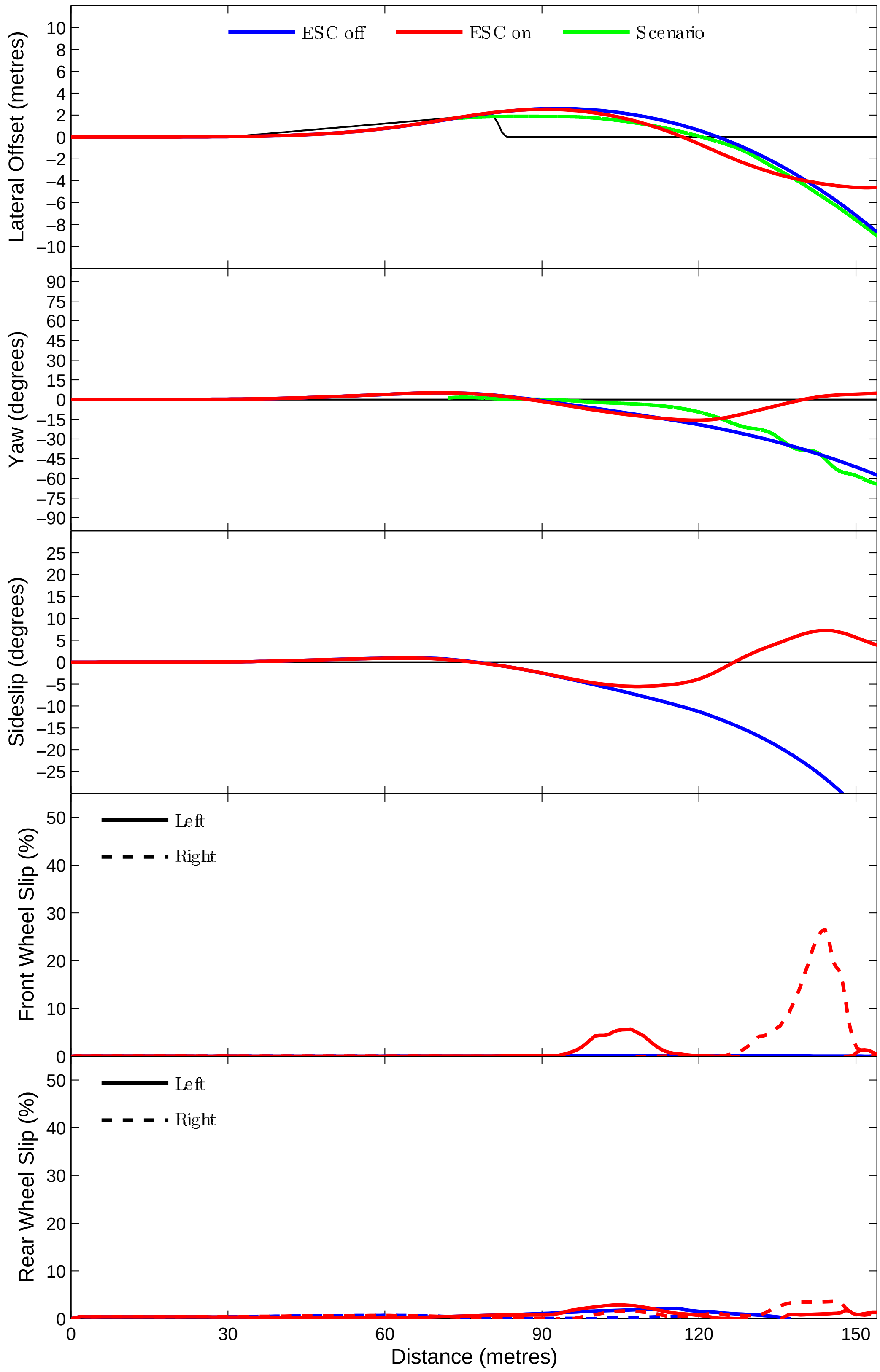


Fig. 7.26: Effect of ESC (scenario 10)

7.2.11 Summary of effects of ESC

The addition of ESC was able to prevent the simulated rear wheel drive vehicle from losing stability and entering a yaw in all of the scenarios. In nine of the scenarios this was likely to have resulted in the complete avoidance of a collision. However, in Scenarios 3, 5, 7, 9, and 10 there was still a degree of lateral offset beyond the edge of the vehicle's driving lane. Apart from Scenario 3, these instances of lateral offset appeared innocuous for the specific circumstances of the scenarios in which they occurred, although they would have had the potential to lead to collisions if other vehicles, roadside objects, or pedestrians were present. In Scenario 3, another vehicle was travelling in the oncoming lane and some interaction with this vehicle was likely to have occurred. A collision was still considered likely to have occurred in Scenario 2 but with a frontal impact rather than a side impact.

Table 7.5 presents a summary of the effects of ESC in each scenario. The maximum lateral offset, maximum yaw, and maximum sideslip that was achieved by the vehicle with and without ESC is presented. When comparing the maximum values with and without ESC it is important to remember the issues with the driver model parameter values that were mentioned in the introduction of Section 7.2. That is, the driver model parameter values may not be appropriate past the first intervention which may result in excessive lateral offset or yaw. In addition, note that the maximum values with and without ESC in each scenario are not necessarily representative of the same point in the vehicle's trajectory.

The relationship between the maximum values of lateral offset, yaw, and sideslip for simulations with and without ESC are shown in Figures 7.27 to 7.29 where the data from Table 7.5 has been plotted on axes with equivalent scales. It can be seen that, except for one instance (where maximum lateral offset was increased), there was a decrease in maximum lateral offset, yaw, and sideslip after the addition of ESC.

The goal of ESC, as was outlined in Section 2.3, is to limit the amount of sideslip to within a certain threshold and this effect can clearly be seen in Figure 7.27. Without ESC the average maximum sideslip was 39.8 degrees ($\sigma = 12.9$). After the addition of ESC the average maximum sideslip was reduced to 6.0 degrees ($\sigma = 1.2$).

In Section 6.2 it was explained that the Bosch vehicle and ESC models were de-identified and encrypted. While the RWD ESC model was validated as operating satisfactorily, there were no details provided on how it was tuned. That is, what amount of sideslip the ESC system was programmed to allow before eliciting a braking intervention. The results observed here, where average maximum sideslip was reduced to six degrees with only a small amount of variance, provide some indication of how the RWD ESC model was tuned. However, in the absence of results from other ESC systems for comparison, it is not possible to determine if the RWD ESC model tuning should be considered typical, harsh (applies interventions early), or loose (applies interventions late).

The reductions in maximum lateral offset and yaw were an expected, and desired, consequence of the reduction in maximum sideslip brought about by ESC. Maximum lateral offset was reduced from an average of 7.0 metres ($\sigma = 3.0$) to 3.2 metres ($\sigma = 1.5$). Maximum yaw was reduced from an average of 58.3 degrees ($\sigma = 16.6$) to 13.4 degrees ($\sigma = 4.6$).

It can be seen that, further to the reductions in the mean values, the addition of ESC also resulted in a reduction of the variance in the maximum lateral offset, yaw, and sideslip observed during each simulated loss of control scenario. It is worth noting that the size of this reduction in variance was much greater for maximum sideslip compared to the maximum lateral offset and yaw. The variance of the maximum sideslip was reduced by a factor of 10.75 (12.9/1.2), while the variance in the maximum lateral offset and yaw were reduced by factors of 2.00 (3.0/1.5) and 3.61 (16.6/4.6) respectively.

There are several explanations for the greater amount of variability in the maximum lateral offset and yaw results. The first is that the different circumstances in each scenario mean there is a differing requirement for various amounts of yaw and lateral offset. For example, in one situation a driver may be attempting to increase yaw and lateral offset to avoid an object, while in a different situation a driver may have drifted off the road and be attempting to return to a more neutral lateral offset without any yaw. These two types of loss of control recovery would both benefit from a reduction in sideslip but would elicit different levels of lateral offset and yaw.

Another explanation that cannot be discounted is that the issues with the appropriateness of the driver model parameters for the simulations with ESC may have caused additional variability in the maximum lateral offset and yaw.

The method used to define lateral offset may also have affected the variance of that variable specifically. Since lateral offset is defined relative to the centre of the driving lane, both a curve in the road and a laterally shifting vehicle can cause a change in the observed lateral offset. Thus, some of the variability in the maximum lateral offset may be due to variability in the curvature of the roads in each of the scenarios.

Finally, some of the variability may be the result of the differences in speed during each scenario. To further explore this possibility, the relationship between the maximum values of lateral offset, yaw, and sideslip and the initial travelling speed was investigated. The maximum sideslip, lateral offset, and yaw achieved during the simulations with and without ESC are shown relative to the initial simulation speed in Figures 7.30 to 7.32. In each figure trend lines were fitted to the data points corresponding to simulations with ESC.

As was shown earlier, the maximum sideslip with ESC was reduced to an average of 6.0 degrees with little variance. There did not appear to be any relationship between maximum sideslip and initial speed as indicated by the poor goodness of fit for the trend line in Figure 7.30. A similar non-relationship was found for maximum lateral offset and initial speed, shown in Figure 7.31. The fitted trend line indicated an increase in maximum lateral offset as initial speed increased but the goodness of fit for this line was poor. There was evidence for a relationship between maximum yaw and initial speed, however. Figure 7.32 shows that as initial speed increases the maximum yaw decreases.

The reduction in maximum yaw at higher initial speeds is probably related to the fact that understeer is more likely at higher speeds. In Section 3.3 it was noted that in critical situations ESC systems prioritise the mitigation of oversteer at the expense of understeer. As a result of this prioritisation it would be expected that excessive sideslip angle would be reduced at the expensive of steerability; that is the vehicle would be more likely to maintain its initial heading or plough straight ahead.

This expectation is consistent by the findings presented in this section. The addition of ESC resulted in large reductions in maximum sideslip and associated reductions in maximum lateral offset and yaw, with the reductions in maximum yaw being greater at higher speeds (ostensibly due to an increase in understeer).

Tab. 7.5: Summary of the effects of ESC during the simulation of the representative value sets associated with each loss of control scenario

Simulation	Max. lateral offset (m)		Max. yaw (deg.)		Max. sideslip (deg.)	
	without ESC	**with ESC**	**without ESC**	**with ESC**	**without ESC**	**with ESC**
Scenario 1 (set 1)	11.7	5.7	50.5	10.2	28.8	6.2
Scenario 1 (set 2)	9.7	5.4	46.1	9.5	27.5	6.0
Scenario 1 (set 3)	9.9	2.8	76.3	12.1	55.8	6.7
Scenario 1 (set 4)	7.8	2.3	74.9	5.8	62.0	3.2
Scenario 2	5.1	4.3	27.7	12.2	16.3	5.8
Scenario 3	3.1	3.2	44.7	18.8	27.9	6.6
Scenario 4 (set 1)	7.3	0.8	39.6	9.1	30.5	4.2
Scenario 4 (set 2)	6.5	0.5	37.9	9.3	29.3	5.1
Scenario 5 (set 1)	4.0	2.3	78.7	17.5	52.7	6.2
Scenario 5 (set 2)	2.9	2.1	59.9	14.9	44.3	6.9
Scenario 6	6.3	1.8	61.4	8.6	42.3	5.5
Scenario 7	3.9	3.5	75.9	21.4	53.5	6.1
Scenario 8 (set 1)	6.4	4.3	63.4	19.0	39.1	8.3
Scenario 8 (set 2)	5.4	3.7	53.9	13.1	35.8	5.4
Scenario 9	12.8	4.1	83.6	17.4	52.8	7.1
Scenario 10	8.9	4.6	58.5	15.8	38.5	7.3

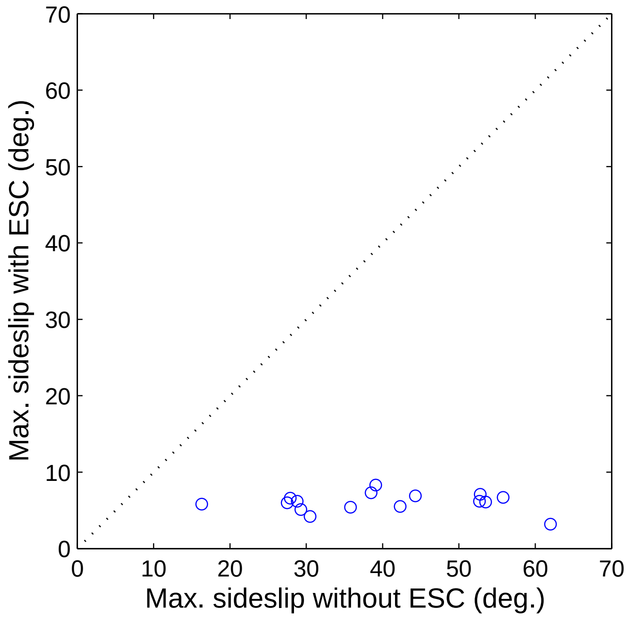


Fig. 7.27: Relationship between maximum sideslip for simulations with and without ESC

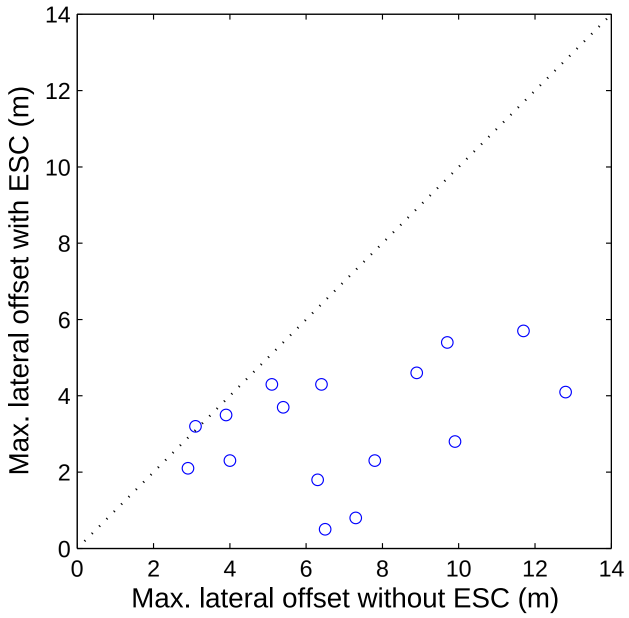


Fig. 7.28: Relationship between maximum lateral offset for simulations with and without ESC

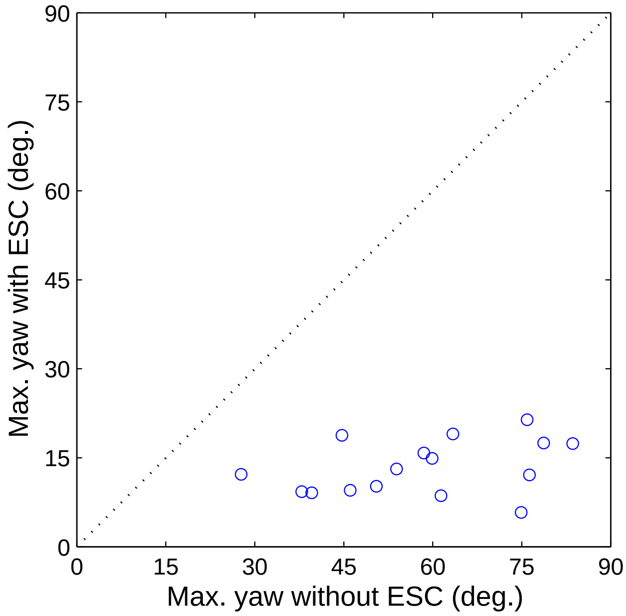


Fig. 7.29: Relationship between maximum yaw for simulations with and without ESC

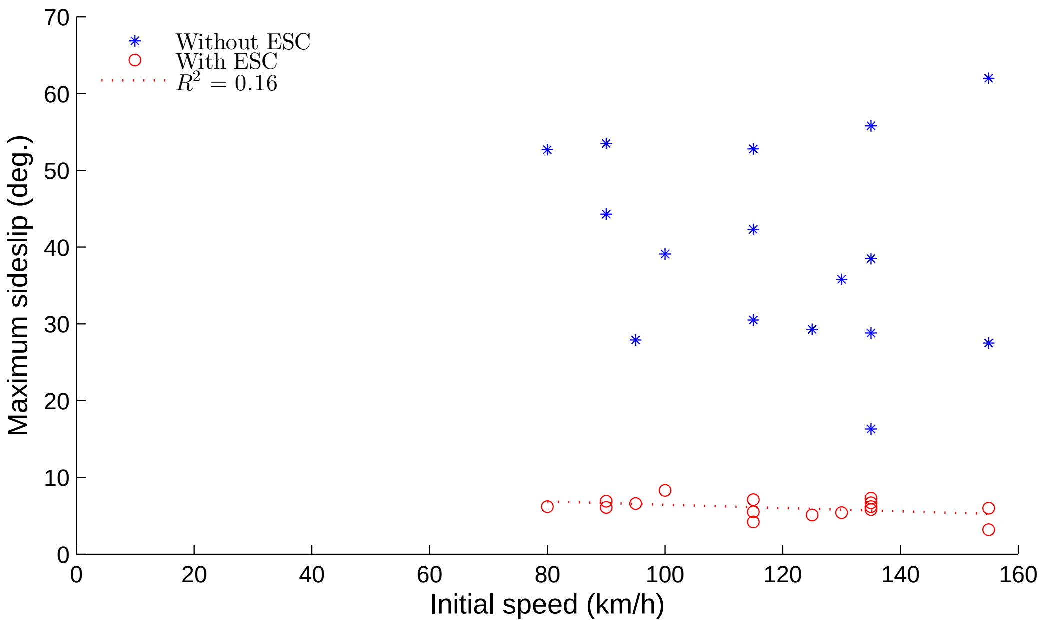


Fig. 7.30: Maximum sideslip at various initial speeds both without and with ESC

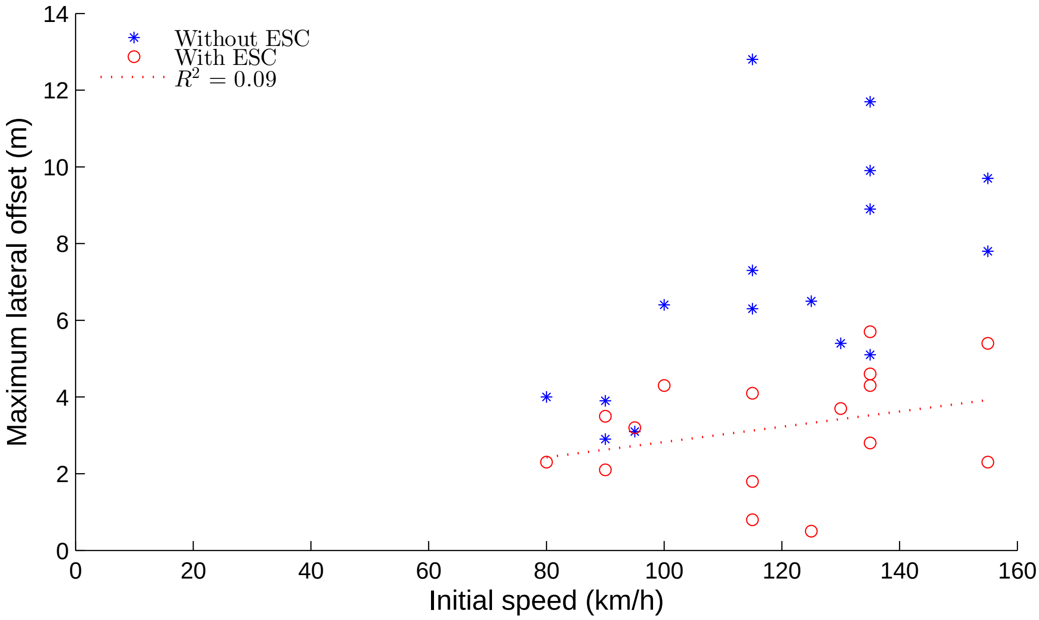


Fig. 7.31: Maximum lateral offset at various initial speeds both without and with ESC

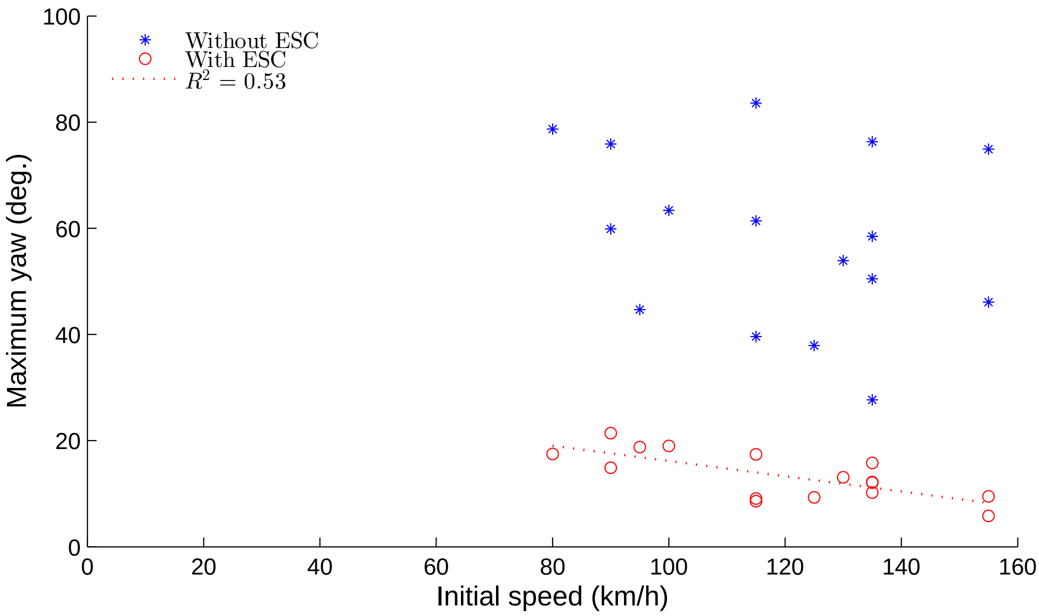


Fig. 7.32: Maximum yaw at various initial speeds both without and with ESC

7.3 Interaction between ESC and other rural road safety measures

Two road safety measures commonly used to reduce loss of control crashes on high speed rural roads are reduced speed limits and roadside shoulder sealing (or the sealing of unsealed roads). Further simulations were run to explore how the actions of ESC are affected by these rural road safety measures. The loss of control scenario simulations were run again with some parameters of the representative value sets altered to emulate the rural road safety measures. The altered parameter values that were used to emulate each of these rural road safety measures are shown in Table 7.6. A lower speed limit was emulated by a reduction in the simulation initial speed of five kilometres per hour and an increase in coefficient of friction was used to emulate a sealed road or roadside shoulder.

Tab. 7.6: Variables altered for emulation of various road safety features

Safety measure	Parameter	Altered value
Slower travelling speed	Initial speed	-5 km/h
Sealed shoulder	Shoulder friction	0.7 (dry), 0.6 (wet)
Sealed road	Road friction	0.7 (dry), 0.6 (wet)

The results of the altered parameter simulations are presented in figures (see Appendix C) which show the trajectory, sideslip angle, and the slip at each wheel for the ESC equipped and non-ESC equipped vehicle models in a similar manner to the figures presented in Section 7.2. However, the reliability of the results shown in these altered parameter figures is questionable and caution is advised in their interpretation. It was mentioned in the introduction to Section 7.2 that the reliability of the simulation results can degrade beyond the initial ESC braking intervention if the selected driver model parameter values become inappropriate for the new vehicle trajectory. This remains a factor to be considered but the altering of parameters to emulate rural road safety measures has further implications for the reliability of the simulations. Any changes to the representative set of parameter values will effect the trajectory of the vehicle and thus the steering behaviour of the driver model. As a result, the selected values of preview time and lag time for the driver model may no longer be appropriate for the circumstances of the scenario and the steering response may become unrealistic or erratic. Additionally, the original circumstances of some scenarios may no longer be reasonable. For example, a driver who steered excessively back towards the road after drifting onto the unsealed shoulder may not react in the same way when drifting onto a sealed shoulder.

Because of these potential inaccuracies in the results there was little value in an in-depth analysis of the effect that ESC had on vehicle trajectory for the simulations with the altered parameter sets; it would not be possible to differentiate which trajectory changes were due to the rural road safety measures and which were the result of inappropriate driver model parameter values.

8. INVESTIGATING THE INTERVENTIONS MADE BY ESC DURING LOSS OF CONTROL SCENARIOS

The effectiveness of ESC in altering vehicle trajectories and avoiding collisions was explored in Chapter 7. In order to generate these changes in vehicle trajectory, the ESC system utilises controlled and targeted braking interventions. This chapter investigates what braking interventions were made during each of the simulated scenarios and then presents an analysis of braking intervention characteristics.

In Section 8.1 the major braking interventions in each scenario simulation are summarised in tables that show which wheels were braked, the peak value of slip achieved, and the duration of the intervention. Then, in Section 8.2, the characteristics of the major interventions are discussed and compared to the major interventions elicited during the sine with dwell test manoeuvre.

8.1 Summary of major ESC interventions

When analysing the graphs of wheel slip from the figures presented in Section 7.2, the precise definition for a single braking intervention is not immediately clear. The ESC system may apply and then continuously adjust the amount of wheel slip at each wheel and this makes it difficult to quantify individual interventions. However, a definitive number of major interventions were identified in each simulation by applying a threshold. A major intervention was defined as any increase in wheel slip where a peak value of at least five per cent was achieved. The start and end of the intervention were then defined as the points either side of the peak where the wheel slip was equal to five per cent.

The major braking interventions that were elicited during the simulation of each representative value set using the ESC equipped vehicle model are presented below in Tables 8.1 and 8.2 that list at which wheel the intervention was applied, the peak value of slip achieved, and the duration of the intervention (in seconds).

Table 8.3 lists the major interventions made during each run of the sine with dwell test manoeuvre that was performed during the vehicle model validation in Section 6.2. These can be compared to the interventions during the scenario simulations (Tables 8.1 and 8.2).

Tab. 8.1: Major ESC interventions for RWD vehicle model during loss of control scenario simulations (part 1)

Simulation	#	Wheel	Peak slip (%)	Duration (s)
Scenario 1 (set 1)	1	Front right	7.3	0.26
Scenario 1 (set 2)	1	Front right	5.4	0.12
	2	Front left	7.1	0.18
Scenario 1 (set 3)	1	Front right	9.7	0.26
	2	Front left	15.9	0.36
Scenario 1 (set 4)	——no major interventions——			
Scenario 2	1	Front left	14.2	0.53
	2	Front right	38.2	0.29*
	3	Front left	23.1	0.27*
	4	Front right	7.9	0.23*
	5	Front left	6.5	0.14*
Scenario 3	1	Front right	12.0	0.38
	2	Front right	5.1	0.02
	3	Front right	9.4	0.17
	4	Front right	10.9	0.28
	5	Front right	15.7	0.38
Scenario 4 (set 1)	1	Front left	18.1	0.32
Scenario 4 (set 2)	1	Front left	16.7	0.25
	2	Front left	6.3	0.05*

* intervention truncated due to termination of simulation run

Tab. 8.2: Major ESC interventions for RWD vehicle model during loss of control scenario simulations (part 2)

Simulation	**#**	**Wheel**	**Peak slip (%)**	**Duration (s)**
Scenario 5 (set 1)	1	Front left	39.1	0.20
	2	Front right	28.1	0.64
	3	Front left	15.3	0.42*
Scenario 5 (set 2)	1	Front left	30.9	0.23
	2	Front right	32.4	0.63
	3	Front right	6.0	0.11
	4	Front left	8.5	0.10*
Scenario 6	1	Front left	26.9	0.57
	2	Rear left	6.1	0.23
	3	Front right	9.3	0.25
Scenario 7	1	Front left	6.6	0.14
	2	Front left	26.9	0.14
	3	Front right	30.6	0.64
	4	Front right	6.8	0.16
	5	Front left	13.0	0.27
Scenario 8 (set 1)	1	Front left	28.7	0.69
	2	Rear left	5.3	0.15
Scenario 8 (set 2)	1	Front left	14.9	0.41
	2	Front left	12.6	0.15*
Scenario 9	1	Front left	23.3	0.68
	2	Rear left	5.1	0.16
	3	Front right	11.0	0.17
	4	Front left	7.1	0.19
	5	Front right	25.3	0.55
Scenario 10	1	Front left	5.7	0.13
	2	Front right	26.7	0.49

* intervention truncated due to termination of simulation run

Tab. 8.3: Major ESC interventions for RWD vehicle model during sine with dwell test at various maximum steering wheel amplitudes

Amplitude	**#**	**Wheel**	**Peak slip (%)**	**Duration (s)**
1.5A (44.85°)		———no major interventions———		
2.0A (59.80°)		———no major interventions———		
2.5A (74.75°)		———no major interventions———		
3.0A (89.70°)		———no major interventions———		
3.5A (104.65°)	1	Front left	14.2	0.31
4.0A (119.60°)	1	Front left	24.9	0.36
4.5A (134.55°)	1	Front left	5.0	0.01
	2	Front left	30.5	0.47
5.0A (149.50°)	1	Front left	5.4	0.05
	2	Front left	31.9	0.60
5.5A (164.45°)	1	Front left	35.8	0.78
6.0A (179.40°)	1	Front left	37.8	0.91
6.5A (194.35°)	1	Front left	5.1	0.01
	2	Front left	41.4	0.88
7.0A (209.30°)	1	Front left	41.7	0.96
7.5A (224.25°)	1	Front left	41.8	0.96
8.0A (239.20°)	1	Front left	5.5	0.03
	2	Front left	41.1	1.00
8.5A (254.15°)	1	Front left	5.4	0.03
	2	Front left	40.8	0.96
9.0A (269.10°)	1	Front left	41.8	0.95
9.5A (284.05°)	1	Front left	41.4	0.90

8.2 Analysis of major interventions

This section presents an analysis the major braking interventions that were summarised in Tables 8.1 to 8.3. First, some general comments are made about the major interventions elicited during the scenario simulations. General comments are then made about the major interventions elicited during the sine with dwell test manoeuvre. Next, a discussion of the characteristics of major ESC braking interventions is provided. This discussion includes a comparison of the characteristics of the interventions made during the scenario simulations to those made during the sine with dwell test. The effect that initial speed had upon the characteristics of the initial major braking intervention of each simulation is then explored. Finally, the findings of the analysis are summarised and discussed.

8.2.1 Major interventions during loss of control scenario simulations

Most of the major interventions were applied at the front wheels. The effect that these front wheel interventions had on vehicle trajectory was as expected based on the operation of ESC that was detailed in Section 2.3. That is, an intervention at the front left wheel mitigated oversteer to the right and an intervention at the front right wheel mitigated oversteer to the left.

During some simulations it was common for braking interventions at one of the front wheels to reduce the lateral steering force enough to cause the vehicle to experience some amount of understeer. It was noted in Section 7.2.11 that as initial simulation speed increased, there was a increase in the propensity for the ESC equipped vehicle to understeer; indicated by an increase in maximum lateral offset and a decrease in maximum yaw. A qualitative assessment of each simulation (that included viewing the simulation animations) determined that those simulations with initial speeds of 100 km/h or above showed obvious signs of understeer as a result of front wheel ESC braking interventions.

The peak value of slip achieved by each major intervention varied between 5.1 and 39.1 per cent, while the duration varied between 0.12 and 0.68 seconds. It was not immediately obvious which circumstances elicited an intervention with a particular set of characteristics (percentage of peak slip and duration) due to the dynamic way in which braking interventions manipulate vehicle trajectory. As detailed in Section 2.3, an intervention will create a negative longitudinal force as well as reduce any lateral force at the wheel to which it is applied. Thus, depending on the dynamic state of the vehicle, a powerful intervention, with a high peak slip and/or long duration, may result in only a minor change in trajectory. Conversely, a weak intervention may cause a significant change in vehicle trajectory.

8.2.2 Major interventions during the sine with dwell test manoeuvre

During the first four runs through the sine with dwell test manoeuvre no major interventions were observed. From the fifth run onwards, interventions were observed at the front left wheel. In some runs there was only a single intervention and in others there were two; a smaller intervention followed almost immediately by a larger one. From the fifth run onwards the peak value of slip increased steadily until run eleven, and then remained fairly constant at about 41% for the remaining runs. The maximum peak slip of

41.8% was achieved during the thirteenth run as well as the sixteenth run. From the fifth to the fourteenth run, the duration of the larger intervention applied in each run increased from 0.31 seconds to a maximum of 1.00 second. The duration of the larger intervention then decreased to 0.90 seconds over the course of the remaining runs.

The yaw rate response of the rear wheel drive vehicle to the ESC interventions elicited during the sine with dwell test was presented in Figure 6.15. In this figure understeer can be identified as a reduction in yaw rate prior to the completion of the steering input which occurs at 1.93 seconds. It may be observed that this definition of understeer is fulfilled at steering amplitudes of $3.5A$ (run 5) or greater. However, if the qualitative method of detecting understeer (utilised in the scenario simulations above) was used then it was not until steering amplitudes of $5.5A$ (run 9) or more that overt understeer was observed.

8.2.3 Characteristics of initial major interventions

A linear relationship exists between the amount of peak slip and the duration of the interventions elicited during the loss of control scenarios as well as the sine with dwell tests. That is, interventions with longer durations also tended to have a higher peak slip.

The relationship between the peak slip and duration of initial major braking interventions is shown in Figure 8.1. Only the initial major interventions were selected as the later interventions are less meaningful due to the issues regarding the legitimacy of driver model parameters (as was discussed in Section 7.2). Fifteen initial major interventions were identified during the loss of control simulations and thirteen were identified during runs of the sine with dwell test manoeuvre.

The characteristics of the interventions associated with the scenario simulations appear consistent with those associated with the sine with dwell test, in that there was a positive relationship between intervention peak slip and duration. However, there was some disparity caused by several scenario interventions that had a short duration and large peak slip; interventions of this type were not elicited during the sine with dwell test.

In investigating potential reasons for this disparity it was found that only simulations that did not display obvious signs of understeer (i.e. those with an initial speed below 100 km/h) elicited interventions with a short duration and large peak slip. If these simulation interventions are omitted then the remaining scenario interventions correlate well with the interventions elicited

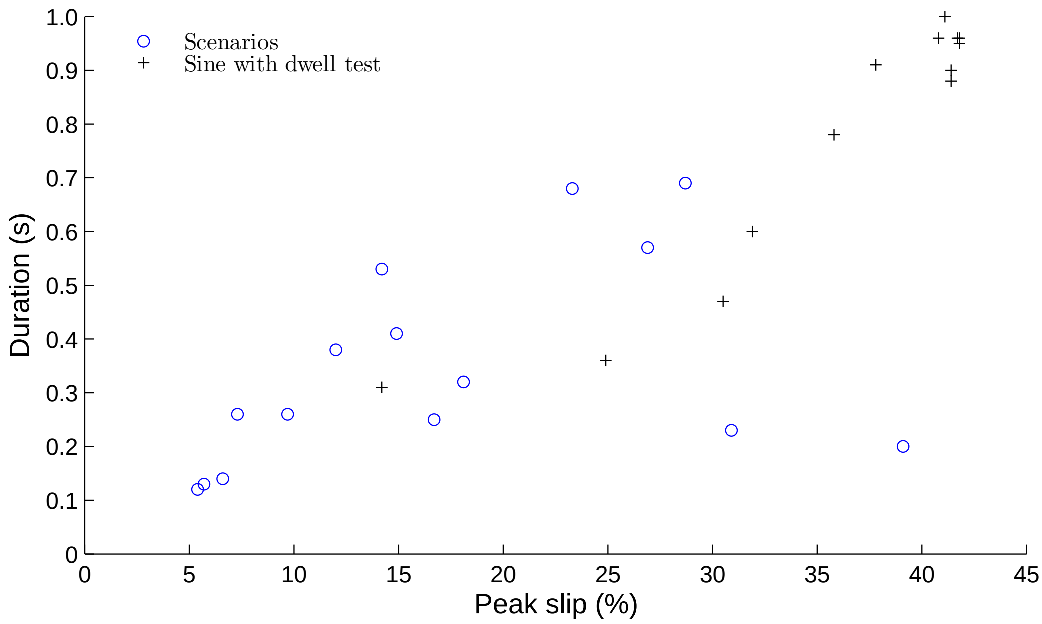


Fig. 8.1: Characteristics of initial major braking interventions

during the sine with dwell test. This is shown in Figure 8.2, where the interventions associated with the sine with dwell test are located in close proximity to a trend line fitted to the interventions of scenario simulations that showed obvious signs of understeer. This correlation is interpreted as a good indication that the interventions elicited during the sine with dwell test manoeuvre are representative of the interventions that are made during typical loss of control scenarios on high speed roads in circumstances where there is sufficient potential instability to necessitate an ESC response that results in understeer.

The interventions associated with the scenario simulations that did not show obvious signs of understeer each displayed rather unique characteristics. Other than the lower initial speeds of the simulations there were no other commonalities identified that could explain the characteristically different

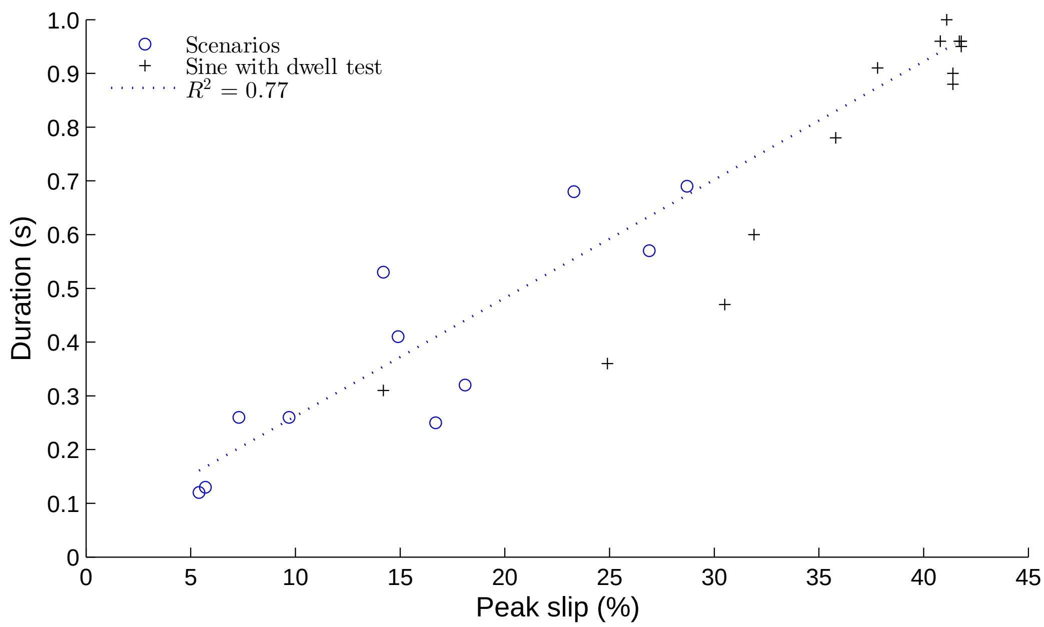


Fig. 8.2: Characteristics of initial major braking interventions for simulations that showed obvious signs of understeer

ESC response. It is suggested that at these lower speeds there is less demand on the ESC system and excessive sideslip can be mitigated without forcing the vehicle to understeer. While any action that prevents a loss of control is beneficial, an action that improves lateral stability without causing a high degree of understeer is clearly more desirable.

8.2.4 Effect of speed on initial major interventions

The way in which the initial major braking interventions were affected by speed was also explored. Figures 8.3 and 8.4 show how intervention peak slip and duration were affected by initial vehicle speed during the scenario simulations that showed obvious signs of understeer as well as the sine with dwell test manoeuvre.

For the scenario simulations it can be seen that both intervention peak slip and duration decrease as initial speed increases. This negative relationship is likely due to a reduction in the level of wheel slip that is required to generate understeer (and consequently mitigate oversteer) at higher speeds. That is, less powerful interventions are required in order to nullify the cornering force of the front wheels, as shown in Section 2.3.1, and cause the vehicle to begin understeering.

Trend lines fitted to the interventions elicited during the scenario simulations (in Figures 8.3 and 8.4) also show a good fit to many of the interventions elicited during the sine with dwell manoeuvre, particularly those manoeuvres that had a steering amplitude of $5.5A$ or greater and displayed obvious signs of understeer. This correlation was taken as further evidence that the sine with dwell test manoeuvre is able to elicit interventions that are representative of interventions that would occur in real world loss of control situations.

It was interesting to note that the sine with dwell test was able to elicit interventions that caused understeer with an initial speed of 80 km/h, while no obvious signs of understeer were found for any of the scenario simulations with initial speeds below 100 km/h. This is an indication that the severity of the steering input plays an important part (in addition to initial speed) in determining how ESC responds to potential lateral instability.

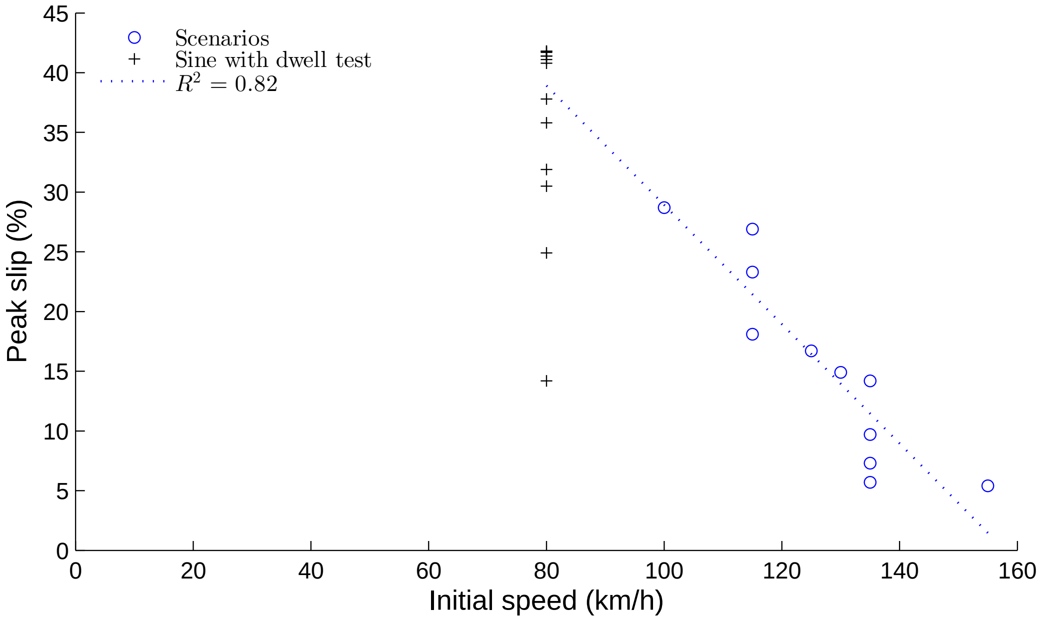


Fig. 8.3: Major braking intervention peak slip relative to initial speed for simulations that showed obvious signs of understeer

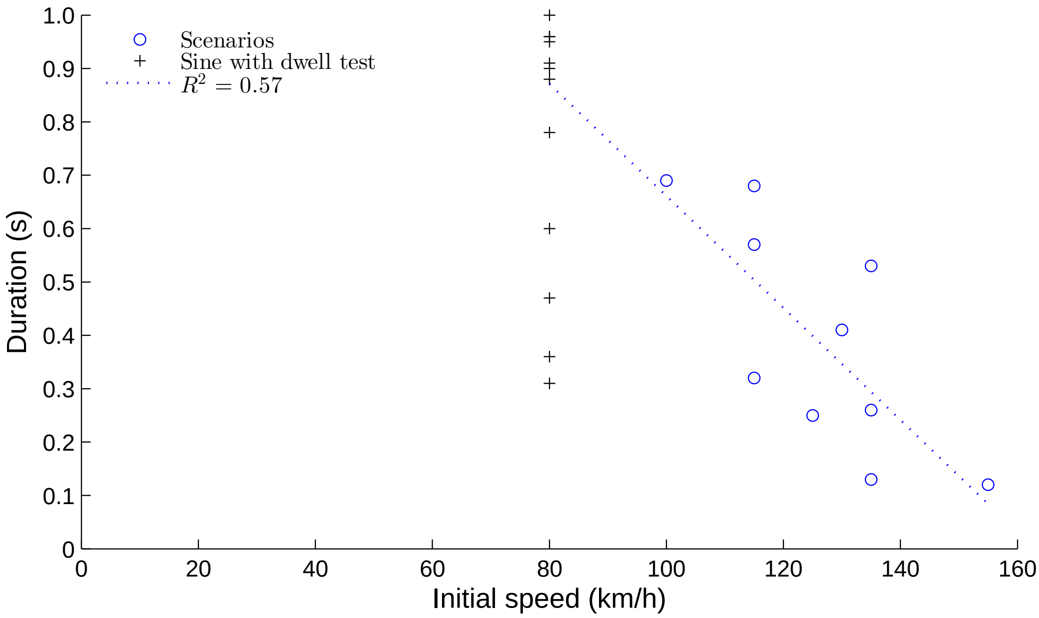


Fig. 8.4: Major braking intervention duration relative to initial speed for simulations that showed obvious signs of understeer

8.2.5 Summary

Most of the major ESC braking interventions elicited during the loss of control scenario simulations were applied at the front wheels. As expected, the effect of such front wheel interventions was the prevention of oversteer through a reduction of vehicle sideslip. In scenarios where the vehicle was travelling 100 km/h or faster this reduction of sideslip was achieved by interventions that caused the vehicle to understeer by varying amounts.

There was a positive relationship between the peak slip and duration for the initial major interventions. This was particularly true for simulations in which the ESC interventions resulted in obvious signs of understeer. For the interventions elicited during these particular simulations there was a good correlation to the characteristics of the interventions elicited during the sine with dwell test.

The effect that the initial speed of a simulation had upon the characteristics of the major braking interventions was investigated. For the simulations where stability was improved through the initiation of understeer, there was a decrease in intervention peak slip and duration as initial speed increased. It was surmised that the reduction in intervention peak slip and duration was likely to be the result of the smaller amount of front wheel braking required to produce understeer at higher speeds.

For the scenario simulations with an initial speed below 100 km/h, it was suggested that a mechanism of improving lateral stability that does not rely on causing the vehicle to understeer was utilised. This alternative control strategy used characteristically different interventions and was deemed to be more favorable due to the absence of overt understeer which can potentially result in an head on or side swipe type collision due to excessive lateral offset.

9. DISCUSSION

This chapter presents a summary of the previous chapters (Section 9.1), a discussion of the main findings with reference to how well they address the thesis aims (Section 9.2), and suggests several areas of potential future work (Section 9.3).

9.1 Summary

In Chapter 1 the way in which nonlinearities in vehicle response can cause drivers to lose control of their vehicles was explained. The emergence of ESC as an in-vehicle technology that endeavours to reduce the incidence and consequence of drivers encountering such nonlinearities was then described.

Chapter 2 presented an analysis of vehicle dynamics in which it was shown that lateral stability, and thus steerability, are reduced for large values of side slip angle that arise during high speed driving. Efforts to counteract this effect prompted two areas of research; rear wheel steering, and active yaw control. Both areas succeeded in achieving increased lateral stability for vehicles driving at high speed but ultimately active yaw control was accepted as the superior technique. Further development of the active yaw control concept brought about the system of sensors, control algorithms, and actuators that together constitute modern Electronic Stability Control.

Section 2.3 then explained how ESC is able to improve the lateral stability of a vehicle during high speed driving. It was explained that the system interprets the driver's steering intentions, gathers information on the current trajectory of the vehicle, and then strategically applies braking interventions to counteract any disparity.

Chapter 3 reviewed literature investigating the effectiveness of ESC systems and identified many studies with findings that showed significant reductions in crash rates. The most notable reductions were found for single vehicle crashes. Overall, ESC reduced single vehicle crash risk by between 27 per cent and 50 per cent. The risk of some specific types of single vehicle crash are reduced even further. Rollover crash risk is reduced by between 39 per cent and 76 per cent, and loss of control crash risk is reduced by between 55 per cent and 70 per cent.

Disaggregation by various parameters revealed greater detail about the effectiveness of ESC. Effectiveness increases for crashes of higher levels of injury severity, crashes involving larger vehicles such SUVs and 4WDs, and crashes on surfaces with a lower coefficient of friction.

In contrast to single vehicle crashes, multiple vehicle crashes appear to benefit little from ESC. Rather, the effect of ESC appears to increase the risk of multiple vehicle crashes by between 3 per cent and 15 per cent.

In Section 3.3 literature covering the selection of a suitable ESC test manoeuvre and the development of a minimum effectiveness criteria was reviewed. Researchers sought a test manoeuvre that could generate a large amount of lateral instability and the sine with dwell test was ultimately selected. The researchers then developed minimum performance criteria based on the principle that a vehicle with an acceptably operating ESC system should not 'spin out'.

From the review of literature several gaps in knowledge were identified. The first was that the actions of ESC during high speed crashes on an individual level had not been analysed. That is, no study had investigated what braking interventions are made by ESC during a situation in which a vehicle without ESC would have crashed and how exactly these interventions affect vehicle trajectory.

Secondly, the way in which ESC interacts with rural road safety measures had not been investigated. The extent to which ESC effectiveness and operation is affected by safety measures such as sealed shoulders, reduced speed limits, or sealed roads was not known.

Lastly, the ability of the minimum ESC effectiveness test (i.e. the sine with dwell manoeuvre) to elicit braking interventions that are comparable to the types of braking interventions that occur during typical loss of control scenarios was unclear.

Before addressing the gaps in literature, Chapter 4 conducted an analysis of high speed rural road crashes to gain an understanding of how, why, and where they occur. The focus was to characterise crashes that result in high severity injuries for the vehicle occupants. Using data from the South Australian statewide crash database (TARS), the relationship between individual categorical variables and crashes that result in high severity injuries was investigated. Tables were constructed that showed the prevalence of high injury severity crashes associated with each individual category of several database variables.

A logistic regression was also conducted for single vehicle crashes on rural roads and three crash characteristics that had a highly significant association with occupant injury severity were identified. The likelihood of high injury severity was increased in crashes that had a high speed limit, occurred in the hours of darkness, and occurred in earlier years.

A further analysis of loss of control crashes on high speed rural roads, which were shown in literature to be one of the major beneficiaries of ESC, was conducted in Chapter 5. This analysis sought to characterise crashes that occurred as a result of a loss of control, and to develop an estimate of the potential maximum benefit of ESC in South Australia. It was not possible to directly identify a loss of control crash within the TARS database so a method for identifying loss of control crashes through a combination of existing TARS variables was developed.

This method involved using data from the CASR in-depth database which contains enough information to identify whether or not crashes occurred due to a loss of control. Crashes from the in-depth database were matched with corresponding records in the TARS database. A loss of control prediction model was then developed through the identification of categorical variables and crash description key words that were associated with loss of control crashes.

This model was then used to investigate the relationship between individual categorical variables and injury crashes that were the result of a loss of control. It was estimated that there were 561 injury crashes on high speed rural roads in South Australia per year (including 33 fatal crashes, and 208 crashes resulting in a hospital admission) that were the result of a loss of control and all of these crashes would have potentially benefited from ESC.

In Chapter 6, a method of using simulations to analyse the effect that ESC braking interventions have upon vehicle trajectory was developed. Suitable simulation software was chosen and two vehicle models with corresponding ESC models were supplied by Bosch Australia. One vehicle represented a front wheel drive small car, and the other a rear wheel drive family sedan. Validation of these vehicle models (Section 6.2) revealed that the rear wheel drive model possessed a lateral stability similar to other generic vehicle models that were classified as large family sedans. In addition, the ESC model associated with the rear wheel drive vehicle was shown to pass the minimum effectiveness criteria and to improve lateral stability in a similar way to the ESC systems of family sedans during real ESC assessment tests. However, the front wheel drive vehicle model was found to behave unrealistically and its use was discontinued.

Section 6.3 described the development of ten loss of control scenarios that were typical to crashes that occur on high speed rural roads in Australia. The accurate simulation of these scenarios using the Bosch rear wheel drive vehicle model was then described in two parts. Section 6.4 presented the first part in which the scenario environment was simulated with a roadway model and values for the coefficient of friction on different areas of the roadway. The second part (Section 6.5) modelled the scenario circumstances and loss of control trajectory by defining parameters for initial speed, braking, and a driver model.

In order to identify the specific parameter values that generated a simulation with the same trajectory as that in each scenario an optimisation procedure was required. This optimisation procedure, described in Section 6.6, made use of the Nelder Mead algorithm to minimise the error between the lateral offset and yaw components of the simulated and scenario trajectories.

The methods developed were applied to obtain a representative set of simulation parameter values for each of the loss of control scenarios (Chapter 7). These representative value sets were used to run simulations of each scenario using a vehicle without ESC and then again using a vehicle with ESC. The effects that ESC had on the vehicle trajectory and crash outcome in each loss of control scenario were then described. Figures that depicted the braking interventions in each scenario were also presented.

Additional simulations with and without ESC were also run after altering specific parameters in the representative value sets to emulate the presence of certain rural road safety measures. However, these altered parameter sets utilised the original driver model parameter values which resulted in simulations with inappropriate steering responses. Because of these inappropriate steering responses the in-depth analysis of the effect that the rural road safety measures have on ESC effectiveness was not possible.

An analysis of the characteristics of the ESC braking interventions that were elicited in each scenario, and how they affected vehicle trajectory, was presented in Chapter 8. The analysis explored the relationship between the peak slip and duration of the braking interventions elicited during the simulations. These relationships were compared to the characteristics of the braking interventions elicited during the sine with dwell ESC test manoeuvre. Additionally, the effect that the initial travelling speed and the various rural road safety measures had on braking intervention characteristics was also examined.

9.2 Findings

The main research reported in this thesis had three aims. The first was to identify the specific braking interventions made during loss of control scenarios typical to high speed rural roads in Australia and examine how they affect vehicle trajectory. The second was to investigate how these interventions may be altered in the presence of rural road safety measures such as reduced speed limits and roadside shoulder sealing. The final aim was to explore the suitability of the minimum ESC effectiveness criteria based on how the interventions made during the sine with dwell test manoeuvre compare to interventions made during typical Australian loss of control scenarios.

The extent to which each of these aims were achieved is discussed in the subsections below.

9.2.1 Identifying ESC interventions during loss of control scenarios

Ten loss of control scenarios were identified and a method that utilised modelling, simulation, and optimisation to determine the braking interventions that would have been made by an ESC equipped vehicle during each scenario was developed (Chapter 6). After applying this method to each scenario, the change in vehicle trajectory and crash outcome as a result of ESC braking interventions was determined and explored (Chapter 7). The nature of each major intervention, the peak value of slip achieved, and the duration were also identified and explored (Chapter 8).

The results of the simulations showed that it is likely that ESC would have prevented a loss of control in all of the scenarios. This maintenance of lateral stability would have prevented a collision from occurring in eight of the scenarios, prevented a collision with a tree in Scenario 3 (though perhaps resulting instead in an collision of unknown severity with an oncoming vehicle), and likely reduced the severity of the collision in Scenario 2 by converting a side impact to a frontal impact.

In terms of trajectory changes, the introduction of ESC resulted in a decrease in maximum sideslip, maximum lateral offset (apart from one scenario), and maximum yaw. Maximum sideslip was reduced from an average of 39.8 degrees with a variance of 12.9 degrees to an average of 6.0 degrees with a variance of only 1.2 degrees. This considerable reduction in both the magnitude and variance of sideslip was consistent with the theory of ESC operation (presented in Section 2.3). The reduction of sideslip to the specific value of 6.0 degrees was considered a characteristic of the rear wheel drive vehicle and ESC models rather than a standard target value for all ESC systems. However, without the opportunity to examine other ESC systems it was not possible to determine if the value of 6.0 degrees should be considered as being typical.

The reduction in sideslip also resulted in reductions in lateral offset and yaw. Maximum lateral offset was reduced from an average of 7.0 metres to an average of 3.2 metres, while yaw was reduced from an average of 58.3 degrees to an average of 13.4 degrees. Along with the reduction in the magnitude of lateral offset and yaw there was also a reduction in the variance; maximum lateral offset and yaw were reduced by 2.0 and 3.6 respectively.

Further exploration of the trajectory changes found that the maintenance of a low sideslip resulted in an increased likelihood of understeer as simulation initial speed increased, particularly for speeds of 100 km/h or above. This understeer was characterised by a smaller reduction in maximum lateral offset and a greater reduction in maximum yaw. This prioritisation of the reduction of excessive sideslip (oversteer) above the reduction of understeer is also consistent with the theory of ESC operation. Indeed, in situations of potentially severe lateral instability an ESC system will actively instigate understeer as a method of preventing oversteer (e.g. during Scenario 2). Thus, it is suggested that as initial speed is increased the severity of lateral instability is also increased and, consequently, the likelihood that understeer will be elicited due to ESC braking interventions increases as well.

It was noted that changes in the vehicle trajectory beyond the first ESC braking intervention had the potential to render the selected driver model preview time and lag time inappropriate for the remainder of the simulation. That is, after the initial braking intervention the steering response of the driver model may no longer have been representative of a typical driver. However, in terms of investigating the effectiveness of ESC in preventing a loss of control the impact of this driver model issue was considered to be minor; a human driver would have adapted favorably to the increased stability in the vehicle trajectory and thus the presented results can simply be regarded as conservative. It is worth stating that the issues with the inappropriate driver model parameter values would likely have been resolved through utilising a more advanced driver model featuring a variable preview time and lag time.

The major ESC braking interventions elicited during each scenario simulation were identified as those with a peak slip of greater than five per cent. The characteristics of these major interventions was explored. However, the analysis was limited to only the initial major interventions in each scenario due to the potential unreliability of subsequent interventions elicited with driver model parameter vales that may not have been appropriate.

A somewhat linear relationship between the peak amount of slip and the duration of each initial major intervention was apparent. That is, interventions with a higher peak slip also tended to have a longer duration. This was especially true for the interventions elicited during simulations with initial speeds of 100 km/h or faster where there were obvious signs of understeer.

The way in which the initial intervention characteristics changed in relation to travelling speed during these simulations with obvious understeer was investigated. It was found that, as the simulation initial speed increased, both the intervention peak slip and duration decreased. The explanation for this finding was that at higher speeds the cornering force provided by the front wheels is small which means less braking power is required to reduce the lateral force (as shown in Section 2.3.1) and initiate understeer.

After analysing both the changes in trajectory and the characteristics of the applied braking interventions a summary of the effects of ESC can be provided. As the severity of potential lateral instability increases (ostensibly due to vehicle speed but also steering severity as will be explained below), the ESC system progresses from a control method that causes no understeer with characteristically unique interventions to another method that causes greater and greater amounts of understeer utilising interventions with progressively lower values of peak slip and duration. While sideslip is reduced to a specific low value in all these situations, the increase in understeer is associated with smaller reductions in lateral offset and greater reductions in yaw which could lead to a vehicle departing the travelling lane and potentially being involved in a head on or side swipe type collision. This general summary of operation is likely to be similar for all ESC systems, but some aspects, such as the transition from non-understeer to understeer at around 100 km/h, may well be unique to the specific rear wheel drive ESC model used in this study.

As a consequence of these findings it is clear that to maximise the effectiveness of an ESC system it should be be supplied with the time and space required to operate at its full, and most effective, potential. This could be achieved through the application of appropriate speed limits that will reduce the possibility of understeer occurring as a result of ESC interventions along with any associated lateral offset. Additionally, the allocation of suitable lane widths and clear zones will limit the potential for a collision in the event of a small amount of lateral deviation resulting from understeer.

9.2.2 Effect of rural road safety measures on braking interventions

The interaction between ESC and reduced speeds and a sealed shoulder/road was examined. These safety measures were modelled by altering specific values in the simulation parameter set for each scenario. Simulations were run using the altered parameters sets using the rear wheel drive vehicle model both with and without ESC. The resulting vehicle trajectories and ESC braking interventions were then presented in figures. The analysis of these figures showed that the effectiveness of ESC in eliminating a loss of control and avoiding a collision in the presence of the modelled safety measures was similar to that during the unaltered simulations.

However, the results produced using the altered parameter sets were deemed to be largely invalid. It was observed that the driver model parameter values from the unaltered parameter sets were no longer representative of a the actions of a human driver when utilised in combination with the altered parameter values. That is, the steering response of the driver model became erratic and unrealistic with regards to the new conditions in the altered simulations. For example, driver model parameter values that produced a panicked response to the conditions during the unaltered simulation would still produce a panicked response in a simulation where the initial travelling speed had been reduced, when in reality there would have been extra time for a more subdued response. In fact, the lower travelling speed coupled with the inappropriate panicked response of the driver model often resulted in even greater lateral instability during the altered simulation as the cornering forces produced for a given steering input are increased at lower speeds.

This outcome was disappointing but it was noted that an improved driver model, that utilises non-static preview time and lag time values which adapt to the current driving situation, should overcome the limitations described above and facilitate the successful simulation of scenarios that have been altered to represent the addition of rural road safety measures.

9.2.3 Suitability of ESC effectiveness criteria

Both the US and Australian (as well as many European) federal governments have enacted laws which require all new passenger vehicles to be fitted with ESC systems. These laws dictate that all such systems must pass the minimum ESC effectiveness criteria described in Section 3.3. As such, the suitability of the minimum ESC effectiveness criteria is critical to ensuring the benefits of ESC systems are maintained in all vehicle models and for all potential driving circumstances.

The basis of the minimum effectiveness criteria is the sine with dwell test manoeuvre which was selected in preference to other manoeuvres for its ability to elicit severe lateral instability from the test vehicle using a series of basic steering inputs.

Analysis of the sine with dwell test results for the rear wheel drive vehicle model showed that, in most cases, only a single major intervention was applied by the ESC system during each test run. The sine with dwell test is thus able to isolate and therefore rate the effectiveness of a single intervention. Given that the single intervention is applied at the front left or front right wheel (depending on the direction of the steering inputs), the assessment is primarily of the ESC system's ability to counter oversteer. The literature concerning the development of the minimum ESC effectiveness criteria indicated that this focus on assessing the ability of ESC to counter oversteer was by design. Although, it should be acknowledged that part of the ESC minimum effectiveness criteria does address understeer by requiring a certain amount of lateral offset (albeit relatively small) as a result of the sine with dwell test steering inputs.

One concern with the minimum ESC effectiveness criteria is that the interventions elicited during the sine with dwell test manoeuvre may not be indicative of typical interventions during the types of driving situations common on high speed roads. The surface friction, steering actions, and speeds during a typical loss of control crash on a high speed rural road may be drastically different to those utilised during the sine with dwell test and thus may elicit a characteristically different response from an ESC system.

Investigation of this concern found a good correlation, in terms of the linear relationship between peak slip and duration, between the major braking interventions elicited during the sine with dwell test and the scenario simulations. This was particularly true when considering only the major interventions elicited during the scenario simulations in which there were obvious signs of understeer. There was also a good correlation between the sine with dwell test interventions and the interventions elicited in the scenario simulations which displayed obvious signs of understeer with regards to the way in which peak slip and duration were affected by initial speed.

The good correlation to the scenario simulations that showed obvious signs of understeer in particular indicates that the sine with dwell test consistently stimulates potential lateral instability of sufficiently high severity that the ESC system is forced into a mode of operation (mentioned above in Section 9.2.1) which limits sideslip through the use of braking interventions that initiate understeer. This means that the sine with dwell test will not address the interventions that are elicited during the ESC control method in which no understeer is generated. However, this is not viewed as an issue since situations which elicit that type of ESC response were regarded as being the result of only low severity lateral instability; the assumption being that if a situation of high lateral instability can be avoided then so can a situation of low severity.

It was interesting to note that the sine with dwell test was able to achieve levels of potential lateral instability sufficient to elicit understeer at a speed of only 80 km/h. In contrast, overt signs of understeer were not observed during any of the scenario simulations with an initial speed below 100 km/h. This indicates that the severity of the steering also plays a role (in addition to speed) in determining the level of potential instability and the response of the ESC system.

With a greater knowledge of how ESC operates during loss of control crashes on high speed rural roads, there is some scope for suggesting how the ESC minimum effectiveness criteria may be improved or altered to provide a quantitative rating of effectiveness. That is, further interpreting the sine with dwell test results to provide a ranking of ESC effectiveness rather than simply a pass or fail.

If it is acknowledged that the minimum effectiveness criteria can identify an ESC system that is able to mitigate oversteer (loss of control) to an acceptable level, then a further rating may be applied on how well the system is able to limit understeer during operation. This appears to be a logical next step as high levels of understeer, brought about by the mitigation of oversteer, appears to be the principal circumstance in which a collision may still occur for a vehicle equipped with ESC. Promoting the continued mitigation of oversteer in combination with lower levels of understeer will result in even greater levels of ESC effectiveness.

One suggestion for how this may be achieved is through monitoring the maximum lateral offset of the test vehicle as the sine with dwell steering amplitude is increased. ESC systems that pass the minimum effectiveness criteria could then be ranked based on the amount of lateral offset the vehicle is able to achieve over the course of the test runs. The higher the lateral offset across the spread of steering amplitudes, the higher the ESC system would be ranked. The implementation of this suggested method would obviously require testing and refinement. There may also be alternative methods of rating understeer propensity during the sine with dwell test.

9.3 Future work

The results presented in this thesis are the first to analyse the braking interventions which ESC applies during individual rural road crash scenarios on high speed roads that would have resulted in a loss of control and collision for a vehicle without ESC. The results allow some conclusions to be made, but also highlight areas of potential future research.

One focus of any future research could be the development of a more quantitative understanding of how the amount of slip and duration of a braking intervention affects vehicle trajectory under various situations. This should include determining whether the slip impulse (the integral of slip over time) is important and whether there is any trade-off in effectiveness for a long single intervention versus several shorter interventions or between an intervention of high slip with short duration versus an intervention of low slip with long duration.

It may also be worth investigating the longitudinal and lateral forces generated by a wheel with a given steering angle with and without an ESC intervention being applied. This would allow the change in longitudinal and lateral force as a result of the braking intervention to be calculated. Using this information a better understanding of how individual braking interventions affect the trajectory of a vehicle will be gained.

Another potential area of future research is in further exploring the braking interventions that are elicited during the sine with dwell test manoeuvre. This could involve analysing what effect the speed of the test or the slope of the road have on the characteristics of the elicited braking interventions. Some investigation of whether the minimum effectiveness criteria is met at higher or lower speeds could then be conducted. In addition, an exploration of how lateral offset is affected by various steering amplitudes and test speeds could also be conducted in order to determine the potential for expanding the effectiveness criteria to assess understeer to a great extent as described in Section 9.2.3.

There are several suggested improvements for the simulation methods presented in this thesis that may assist with future work. The first is the use of an improved driver model that could overcome the limitations encountered with the use of a static preview time and lag time. Secondly, the utilisation of several different vehicle models (with corresponding ESC models) would allow the investigation of how interventions differ among various ESC systems during various circumstances. This should also allow the identification of what is a typical level of sideslip reduction as a result of ESC activation.

Another suggested improvement would be the analysis of driver model steering inputs during scenario simulations. The severity of these driver model steering inputs could then be compared to the sine with dwell steering input to gain some understanding of what type of actions cause various levels of lateral instability. Finally, a greater number of typical loss of control scenarios should be simulated in order to increase the reliability of the results.

APPENDIX

A. LATERAL STABILITY EQUATIONS

The equations presented below are referenced in Section 2.3 to aid in the explanation of how ESC operates to improve vehicle lateral stability.

A.1 Nominal yaw

$$F_{lat.f} = \left(\frac{l_r}{L}\right) m a_{lat} \qquad F_{lat.f} = C_f \alpha_f \tag{A.1}$$

$$F_{lat.r} = \left(\frac{l_f}{L}\right) m a_{lat} \qquad F_{lat.r} = C_r \alpha_r \tag{A.2}$$

$$\alpha_f = \frac{m l_r a_{lat}}{C_f L} \tag{A.3}$$

$$\alpha_r = \frac{m l_f a_{lat}}{C_r L} \tag{A.4}$$

From Figure A.1 and using the law of sines:

$$\frac{R}{sin(\frac{\pi}{2} - \delta + \alpha_f)} = \frac{L}{sin(\delta - \alpha_f + \alpha_r)} \tag{A.5}$$

Using small angle approximation:

$$R = \frac{L}{\delta - \alpha_f + \alpha_r} \tag{A.6}$$

$$\begin{aligned}
\omega &= \frac{v_{long}}{R} && \text{(A.7)}\\
&= \frac{v_{long}(\delta - \alpha_f + \alpha_r)}{L} && \text{(A.8)}\\
&= \frac{v_{long}}{L}\left(\delta - \frac{ml_r a_{lat}}{C_f L} + \frac{ml_f a_{lat}}{C_r L}\right) && \text{(A.9)}\\
&= \frac{v_{long}}{L}\left(\delta - \frac{ml_r v_{long}\omega}{C_f L} + \frac{ml_f v_{long}\omega}{C_r L}\right) && \text{(A.10)}\\
&= \frac{\delta v_{long}}{L} - \frac{ml_r v_{long}^2}{C_f L^2} + \frac{ml_f v_{long}^2}{C_r L^2} && \text{(A.11)}\\
\frac{\delta v_{long}}{L} &= \omega\left(1 - \frac{ml_f v_{long}^2}{C_r L^2} + \frac{ml_r v_{long}^2}{C_f L^2}\right) && \text{(A.12)}\\
&= \omega\left[1 + mv_{long}^2\left(\frac{C_r L_r - C_f l_f}{C_r C_f L^2}\right)\right] && \text{(A.13)}\\
\omega &= \frac{v_{long}\delta}{L\left[1 + \left(\frac{v_{long}}{v_{ch}}\right)^2\right]} && \text{(A.14)}
\end{aligned}$$

Where v_{ch} represents the characteristic speed:

$$v_{ch}^2 = \frac{C_f C_r L^2}{m(C_r l_r - C_f l_f)} \tag{A.15}$$

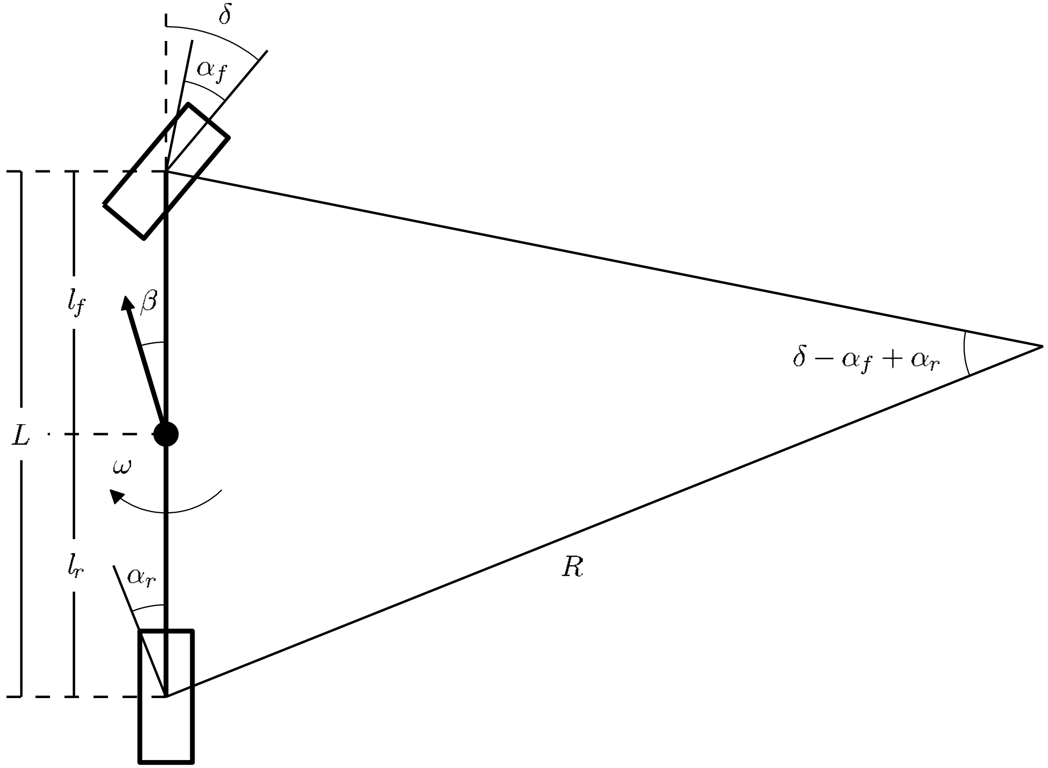


Fig. A.1: Bicycle model

A.2 Side slip angle rate of change

$$\dot{\beta} = \frac{d}{dt}tan^{-1}\left(\frac{v_{lat}}{v_{long}}\right) \tag{A.16}$$

Using the Chain Rule:

$$\dot{\beta} = \frac{1}{1+\left(\frac{v_{lat}}{v_{long}}\right)^2}.\frac{d}{dt}\left(\frac{v_{lat}}{v_{long}}\right) \tag{A.17}$$

By assuming $v_{long} \gg v_{lat}$, such that $\frac{v_{lat}}{v_{long}}^2 \approx 0$:

$$\dot{\beta} = \frac{d}{dt}\left(\frac{v_{lat}}{v_{long}}\right) \tag{A.18}$$

Using the Quotient Rule:

$$\dot{\beta} = \frac{v_{long}\dot{v_{lat}} - \dot{v_{long}}v_{lat}}{v_{long}^2} \tag{A.19}$$

By assuming v_{long} is constant, such that $\dot{v_{long}} = a_{long} = 0$:

$$\dot{\beta} = \frac{\dot{v_{lat}}}{v_{long}} \tag{A.20}$$

Using relative motion the total acceleration a of the vehicle is given as:

$$a = \dot{v_{lat}} + \omega v_{long} \tag{A.21}$$

Since $a_{long} = 0$:

$$a_{lat} = \dot{\beta} v_{long} + \omega v_{long} \tag{A.22}$$

$$= v_{long}(\dot{\beta} + \omega) \tag{A.23}$$

$$\frac{a_{lat}}{v_{long}} = \dot{\beta} + \omega \tag{A.24}$$

$$\dot{\beta} = \frac{a_{lat}}{v_{long}} - \omega \tag{A.25}$$

B. IDENTIFYING REPRESENTATIVE VALUE SETS

In Section 7.1 sets of initial simulation parameter values for each of the scenarios developed in Section 6.3 are presented. However, in order to identify the sets of parameter values that result in a simulated vehicle trajectory that matches the scenario trajectory an optimisation method, as described in Section 6.6, was required.

The resulting set of simulation trajectories, after optimising each initial value set in combination with each of the 36 likely preview time and lag time pairs, are presented schematically below. An example of this schematic is shown in Figure B.1 where the optimised trajectory associated with each pair of initial preview time and lag time values are shown in a matrix. Each of the optimised trajectories consists of a lateral offset component and a yaw component (in red) which is overlaid onto the corresponding components of the scenario trajectory (in black). Note that a blank trajectory indicates that the optimisation process failed for that particular combination of initial parameter values. A shaded circle in the upper left corner of each optimised trajectory indicates the relative size of the error associated with how well it matches the scenario trajectory. A white circle indicates the trajectory with the largest error and a black circle indicates the trajectory with the smallest error. The remainder of the circles are shaded relative to where their error value sits between this minimum and maximum. The optimised trajectory that was selected as that which best represents the scenario trajectory is highlighted with a blue border. The optimised parameter values associated with the chosen trajectory are then recognised as the representative value set.

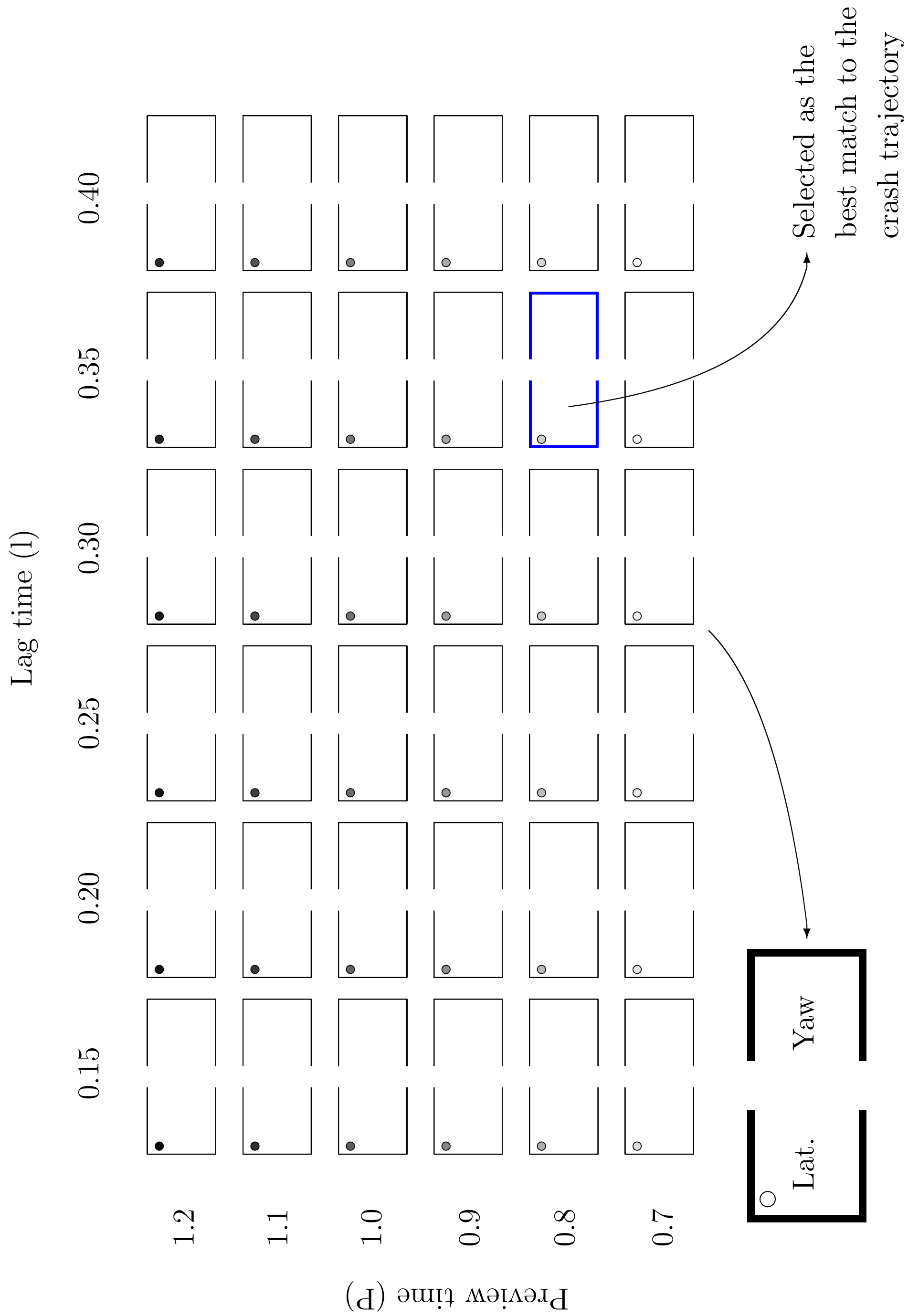


Fig. B.1: Example of the output generated from the optimisation of a group of initial value sets

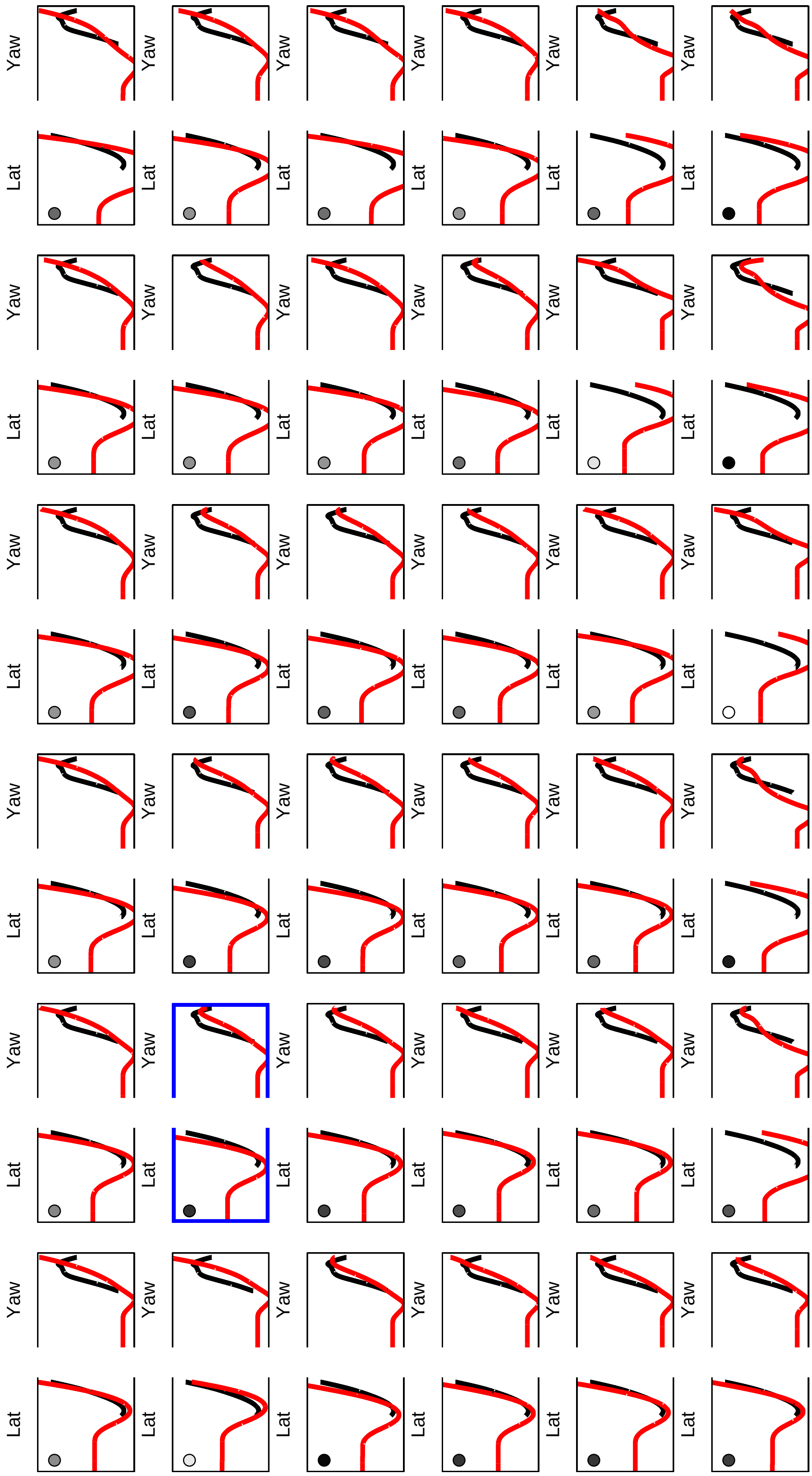


Fig. B.2: Optimised trajectories for set 1 (scenario 1)

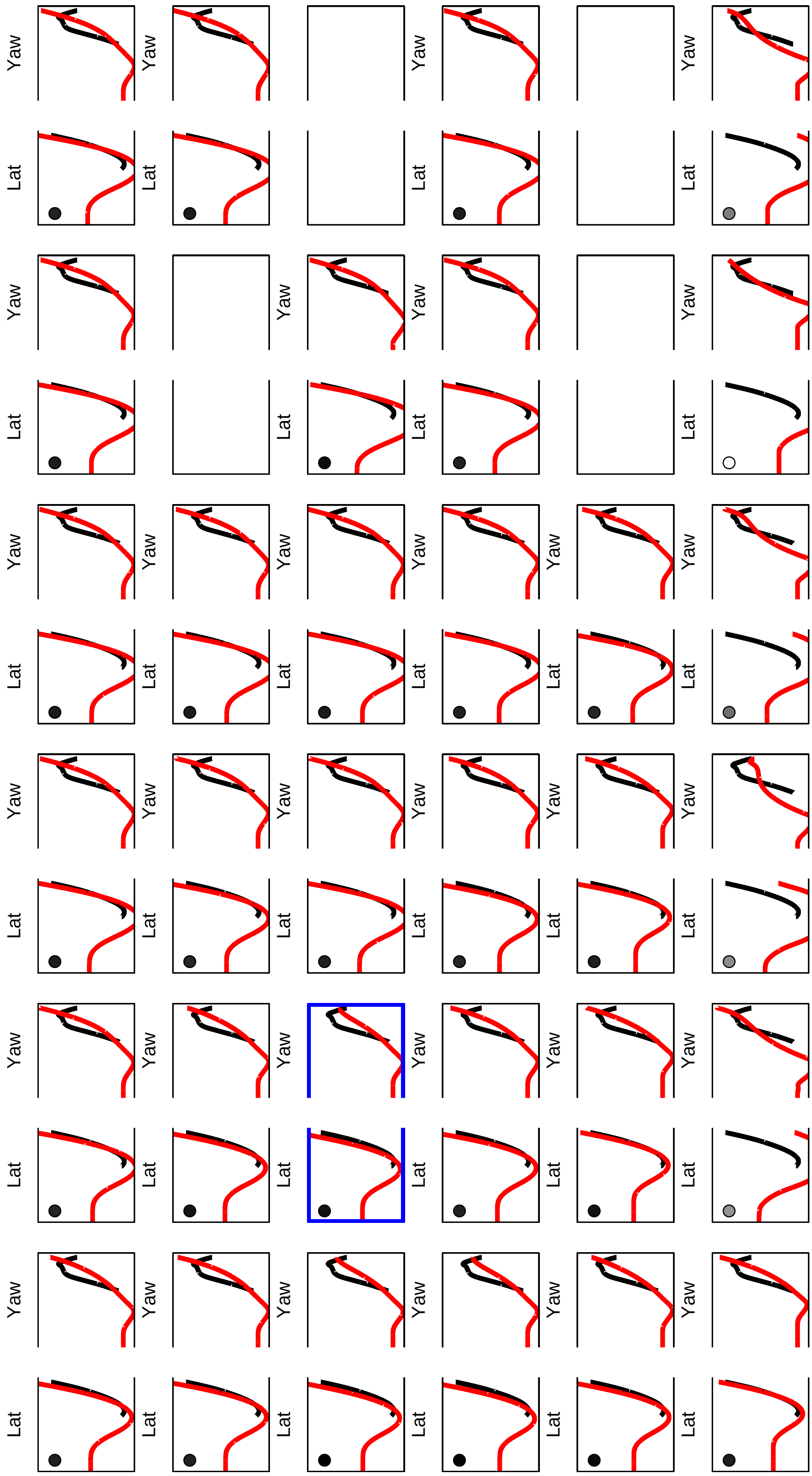


Fig. B.3: Optimised trajectories for set 2 (scenario 1)

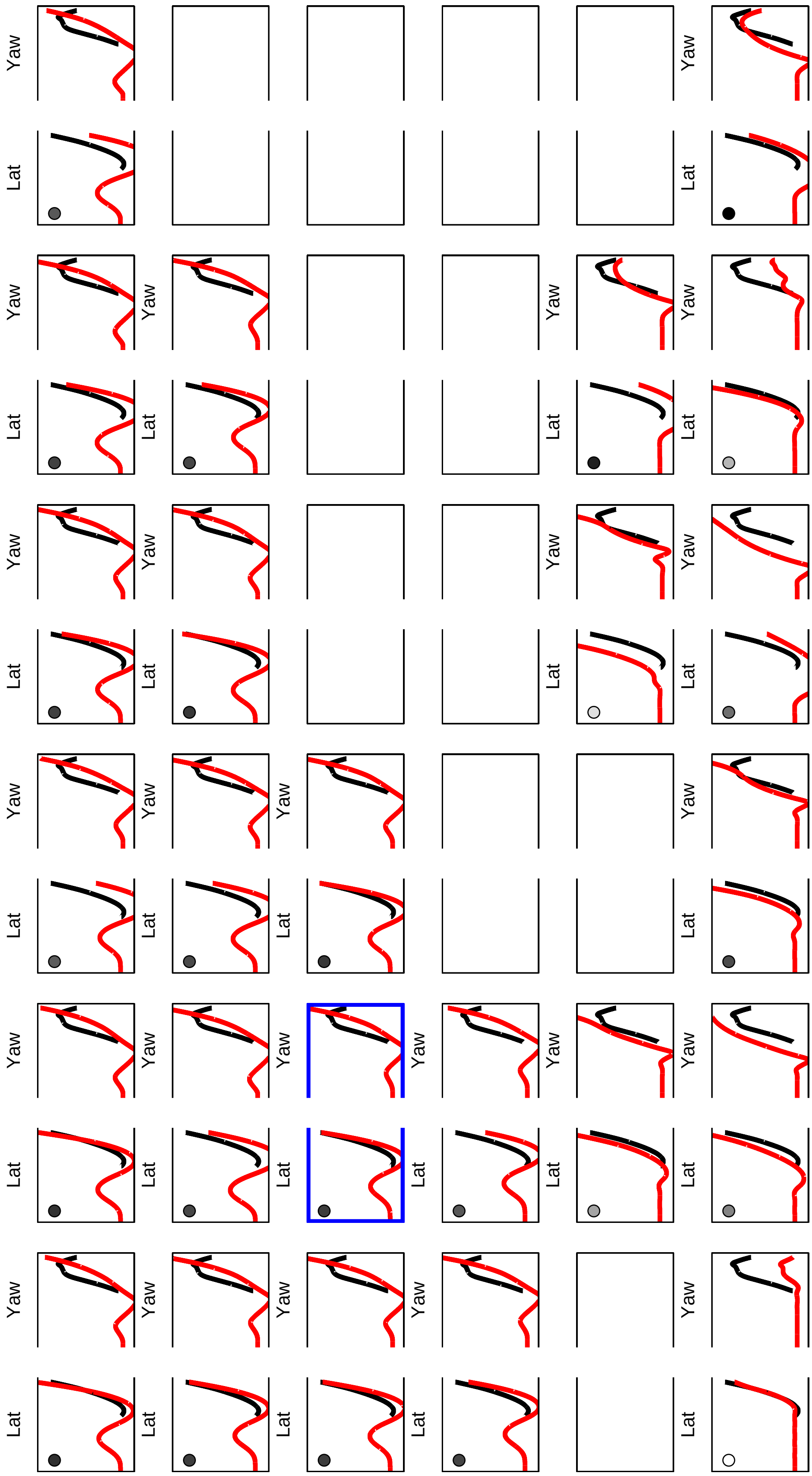


Fig. B.4: Optimised trajectories for set 3 (scenario 1)

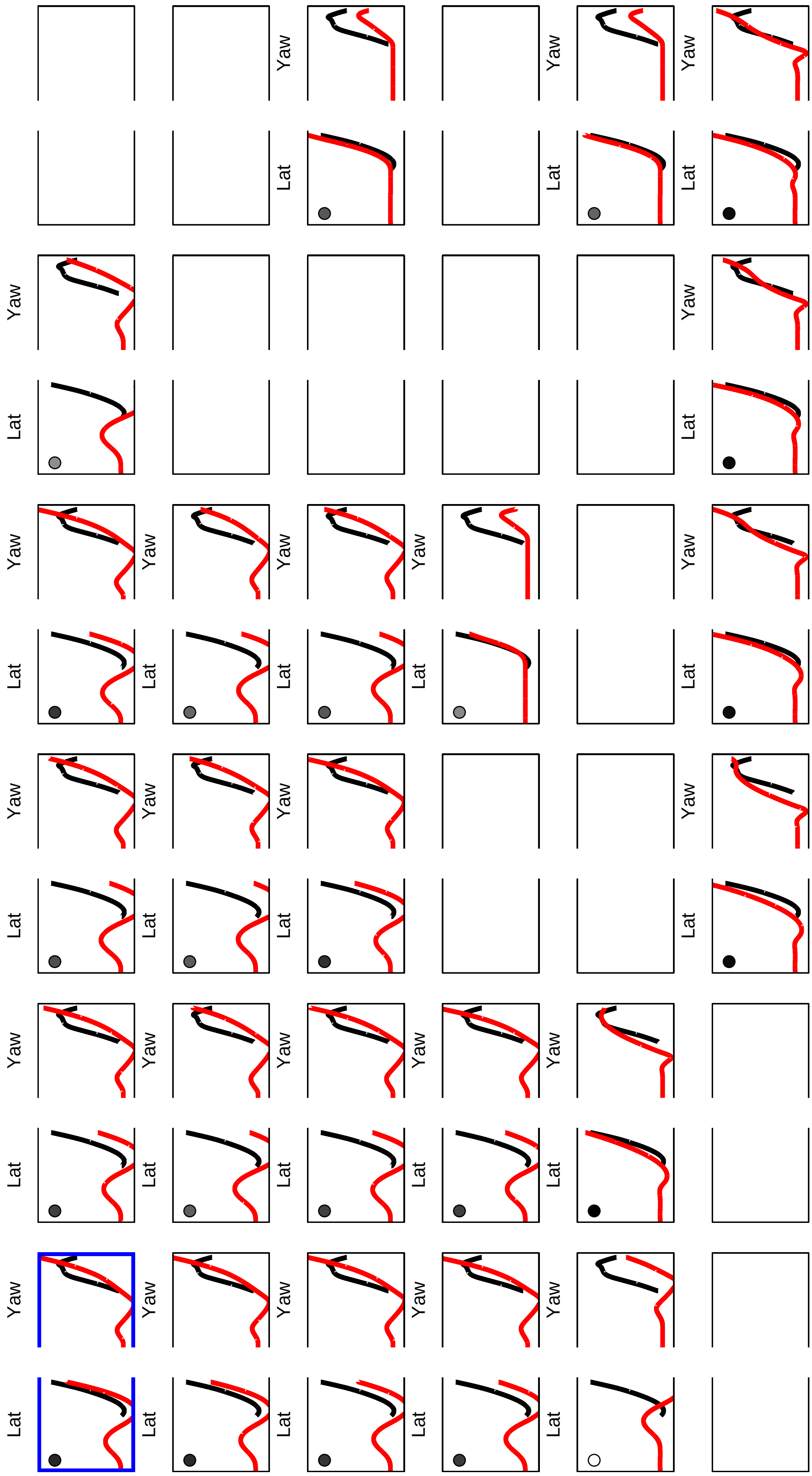


Fig. B.5: Optimised trajectories for set 4 (scenario 1)

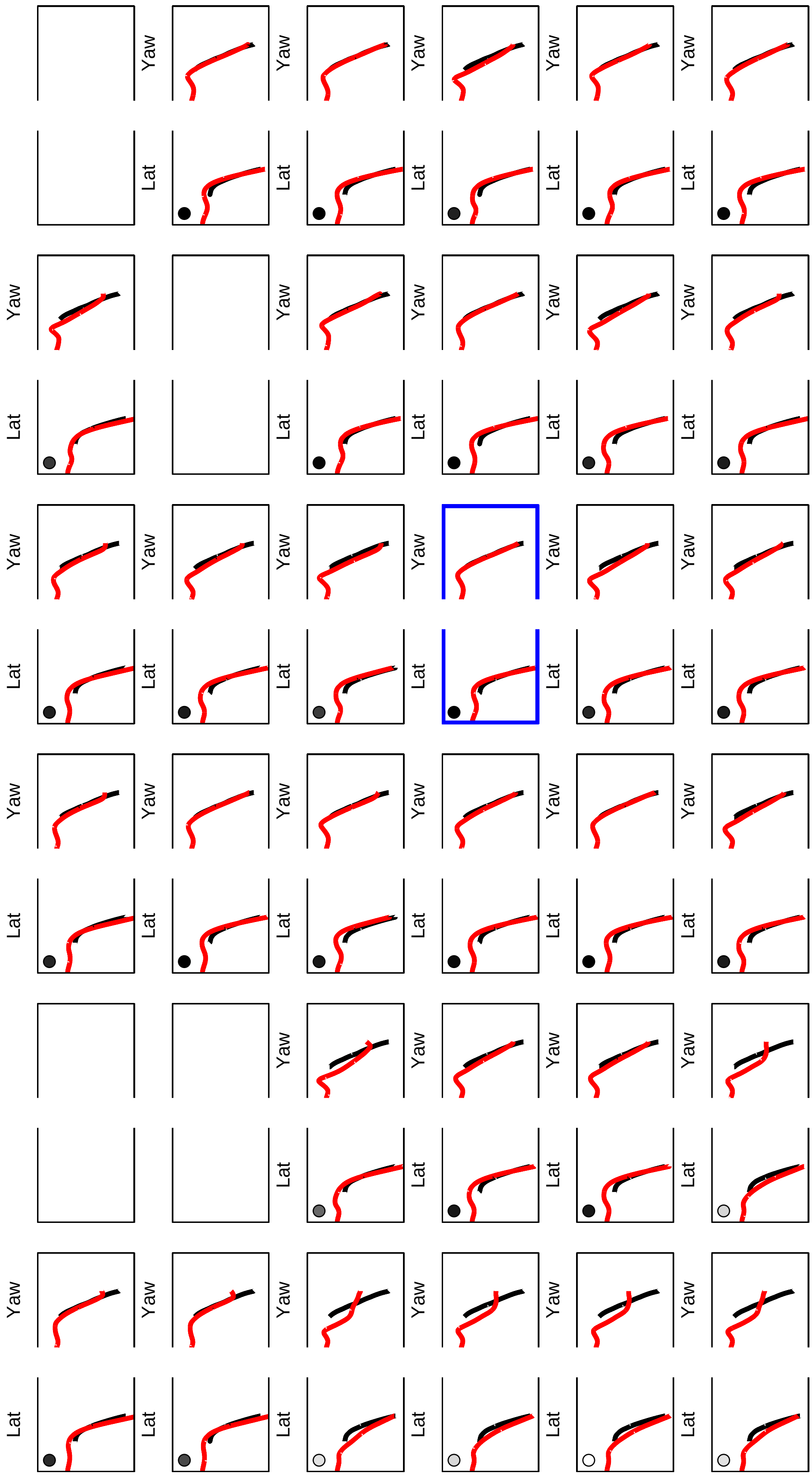


Fig. B.6: Optimised trajectories (scenario 2)

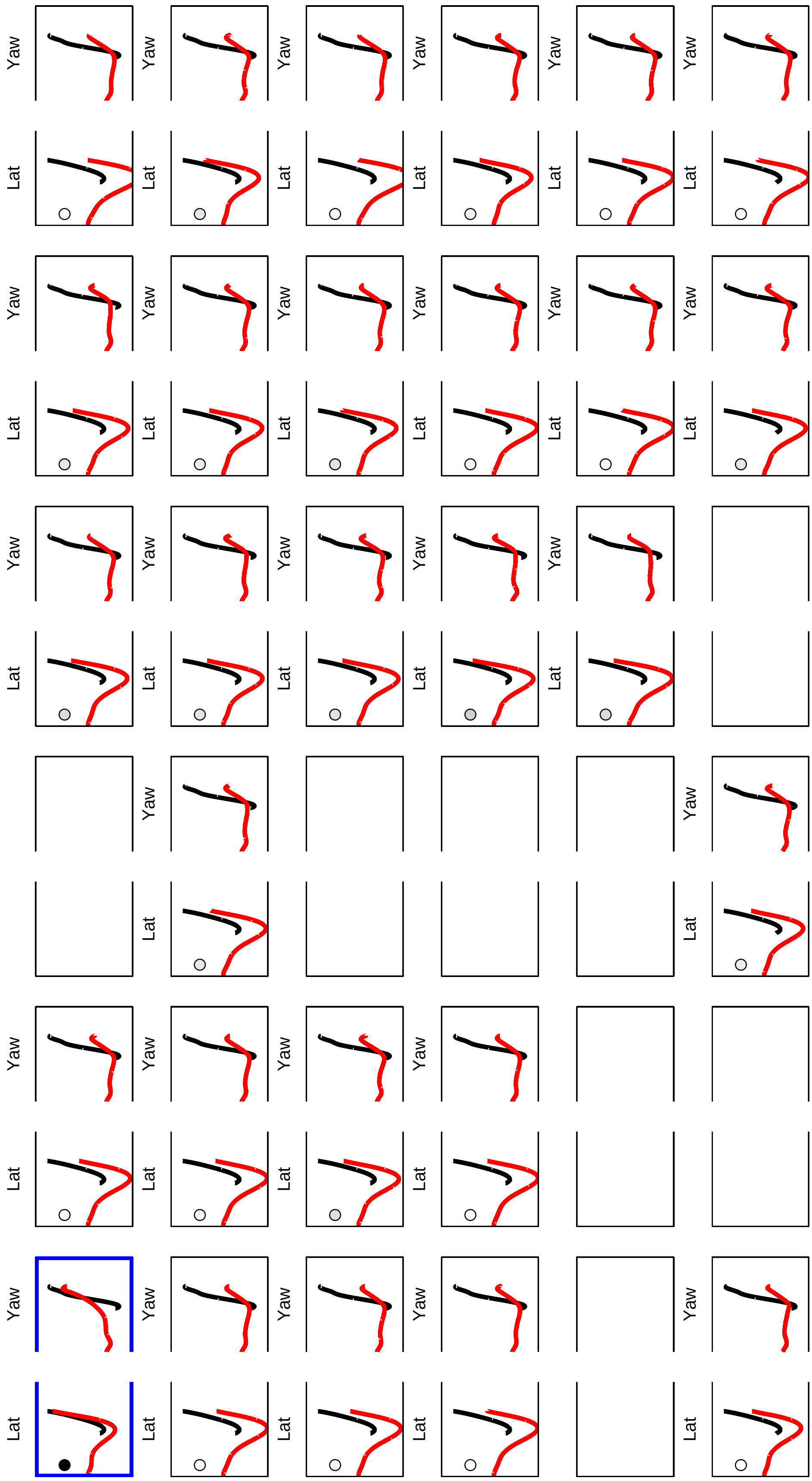


Fig. B.7: Optimised trajectories for scenario 3

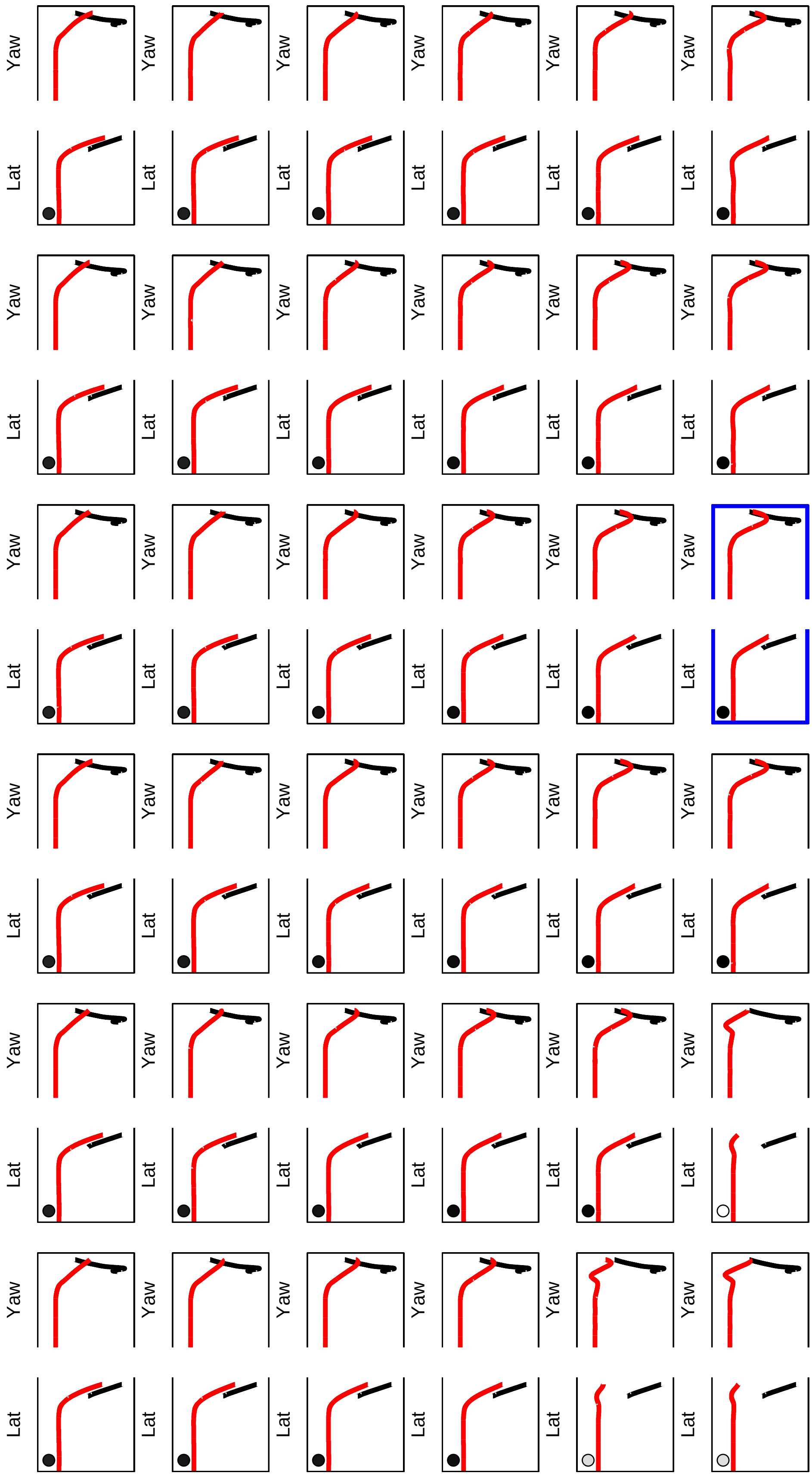


Fig. B.8: Optimised trajectories for set 1 (scenario 4)

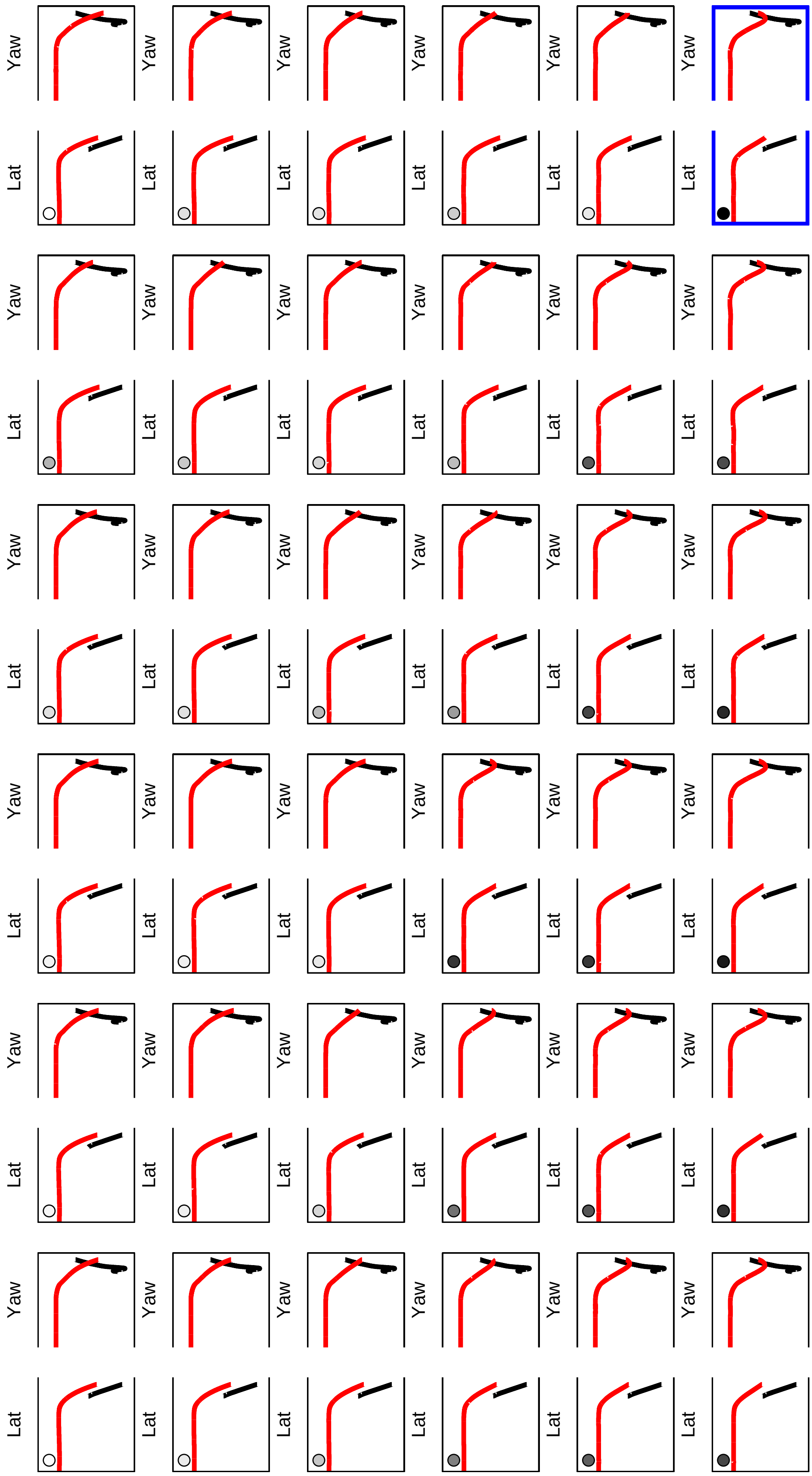


Fig. B.9: Optimised trajectories for set 2 (scenario 4)

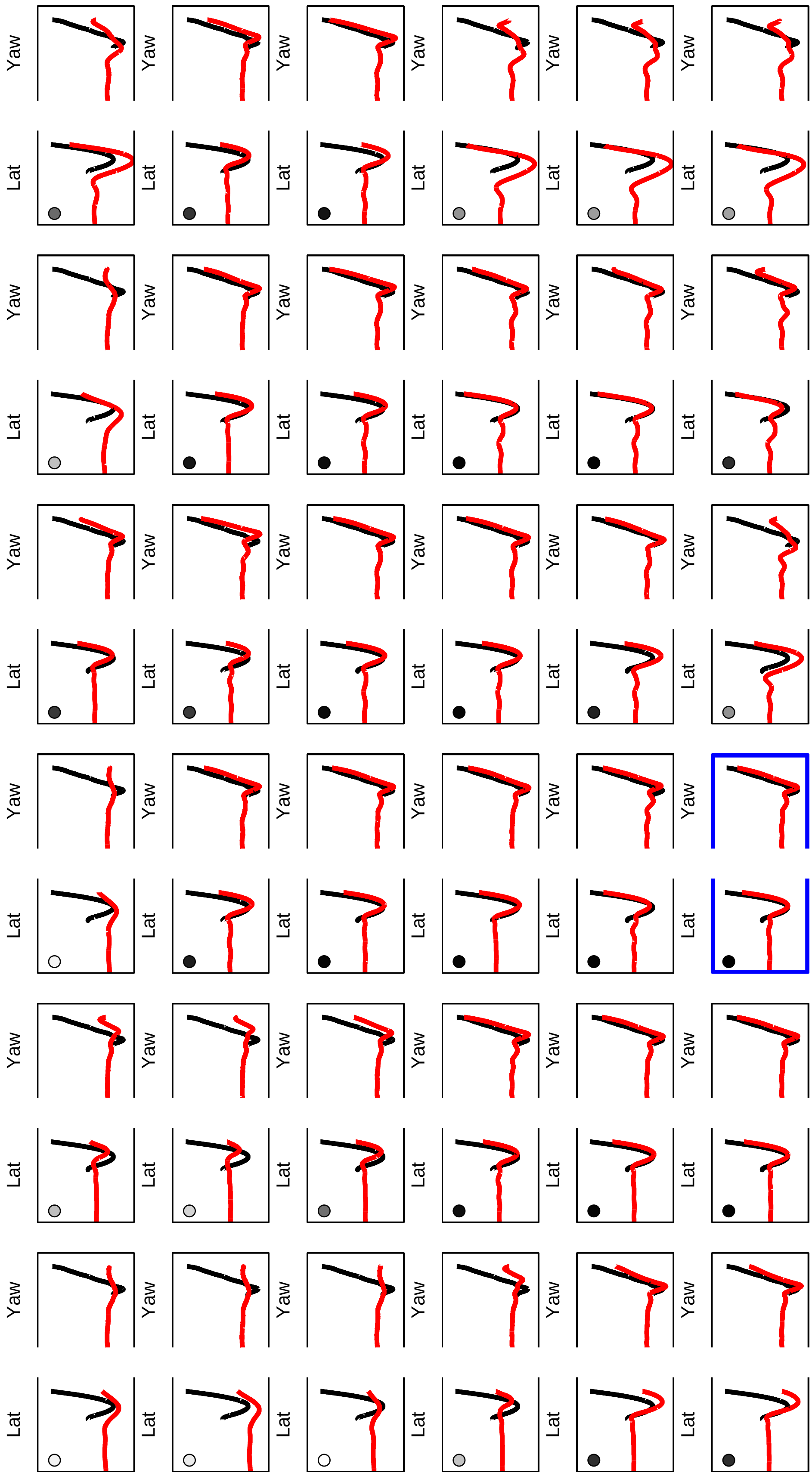


Fig. B.10: Optimised trajectories for set 1 (scenario 5)

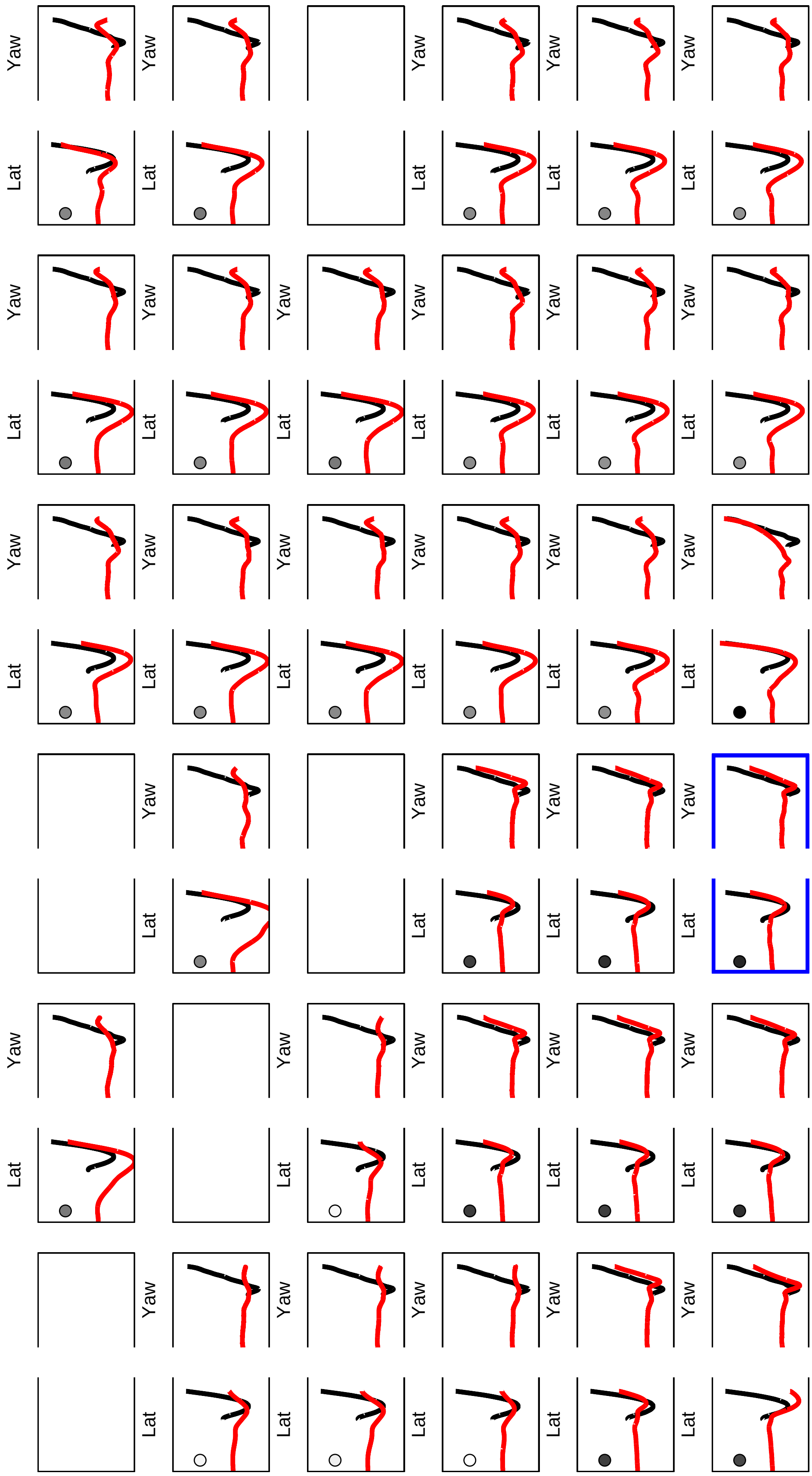


Fig. B.11: Optimised trajectories for set 2 (scenario 5)

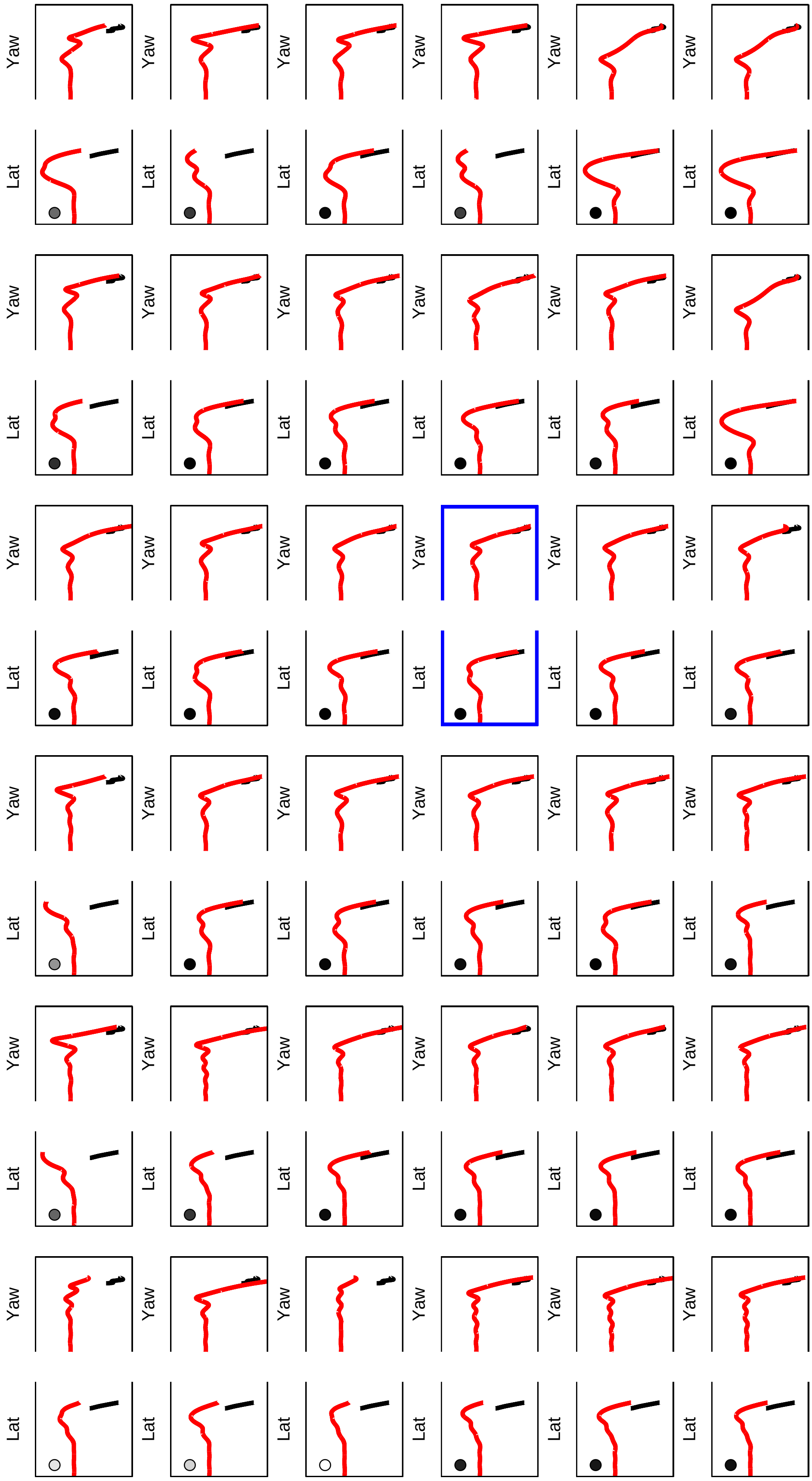


Fig. B.12: Optimised trajectories for scenario 6

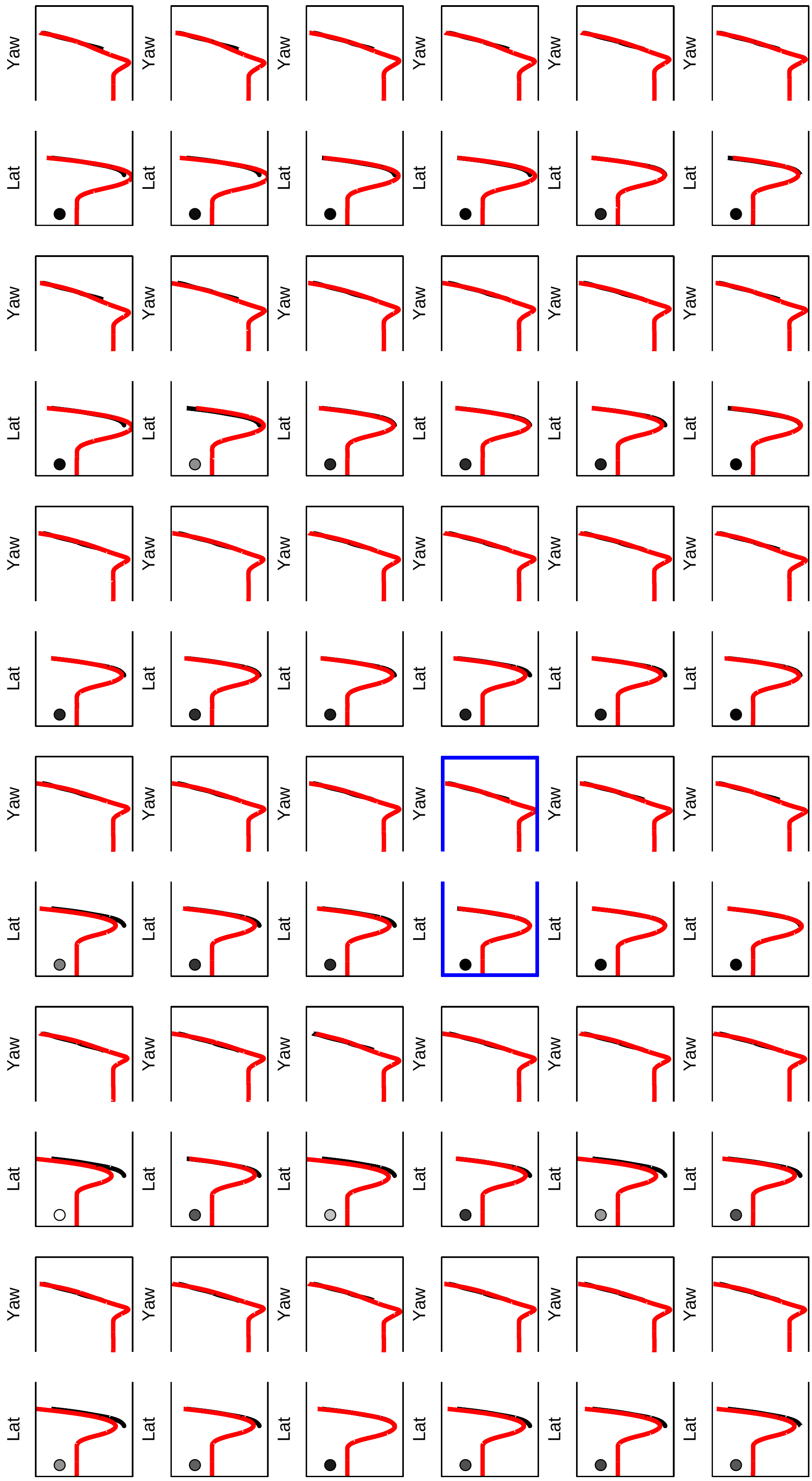


Fig. B.13: Optimised trajectories for scenario 7

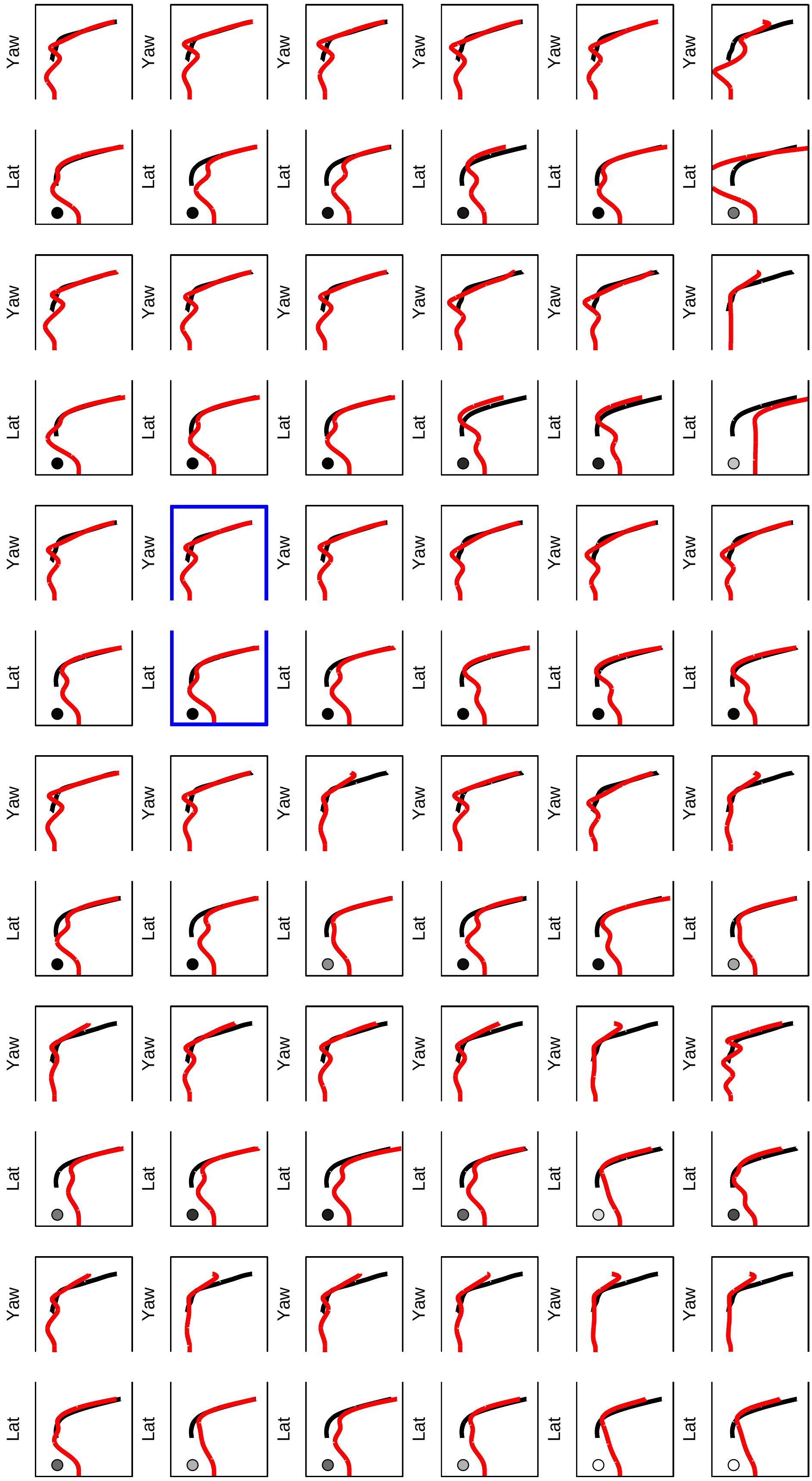


Fig. B.14: Optimised trajectories for set 1 (scenario 8)

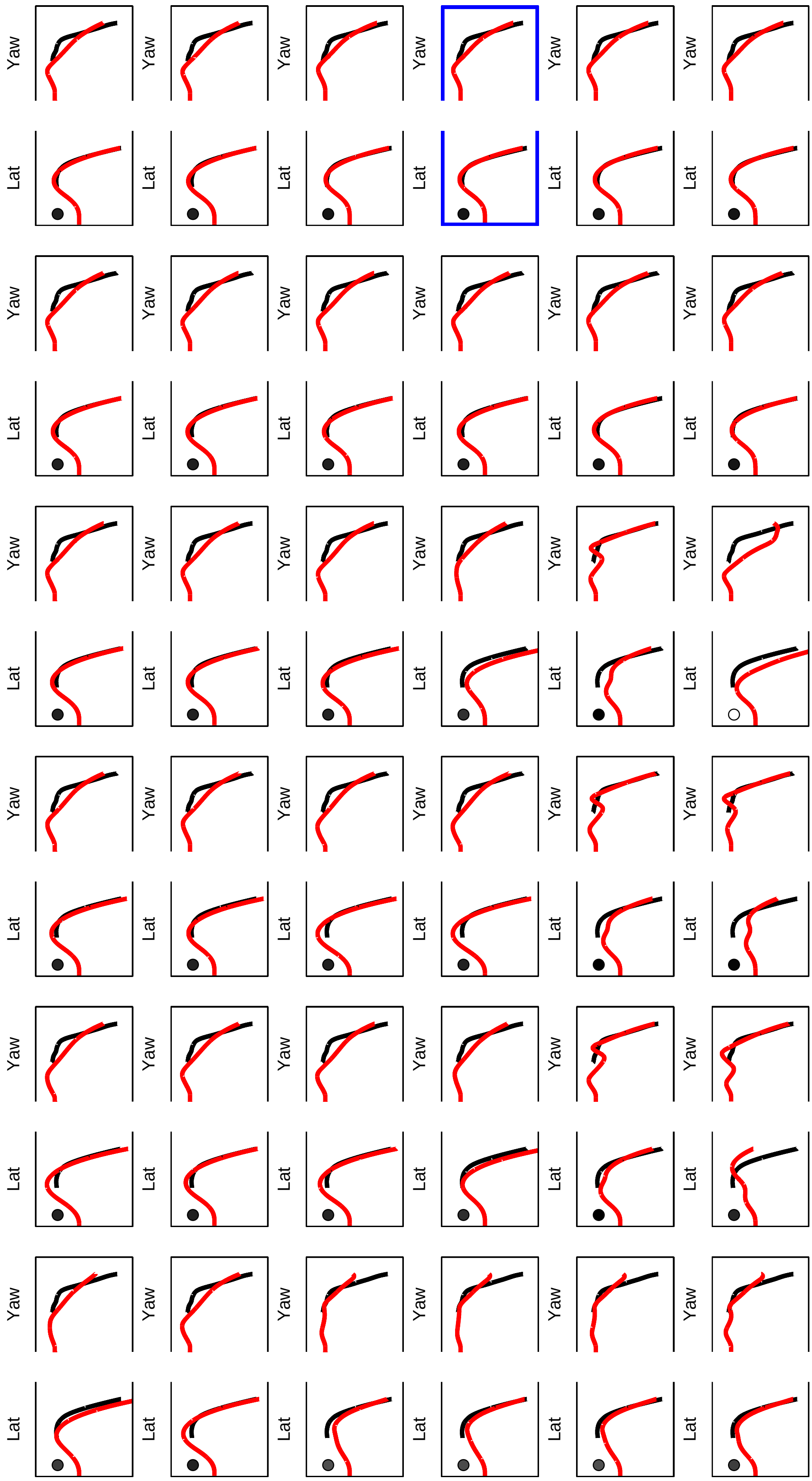


Fig. B.15: Optimised trajectories for set 2 (scenario 8)

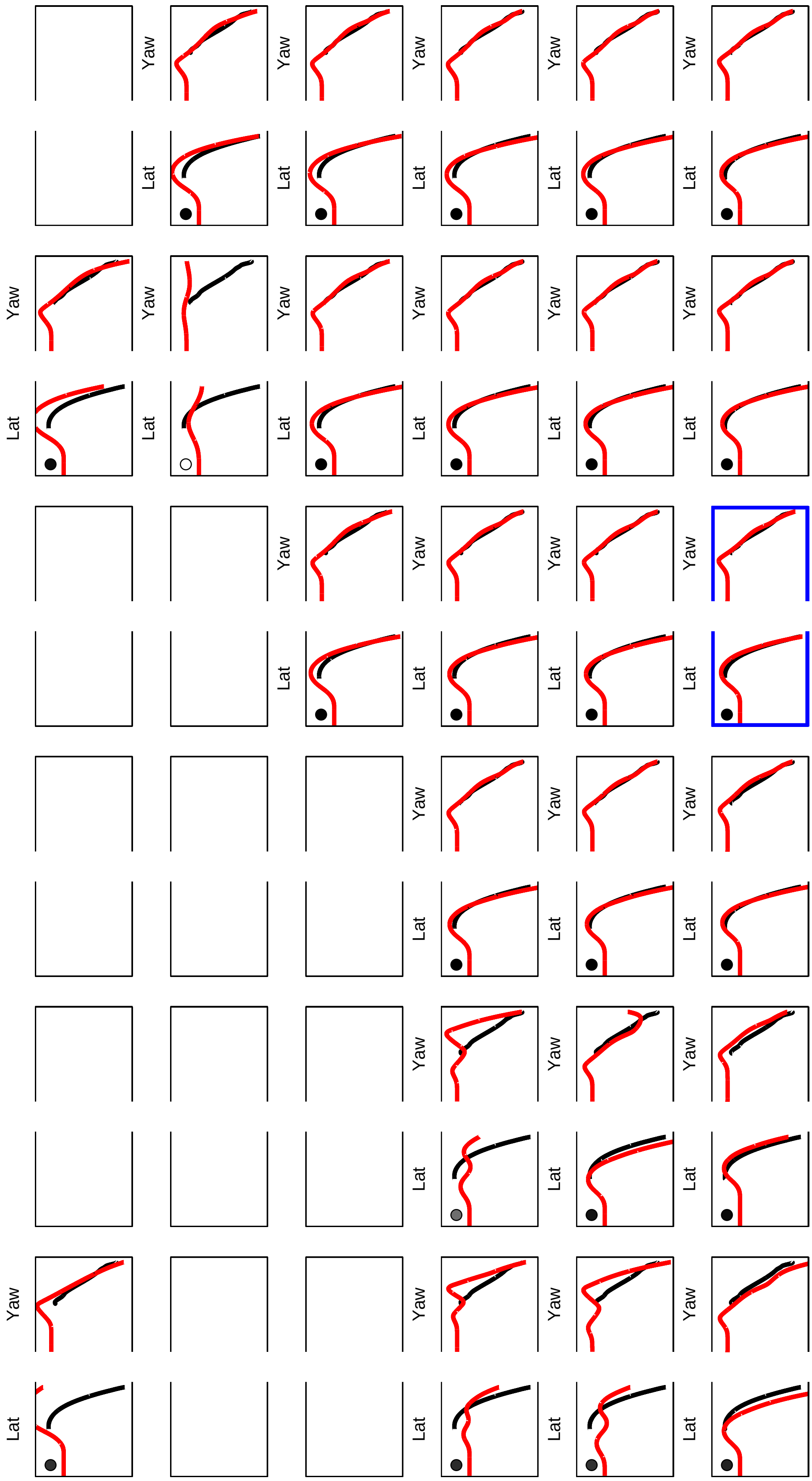


Fig. B.16: Optimised trajectories for scenario 9

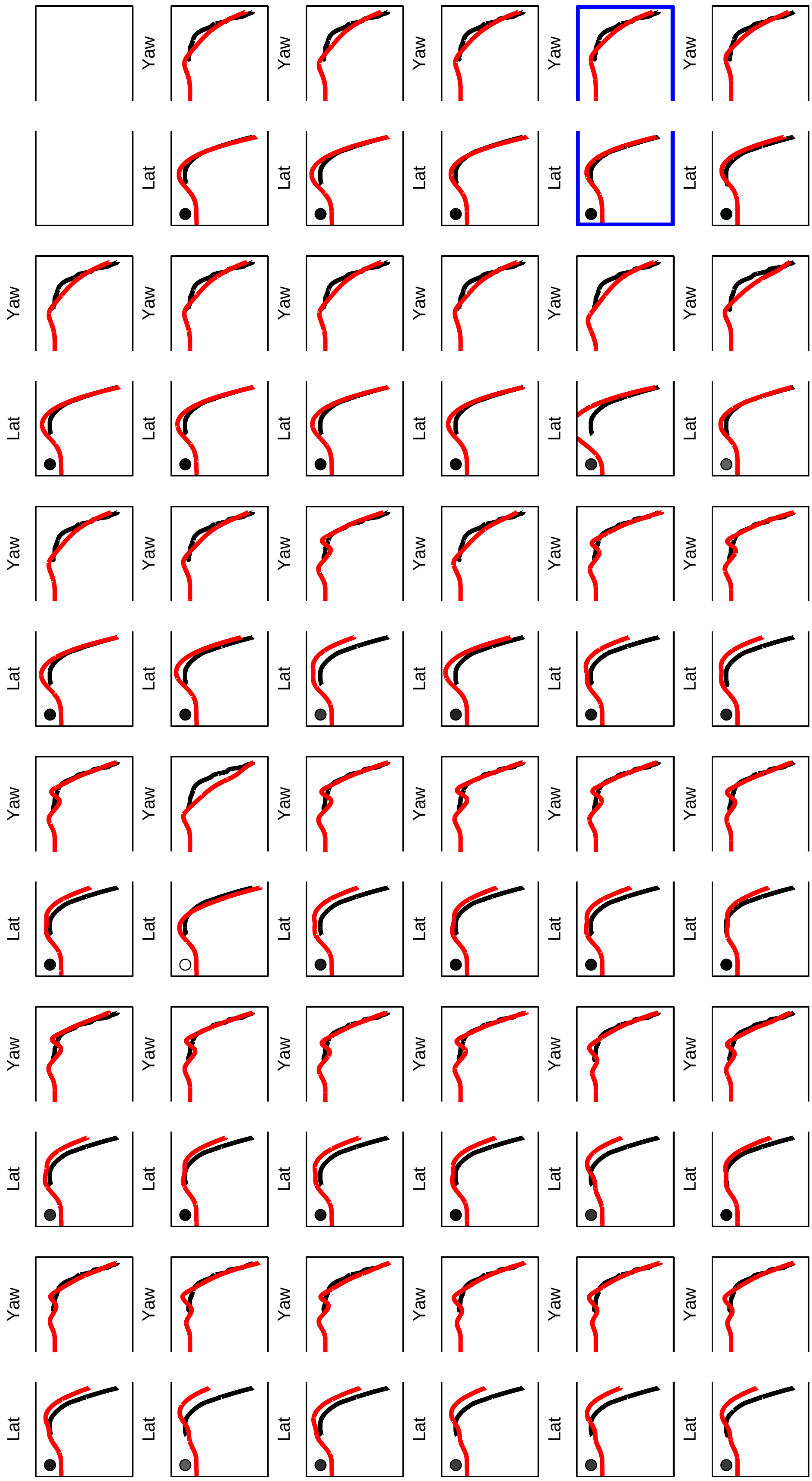


Fig. B.17: Optimised trajectories for scenario 10

C. EFFECTS OF ESC IN COMBINATION WITH OTHER RURAL ROAD SAFETY MEASURES

Figures are presented below that show the effect of ESC in combination with other rural road safety measures for each of the representative parameter sets used to simulate the ten loss of control scenarios. Caution is advised in the interpretation of the figures (see Section 7.3).

Each figure consists of five graphs which share a common abscissa (longitudinal distance along the roadway). In all graphs, a blue line refers to the vehicle without ESC and a red line refers to the vehicle with ESC.

The top graph describes the lateral offset of the vehicle's centre of mass relative to the centre of the left lane of the road. A positive lateral offset is to the left and a negative lateral offset is to the right. A thin black line displays the driver path. A thick black line shows the lateral offset of the scenario trajectory for reference.

The second graph describes the yaw angle of the vehicle relative to the centre of the road. This can be thought of as the angle at which the vehicle is heading, relative to the centre line of the road. A positive yaw is an anti-clockwise angle and a negative yaw is a clockwise angle. A thin black line displays the zero point at which a vehicle is angled exactly longitudinal to the centre of the road. A thick black like shows the yaw of the scenario trajectory for reference.

The third graph describes the slide slip angle of the vehicle. A positive side slip angle indicates the vehicle has some component of velocity to the left and a negative side slip angle indicates some velocity to the right. A thin black line displays the zero point where the velocity of the vehicle is entirely in the forward, or longitudinal, direction.

The fourth and fifth graphs describe the wheel slip, due to braking, at the front and rear wheels respectively. In each graph the left wheel is shown as a solid line and the right wheel as a dashed line.

C.1 Scenario 1

The following figures are presented:

- Effect of ESC on representative value set 1 (lower speed)
- Effect of ESC on representative value set 1 (sealed shoulder)
- Effect of ESC on representative value set 2 (lower speed)
- Effect of ESC on representative value set 2 (sealed shoulder)
- Effect of ESC on representative value set 3 (lower speed)
- Effect of ESC on representative value set 3 (sealed shoulder)
- Effect of ESC on representative value set 4 (lower speed)
- Effect of ESC on representative value set 4 (sealed shoulder)

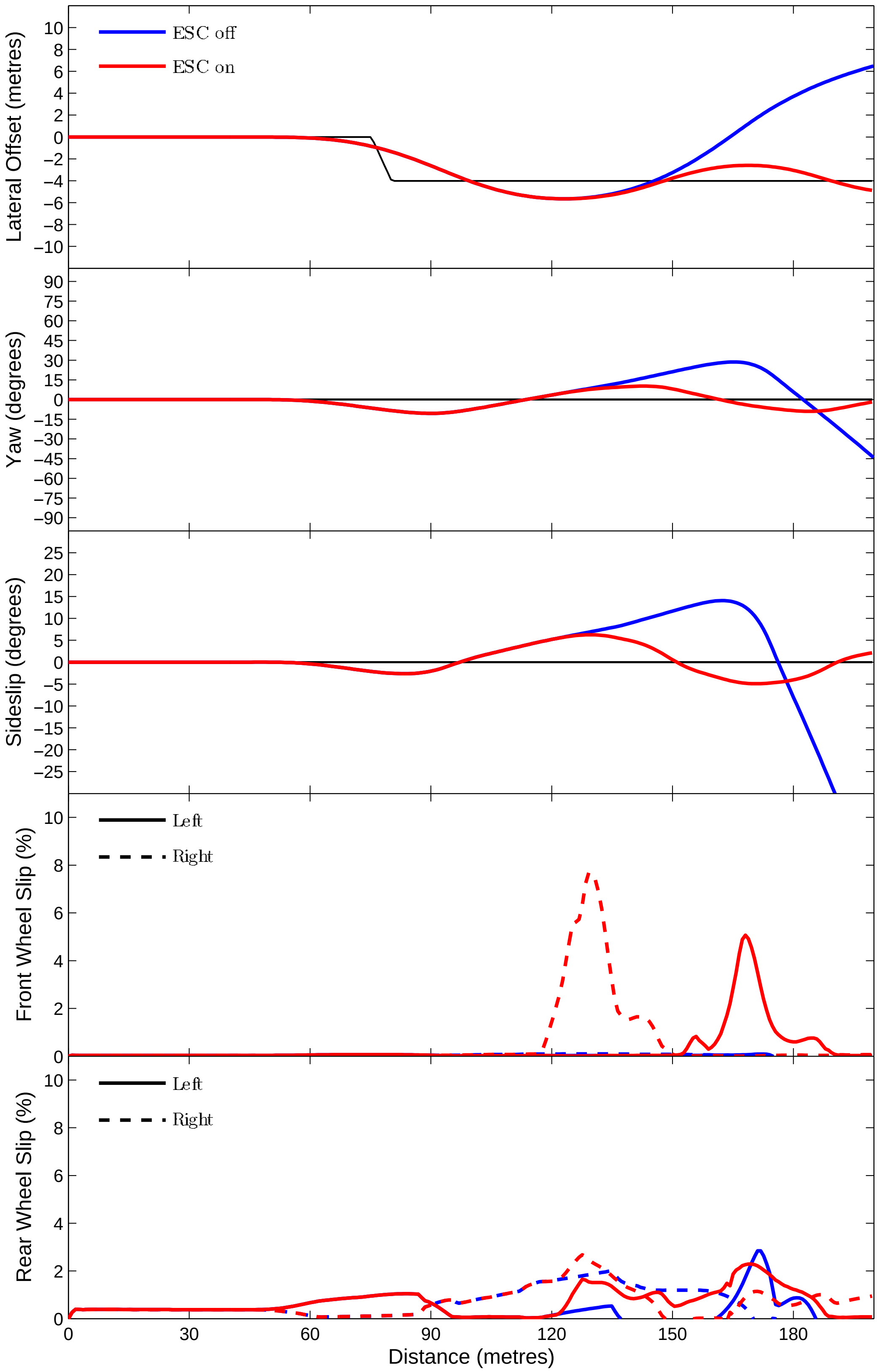


Fig. C.1: Effect of ESC with an initial speed 5 km/h lower (representative value set 1, scenario 1)

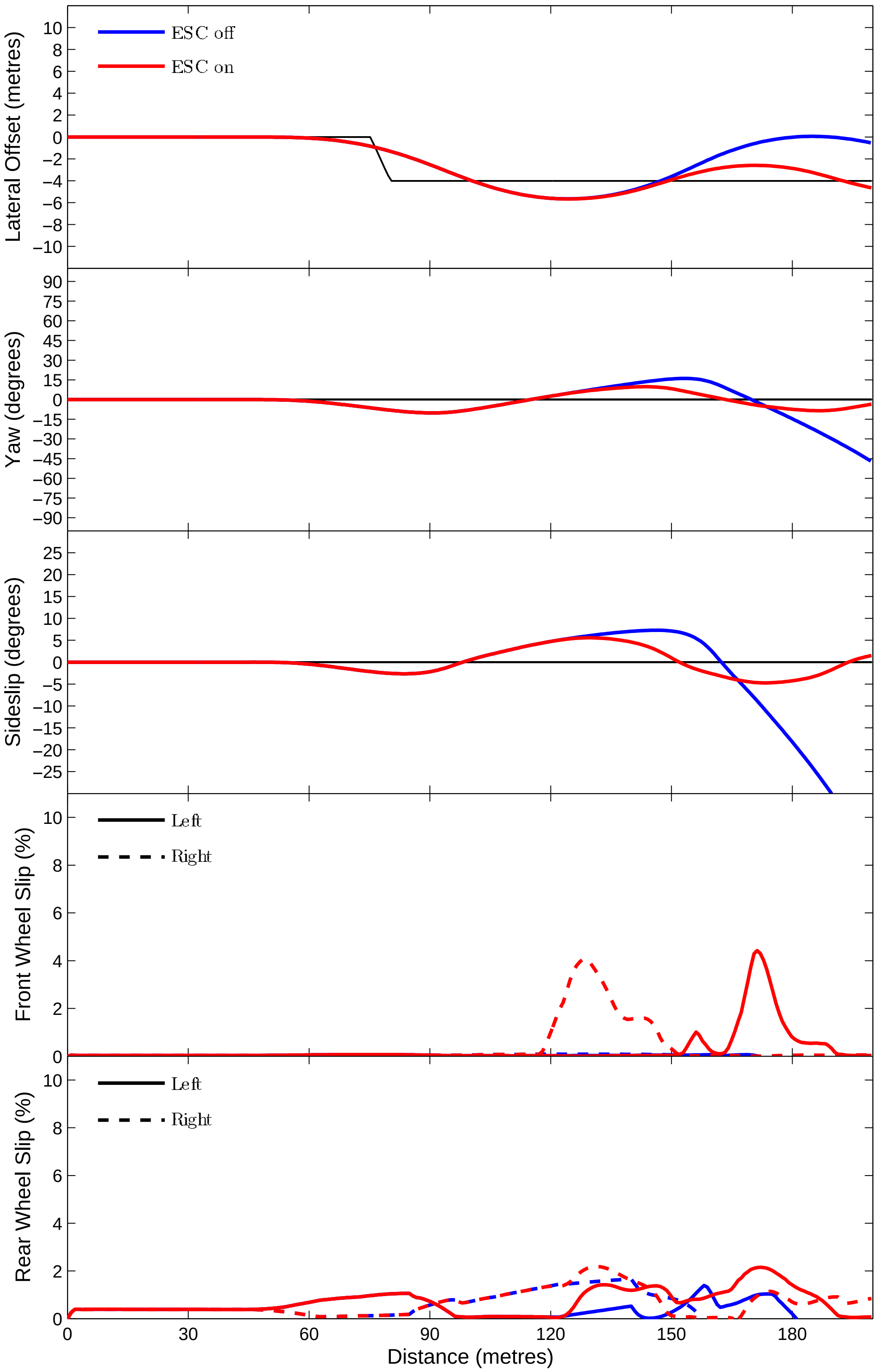


Fig. C.2: Effect of ESC with a sealed shoulder (representative value set 1, scenario 1)

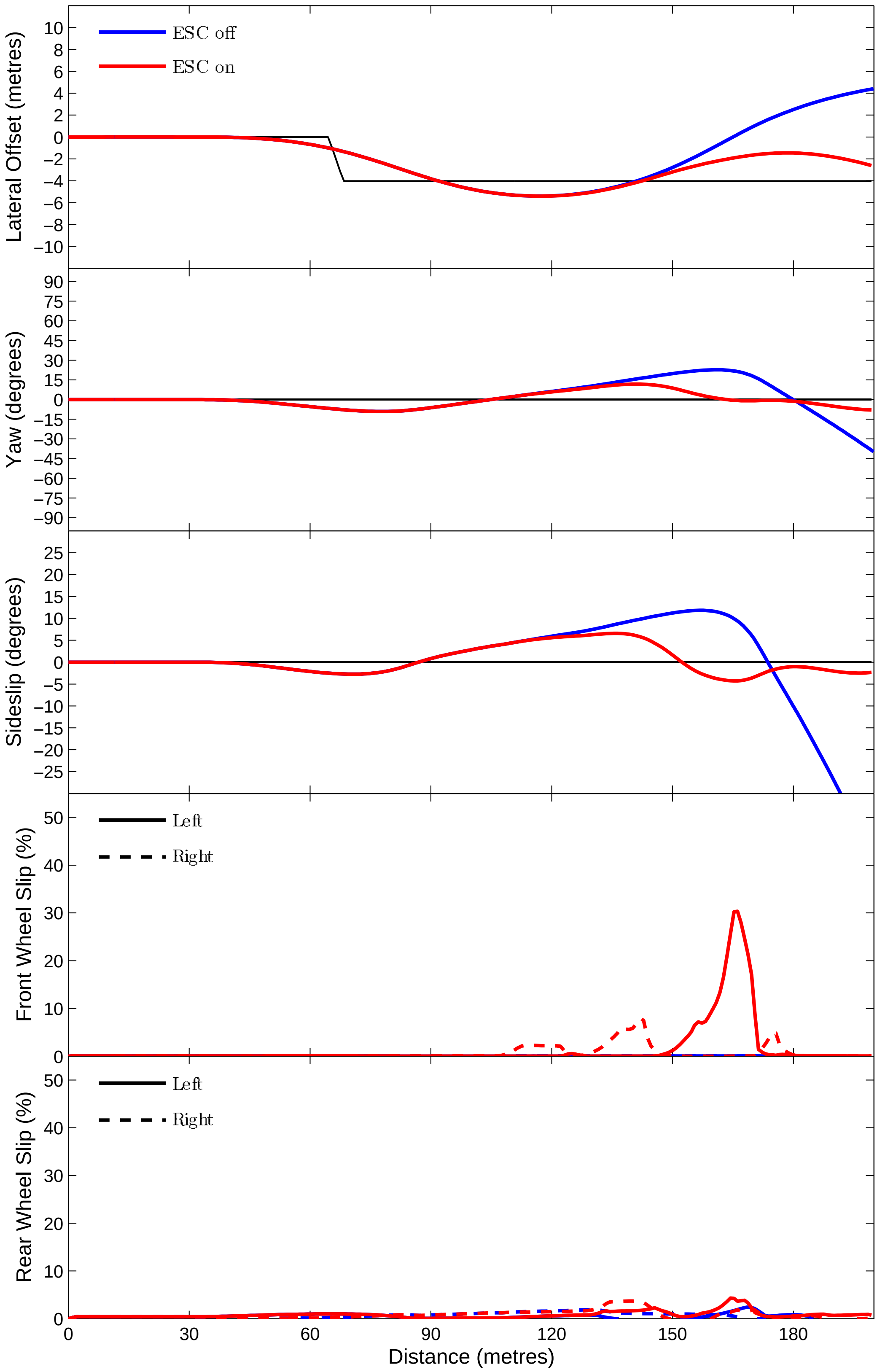


Fig. C.3: Effect of ESC with an initial speed 5 km/h lower (representative value set 2, scenario 1)

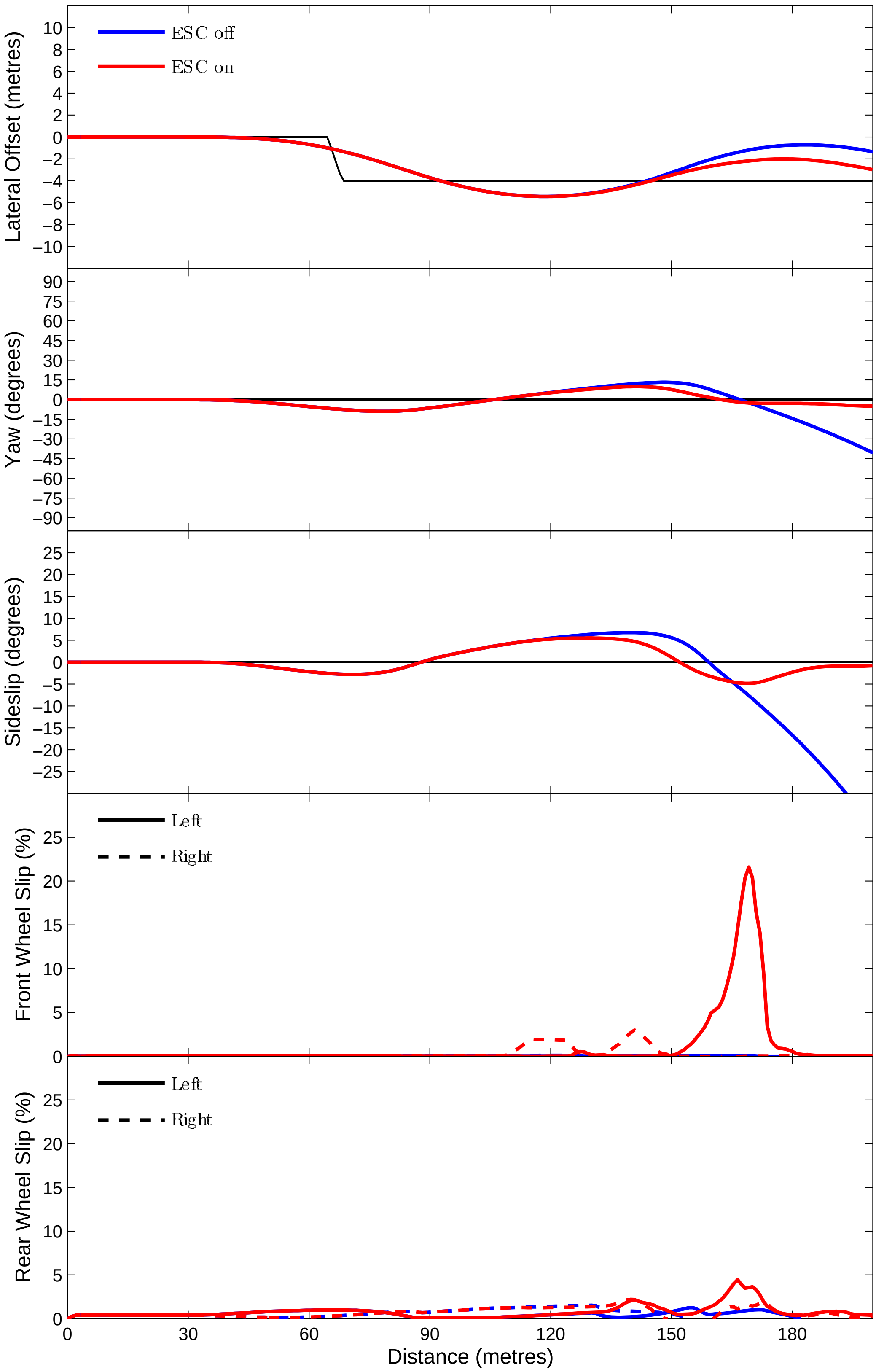


Fig. C.4: Effect of ESC with a sealed shoulder (representative value set 2, scenario 1)

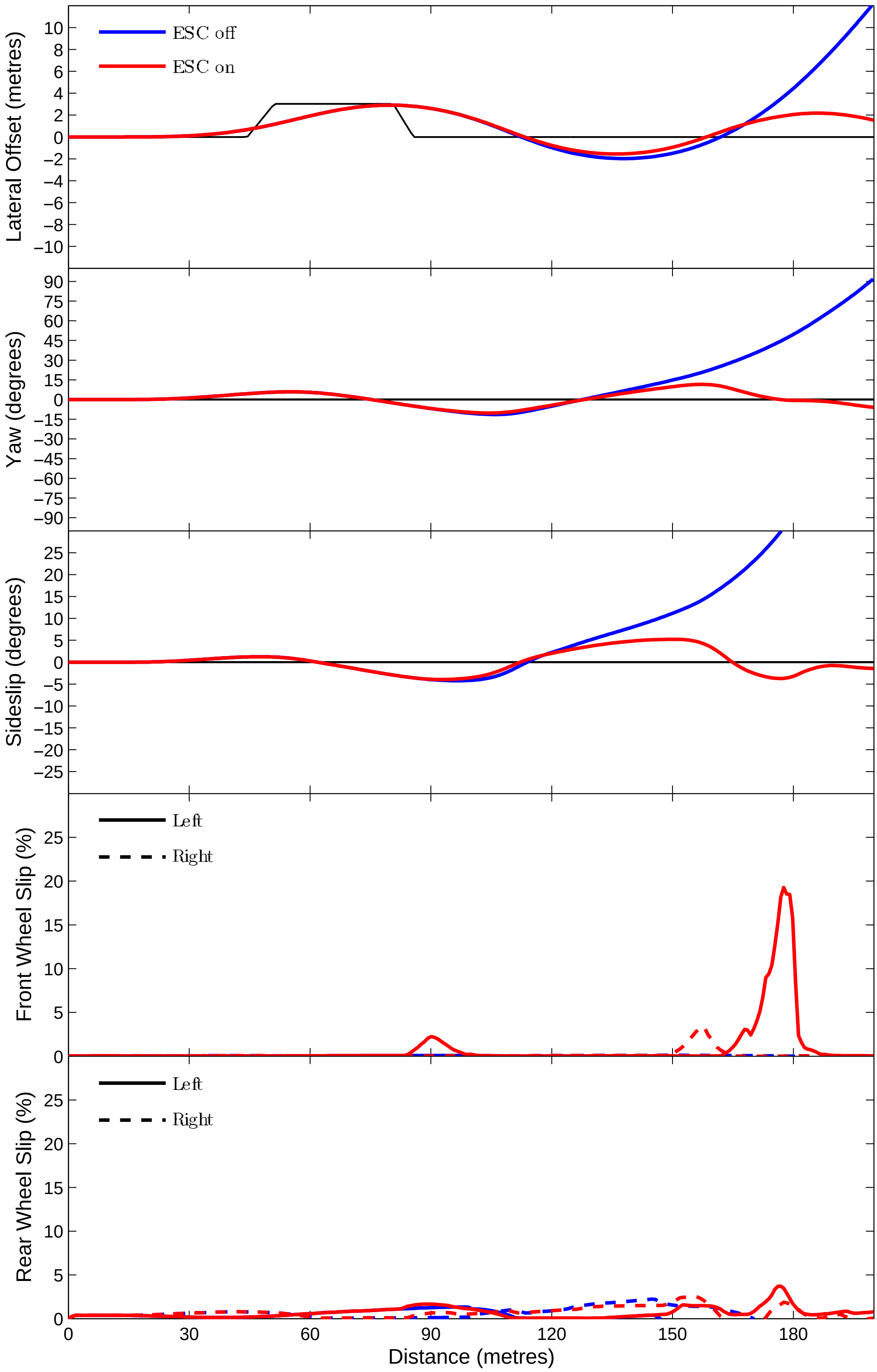


Fig. C.5: Effect of ESC with an initial speed 5 km/h lower (representative value set 3, scenario 1)

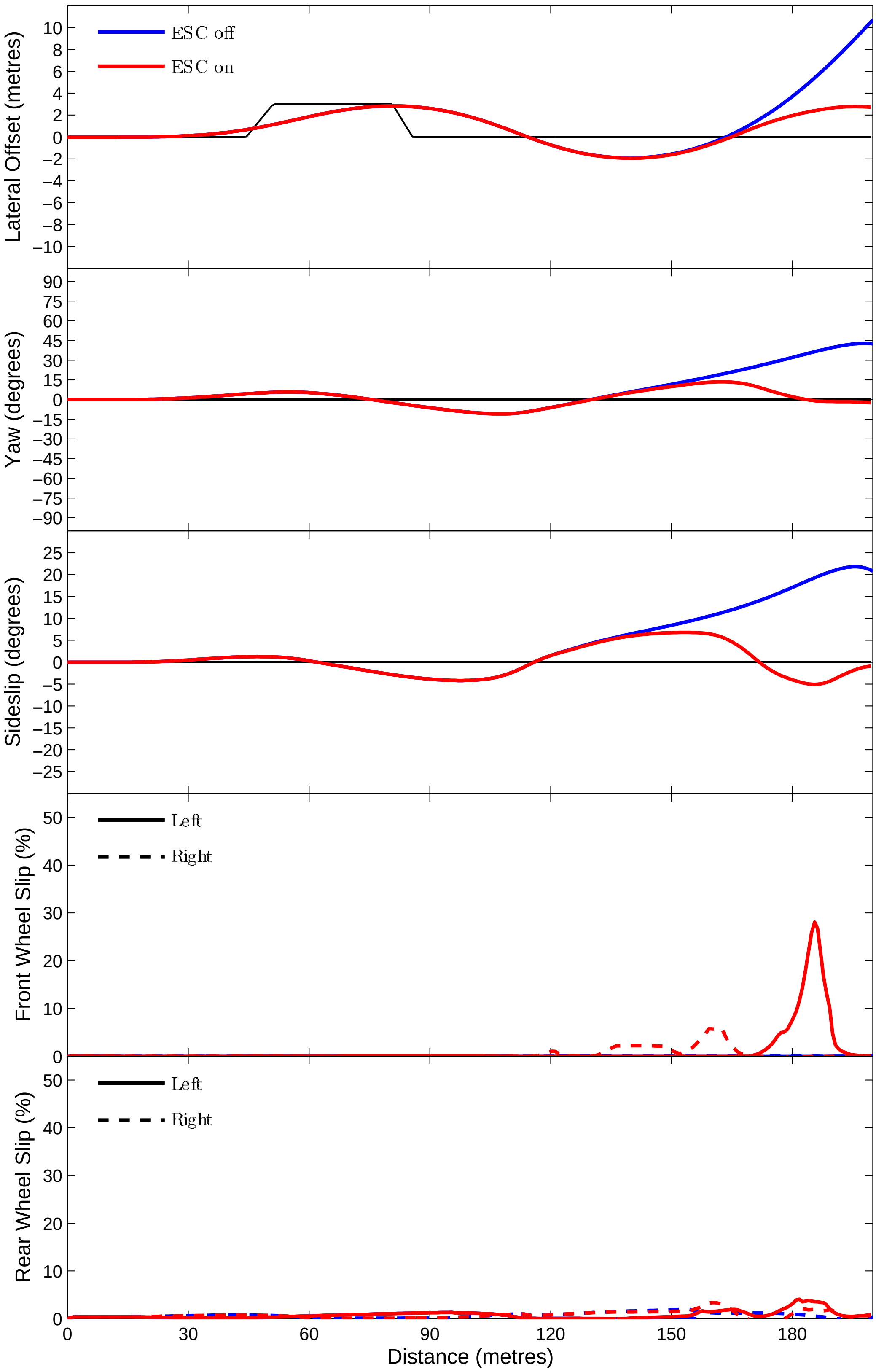


Fig. C.6: Effect of ESC with a sealed shoulder (representative value set 3, scenario 1)

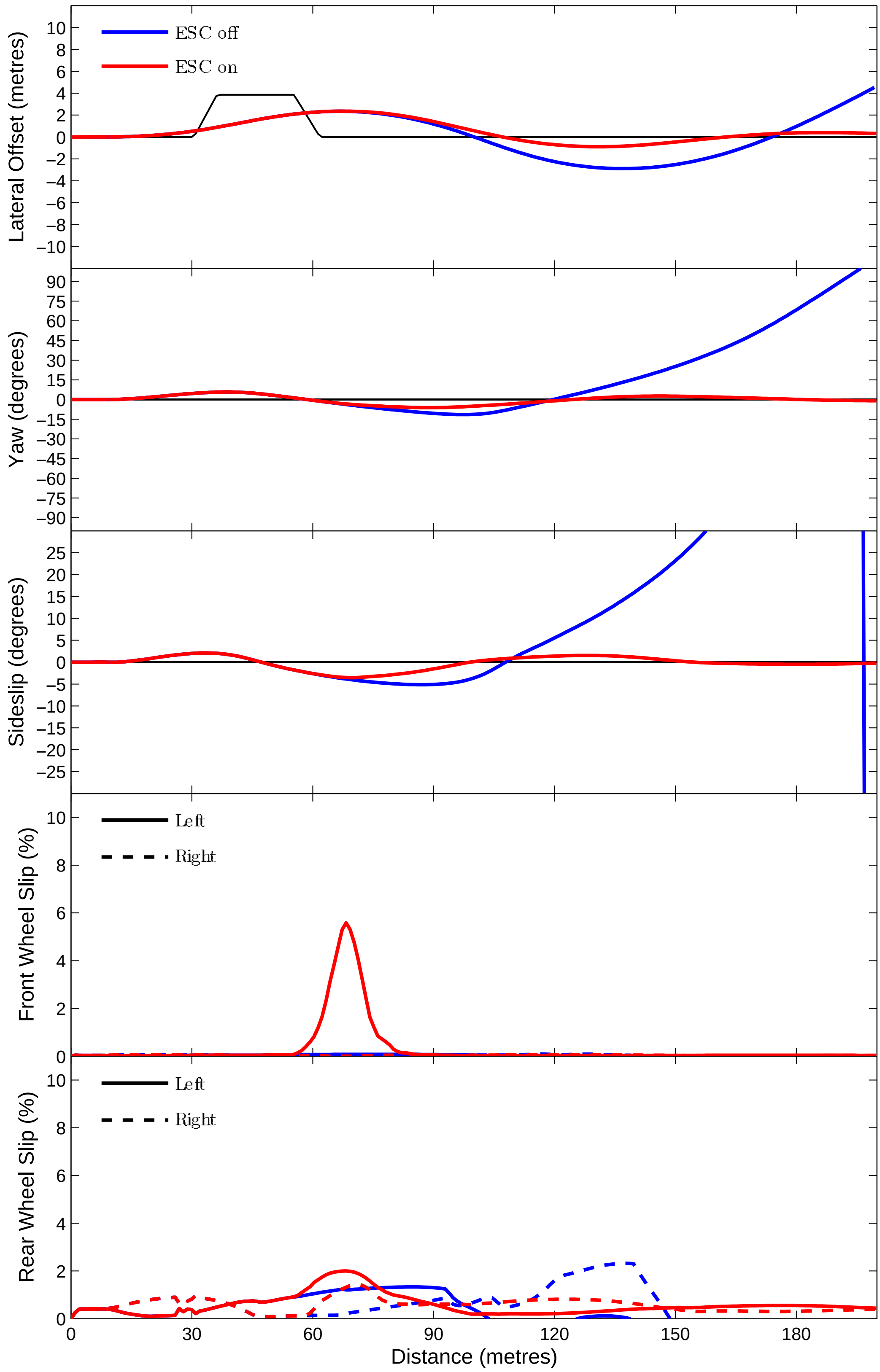


Fig. C.7: Effect of ESC with an initial speed 5 km/h lower (representative value set 4, scenario 1)

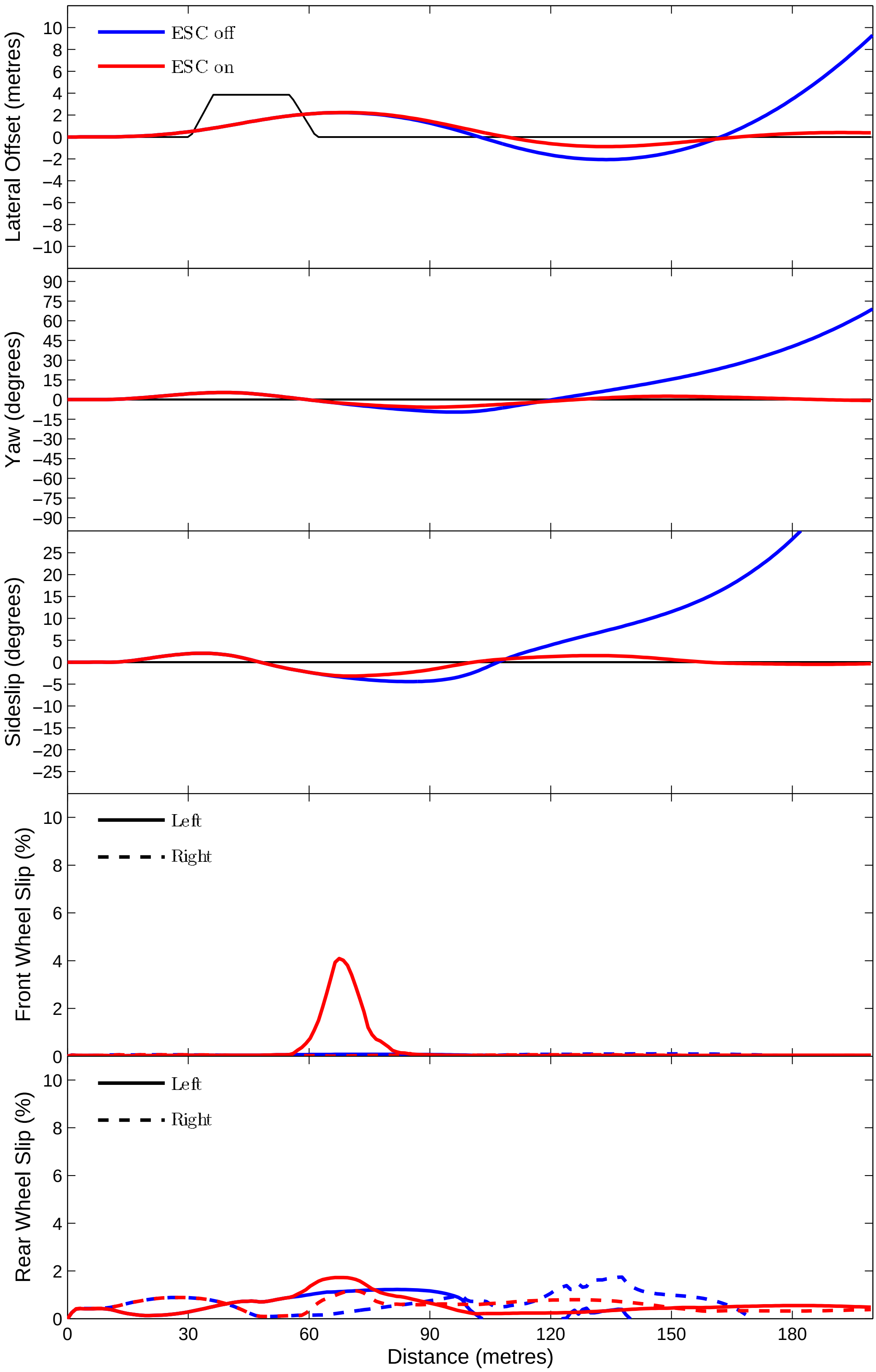


Fig. C.8: Effect of ESC with a sealed shoulder (representative value set 4, scenario 1)

C.2 Scenario 2

The following figures are presented:

- Effect of ESC on representative value set (lower speed)
- Effect of ESC on representative value set (sealed road)

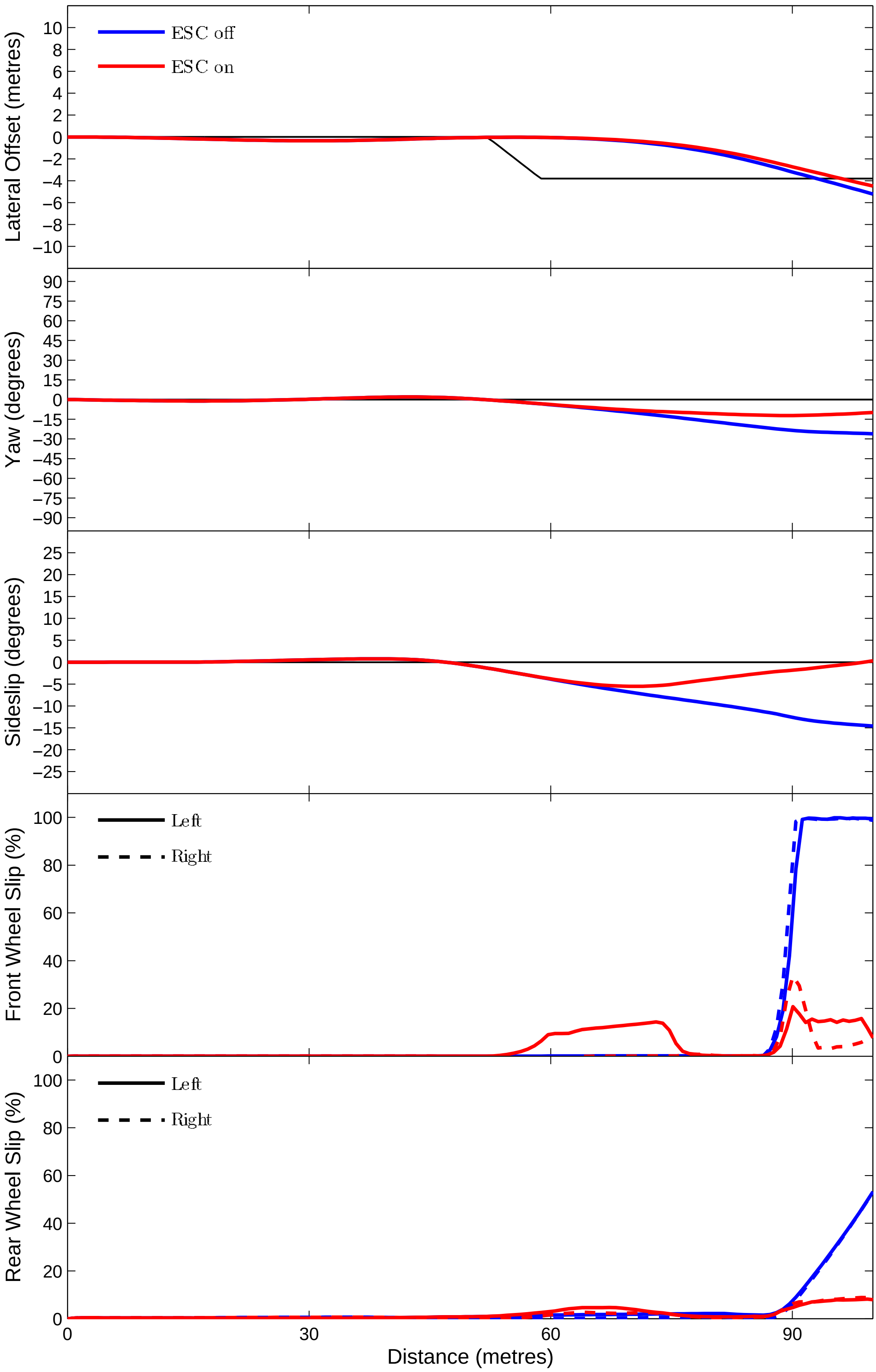


Fig. C.9: Effect of ESC with an initial speed 5 km/h lower (scenario 2)

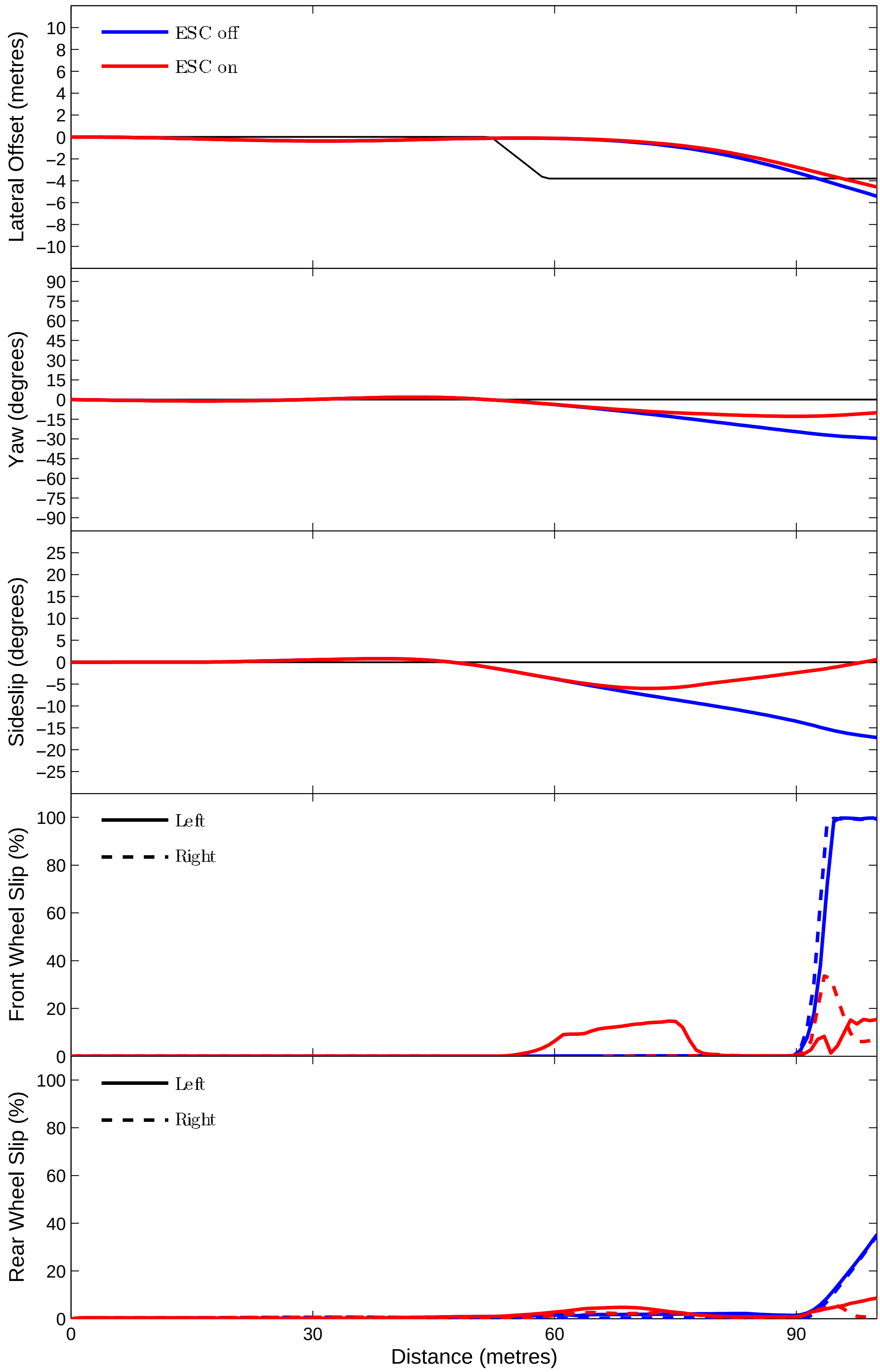


Fig. C.10: Effect of ESC with a sealed road (scenario 2)

C.3 Scenario 3

The following figures are presented:

- Effect of ESC on representative value set (lower speed)
- Effect of ESC on representative value set (sealed shoulder)

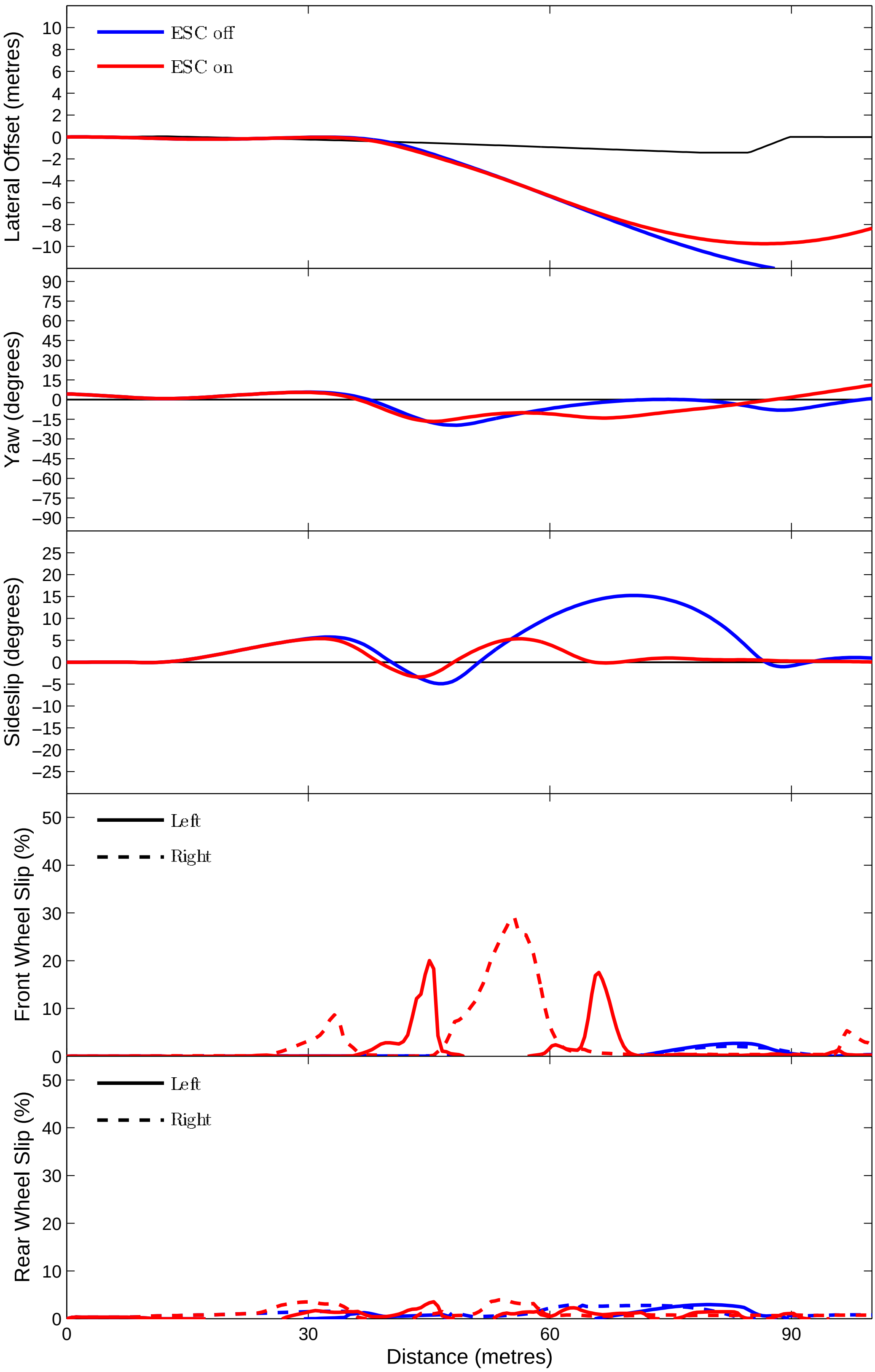


Fig. C.11: Effect of ESC with an initial speed 5 km/h lower (scenario 3)

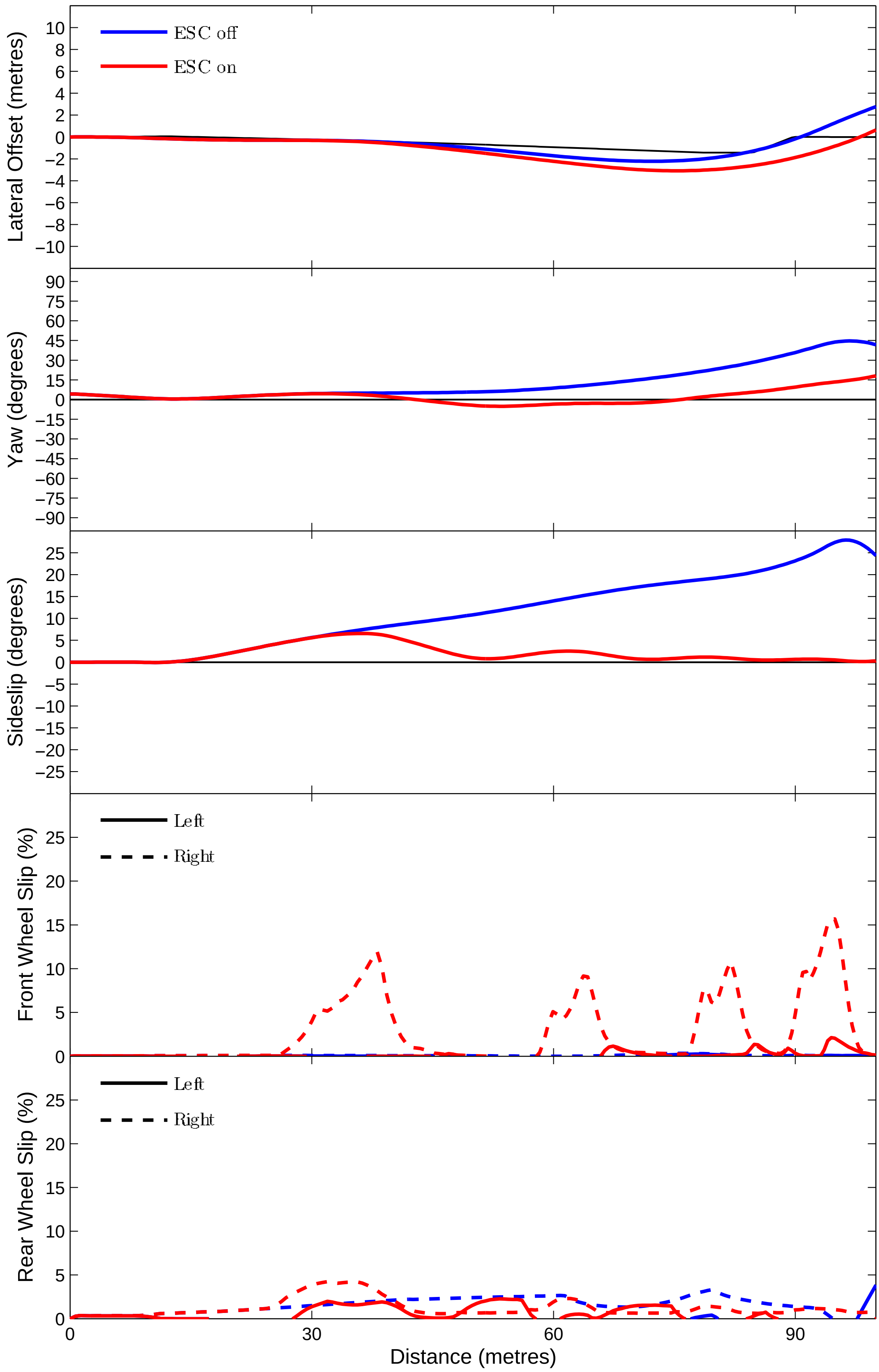


Fig. C.12: Effect of ESC with a sealed shoulder (scenario 3)

C.4 Scenario 4

The following figures are presented:

- Effect of ESC on representative value set 1 (lower speed)
- Effect of ESC on representative value set 1 (sealed shoulder)
- Effect of ESC on representative value set 2 (lower speed)
- Effect of ESC on representative value set 2 (sealed shoulder)

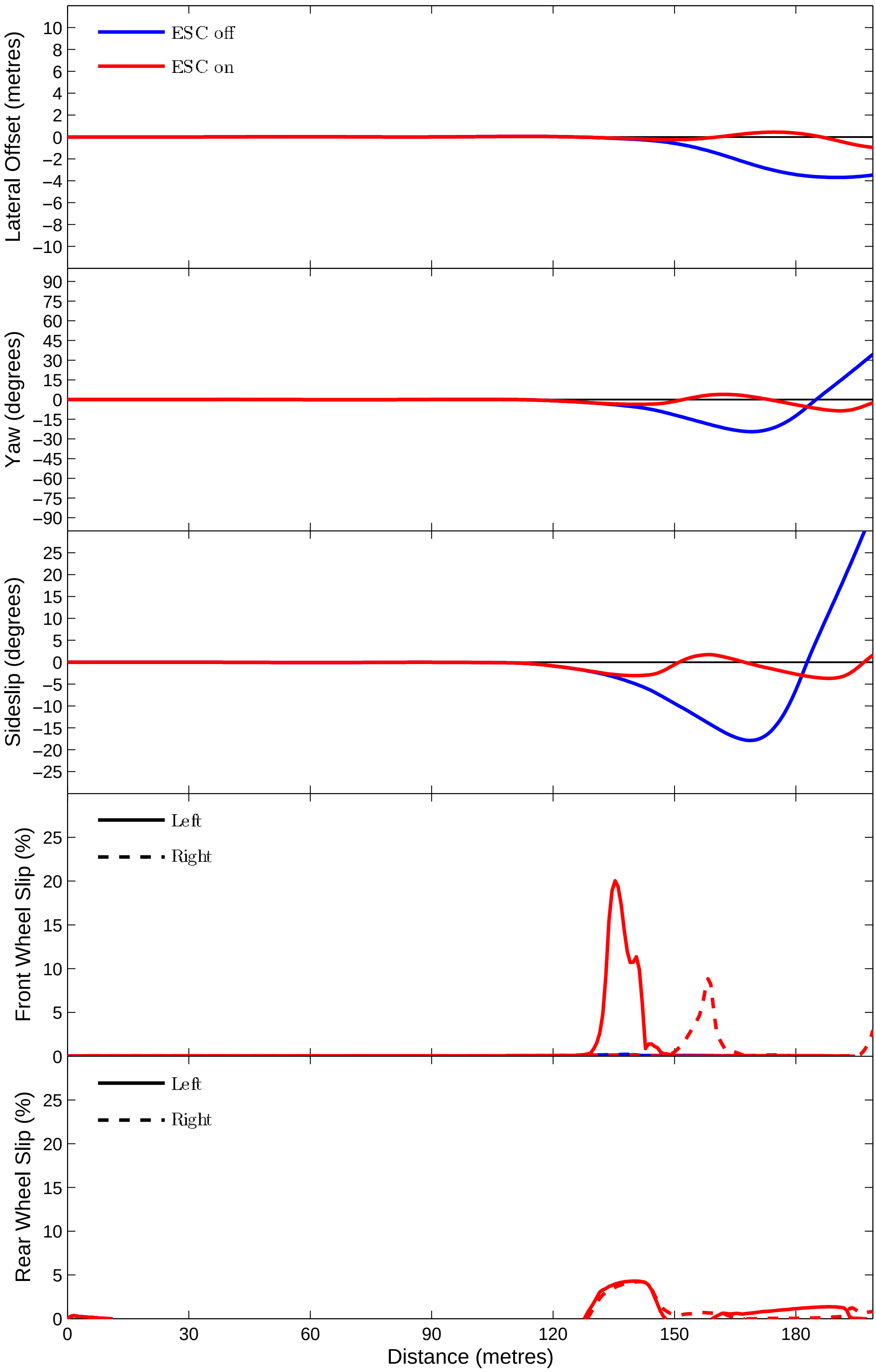


Fig. C.13: Effect of ESC with an initial speed 5 km/h lower (representative value set 1, scenario 4)

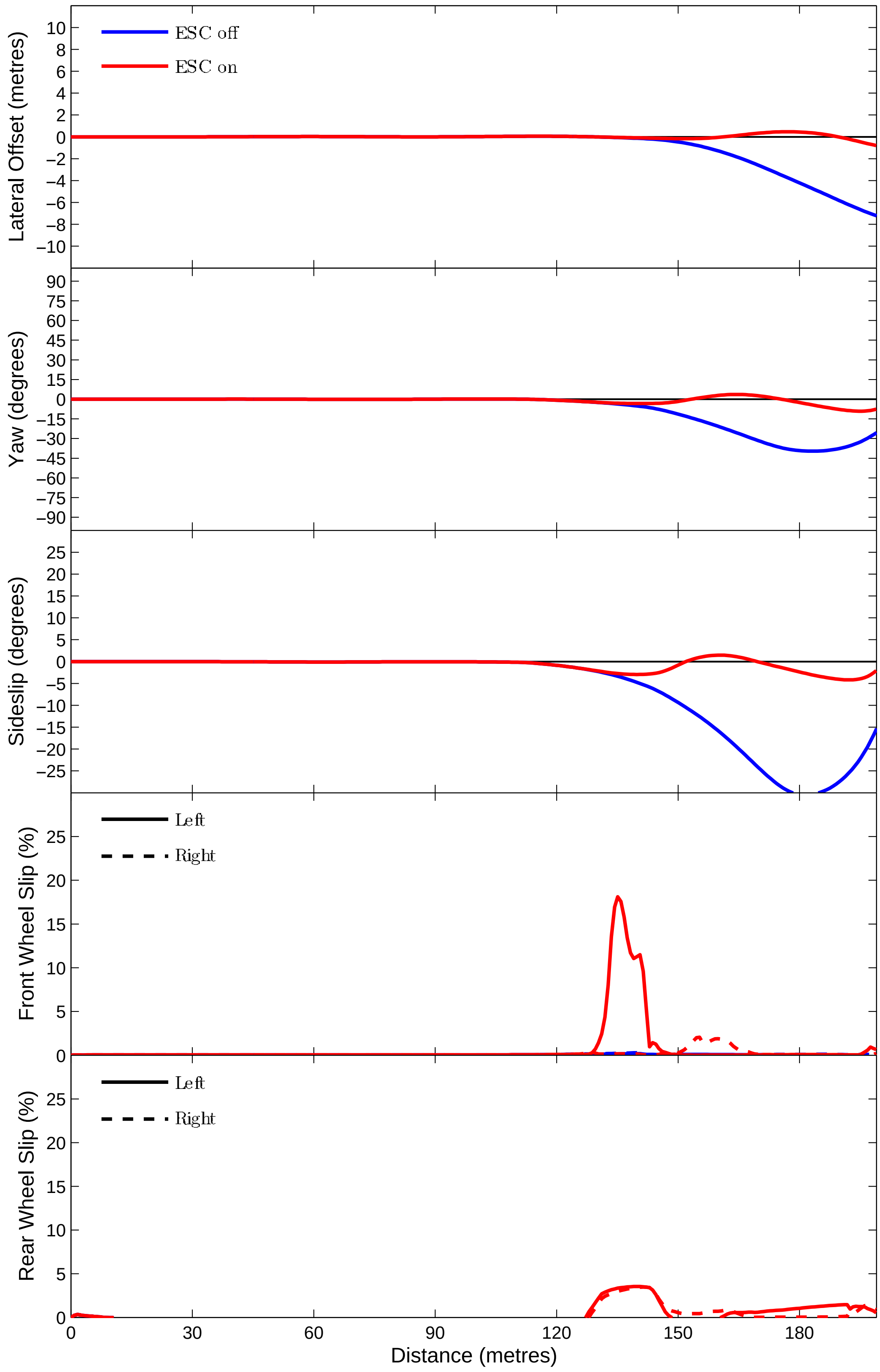


Fig. C.14: Effect of ESC with a sealed shoulder (representative value set 1, scenario 4)

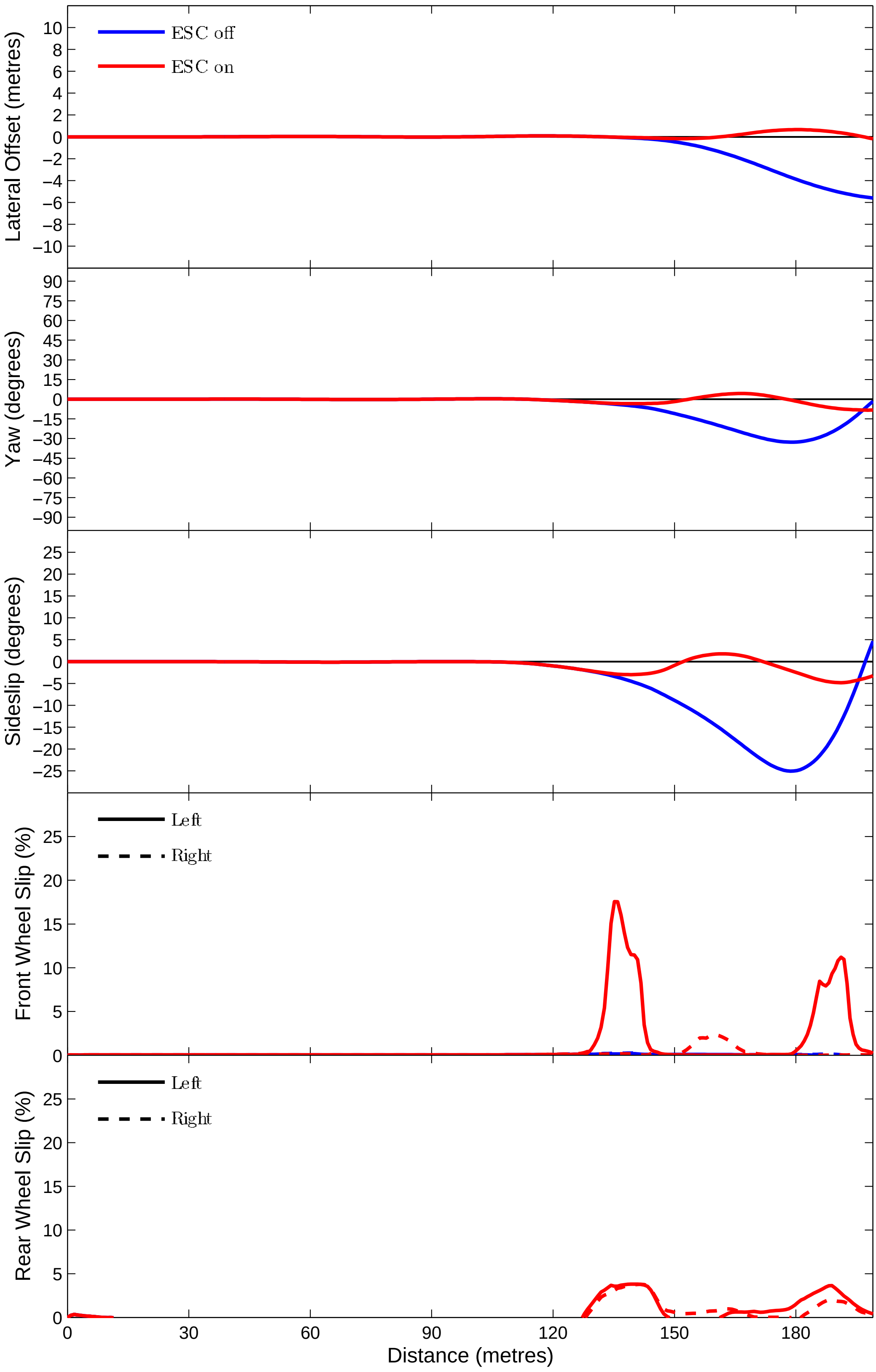


Fig. C.15: Effect of ESC with an initial speed 5 km/h lower (representative value set 2, scenario 4)

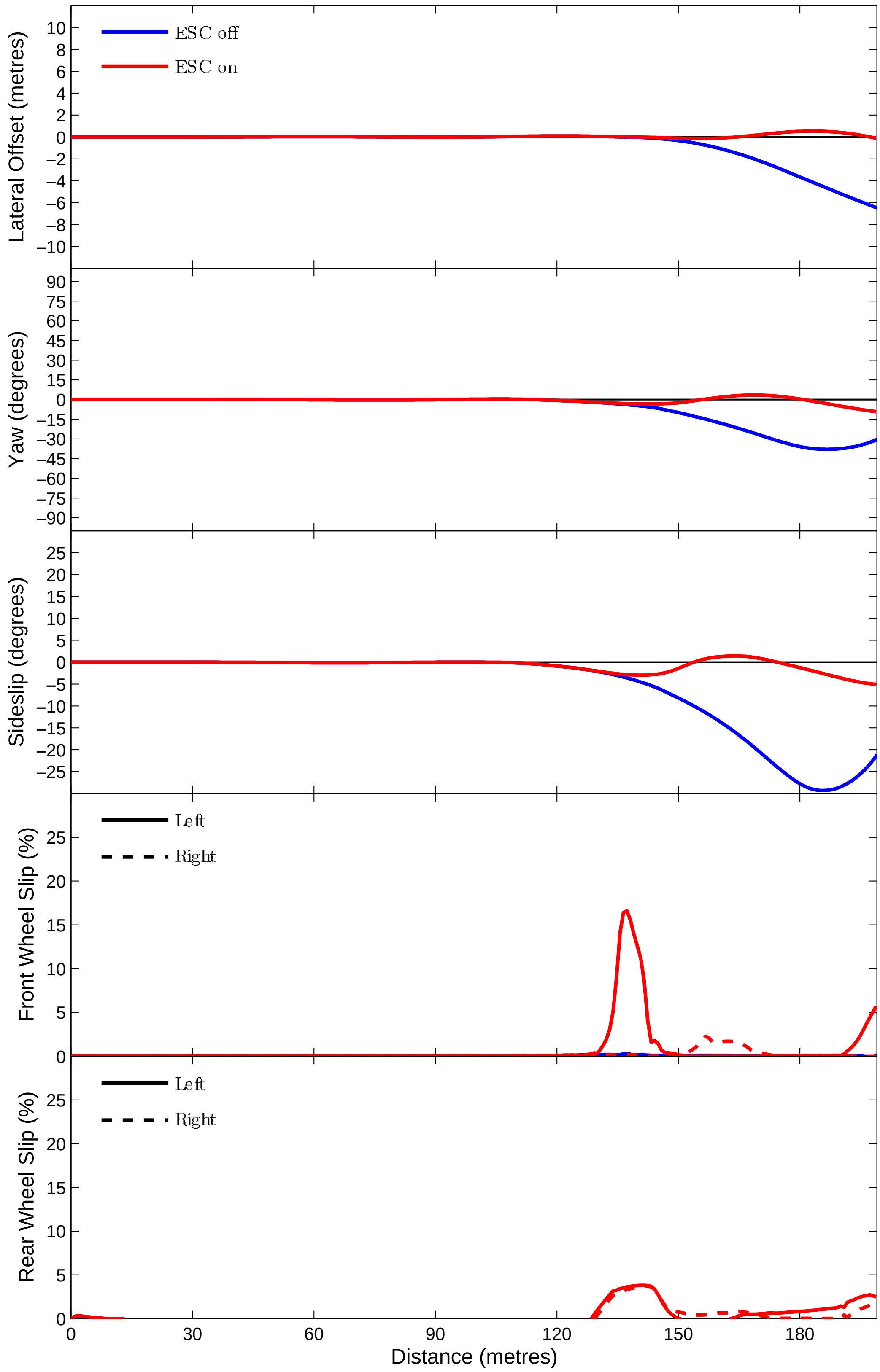


Fig. C.16: Effect of ESC with a sealed shoulder (representative value set 2, scenario 4)

C.5 Scenario 5

The following figures are presented:

- Effect of ESC on representative value set 1 (lower speed)
- Effect of ESC on representative value set 1 (sealed shoulder)
- Effect of ESC on representative value set 2 (lower speed)
- Effect of ESC on representative value set 2 (sealed shoulder)

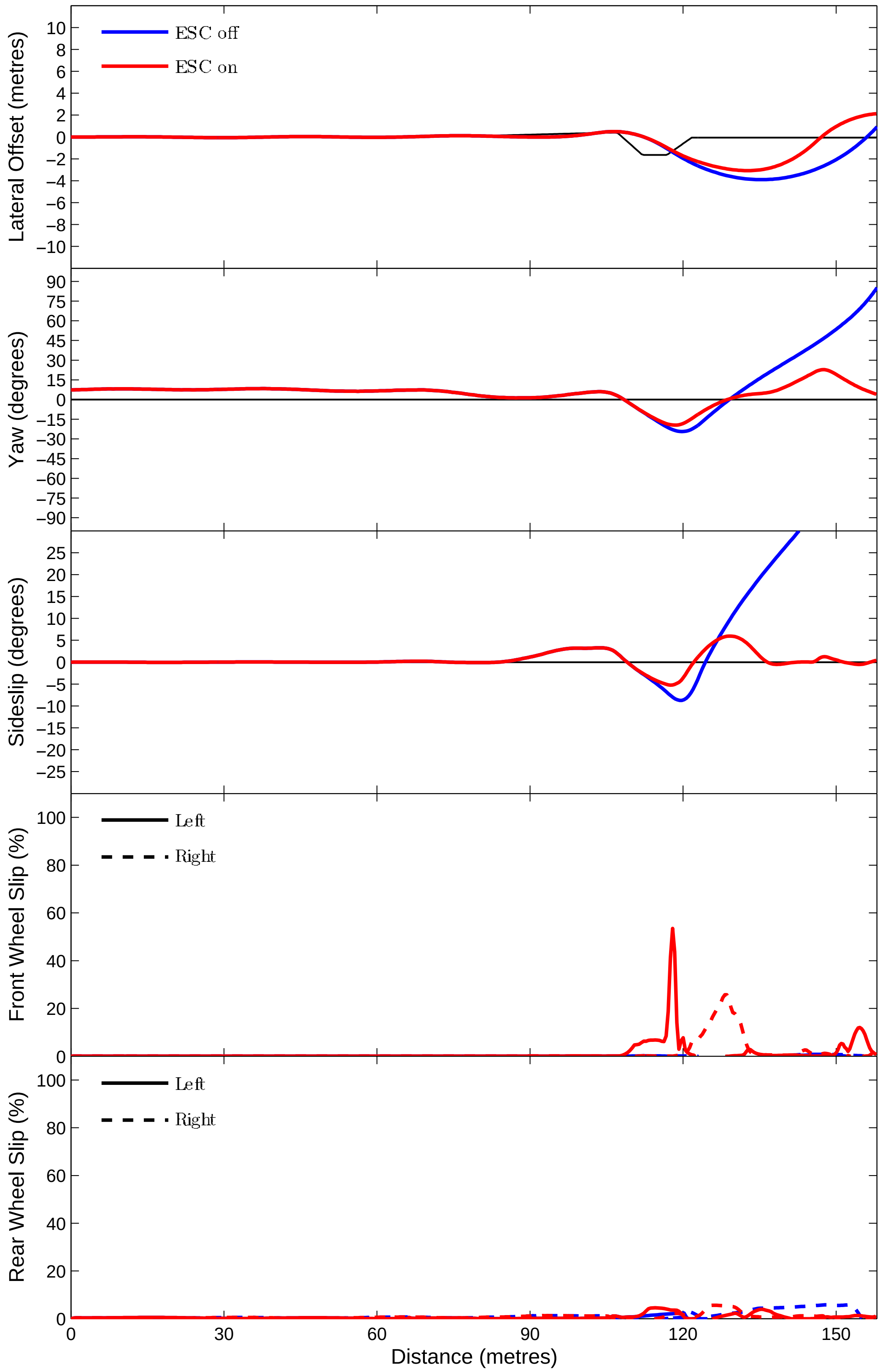


Fig. C.17: Effect of ESC with an initial speed 5 km/h lower (representative value set 1, scenario 5)

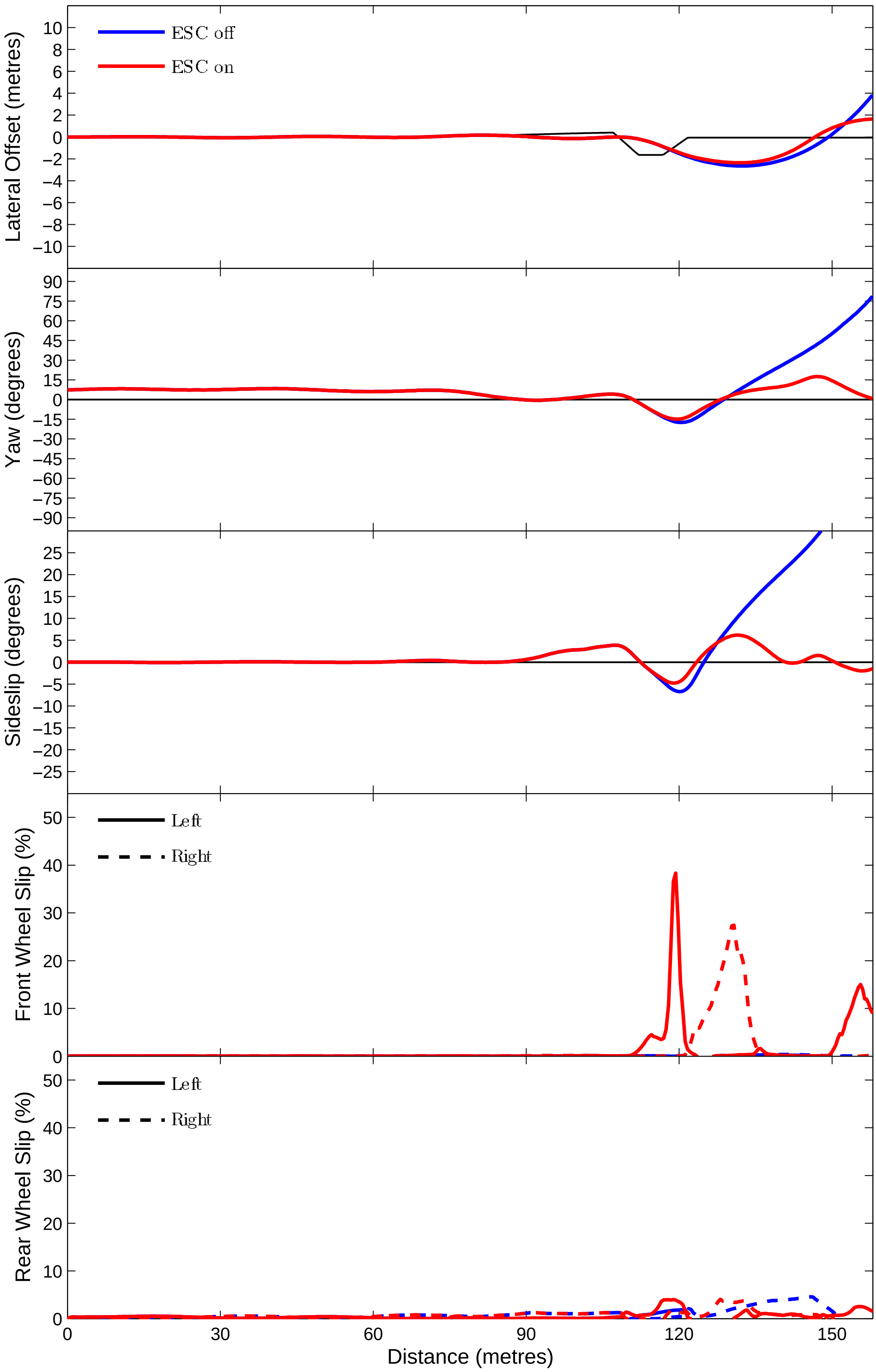


Fig. C.18: Effect of ESC with a sealed shoulder (representative value set 1, scenario 5)

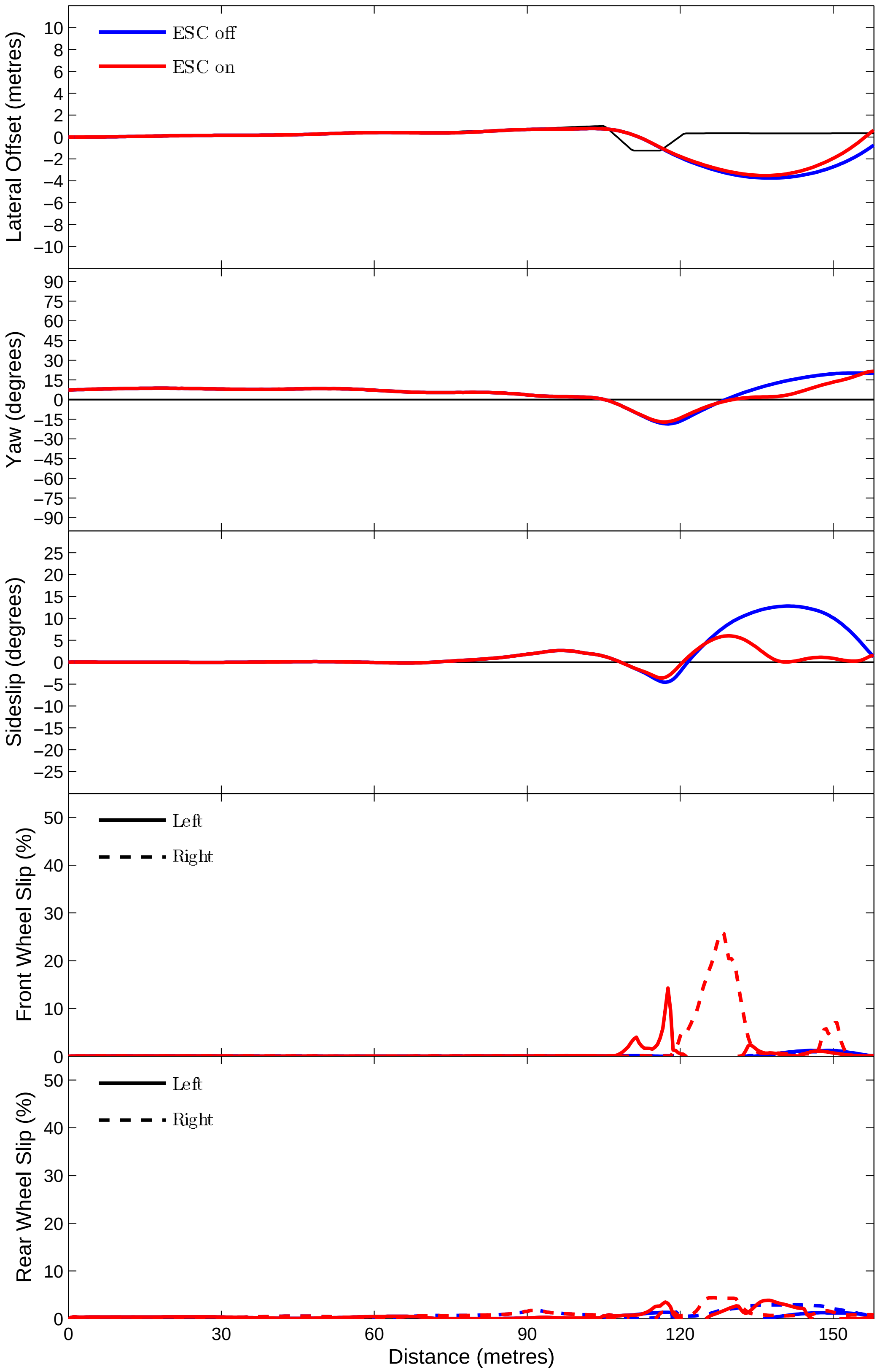


Fig. C.19: Effect of ESC with an initial speed 5 km/h lower (representative value set 2, scenario 5)

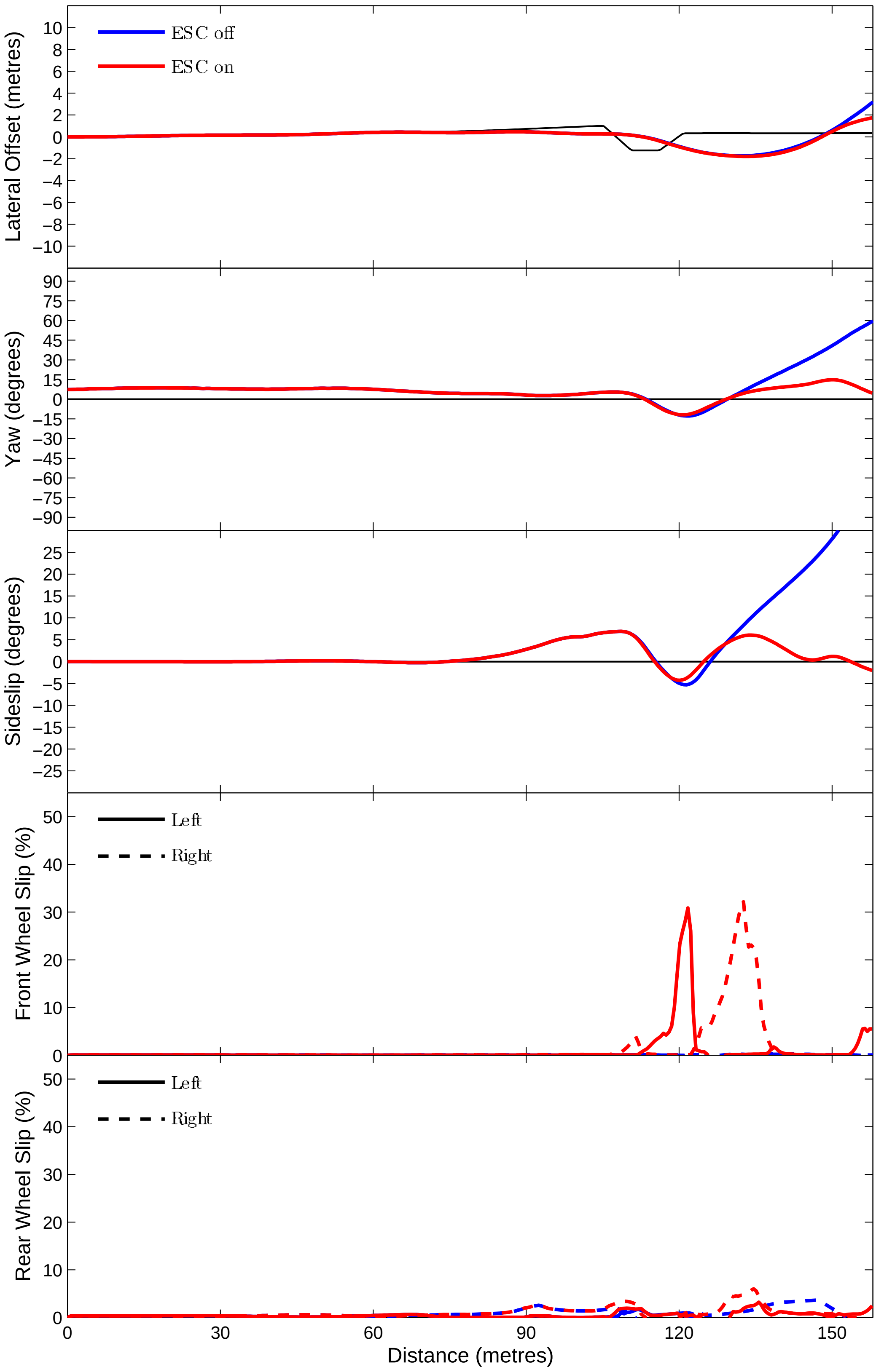


Fig. C.20: Effect of ESC with a sealed shoulder (representative value set 2, scenario 5)

C.6 Scenario 6

The following figures are presented:

- Effect of ESC on representative value set (lower speed)
- Effect of ESC on representative value set (sealed shoulder)

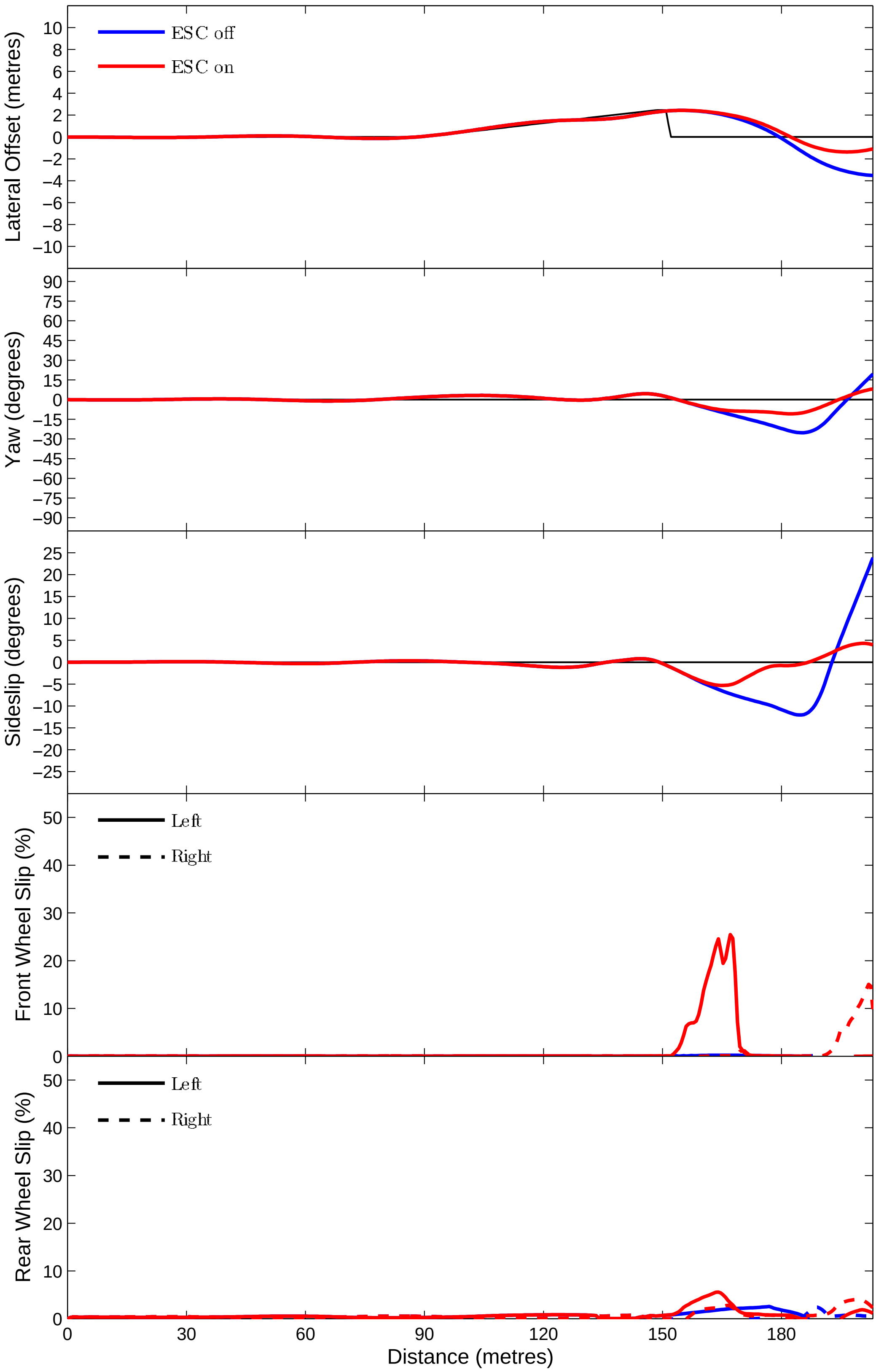


Fig. C.21: Effect of ESC with an initial speed 5 km/h lower (scenario 6)

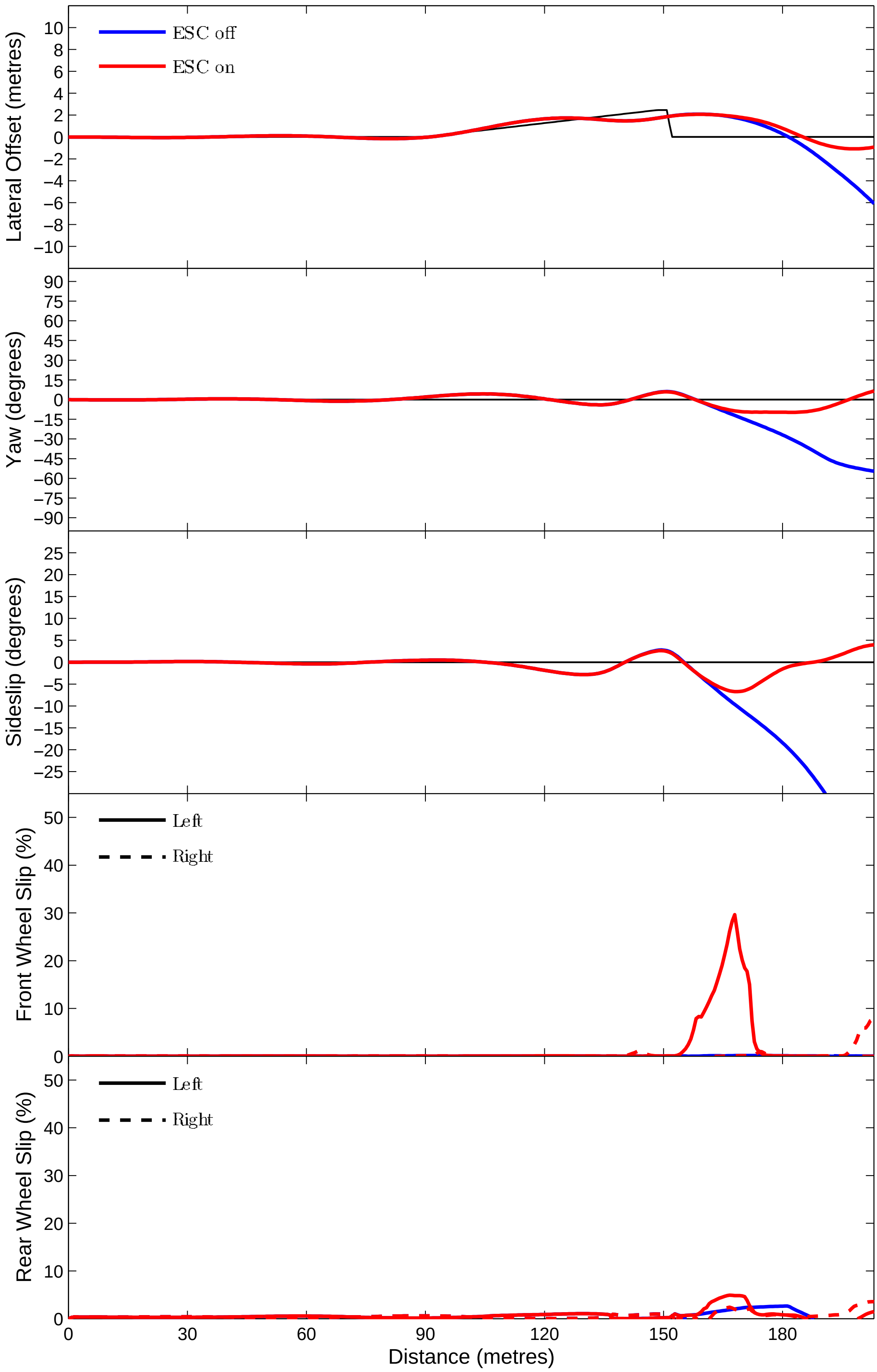


Fig. C.22: Effect of ESC with a sealed shoulder (scenario 6)

C.7 Scenario 7

The following figures are presented:

- Effect of ESC on representative value set (lower speed)
- Effect of ESC on representative value set (sealed shoulder)

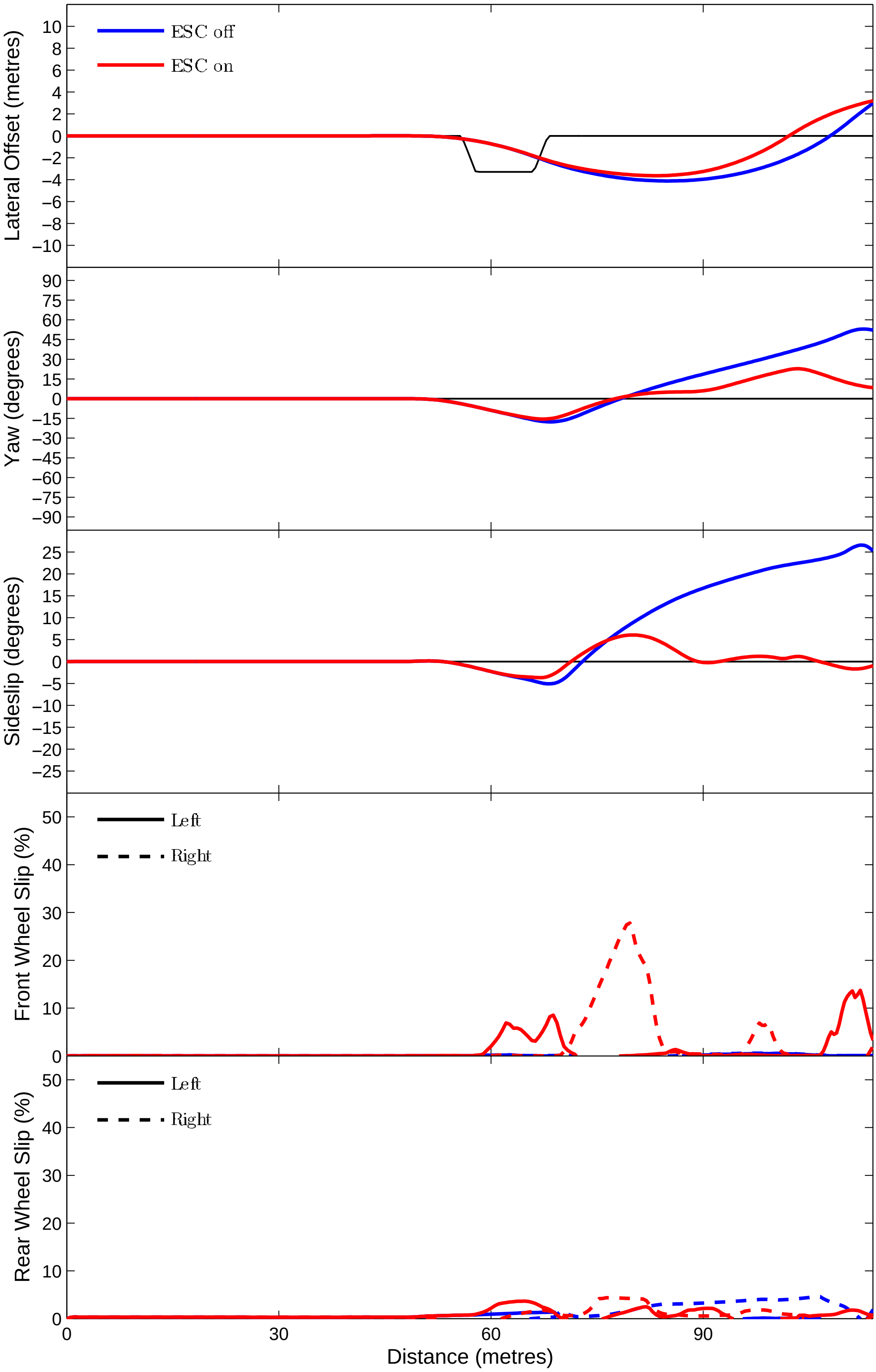


Fig. C.23: Effect of ESC with an initial speed 5 km/h lower (scenario 7)

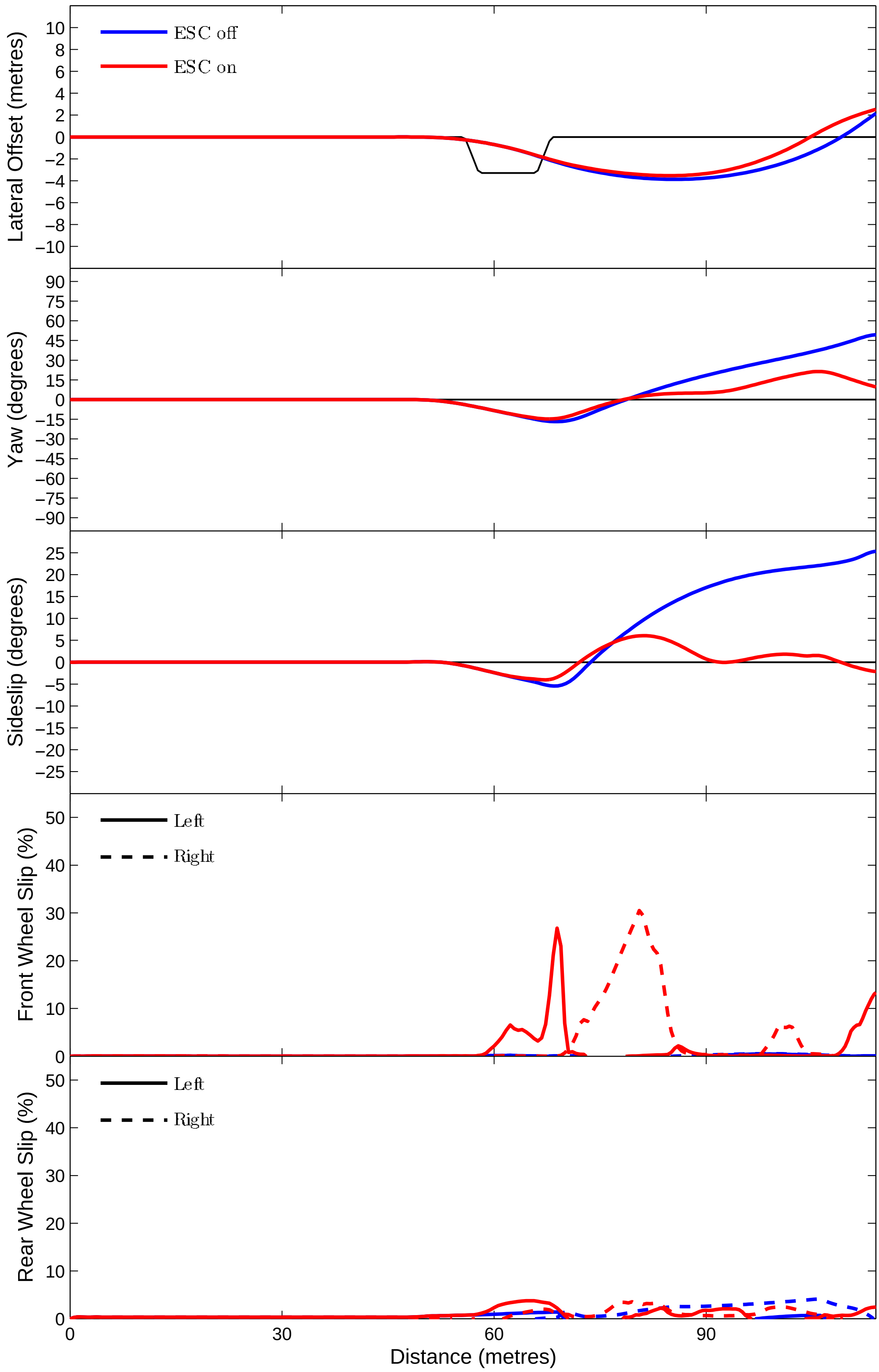


Fig. C.24: Effect of ESC with a sealed shoulder (scenario 7)

C.8 Scenario 8

The following figures are presented:

- Effect of ESC on representative value set 1 (lower speed)
- Effect of ESC on representative value set 1 (sealed shoulder)
- Effect of ESC on representative value set 2 (lower speed)
- Effect of ESC on representative value set 2 (sealed shoulder)

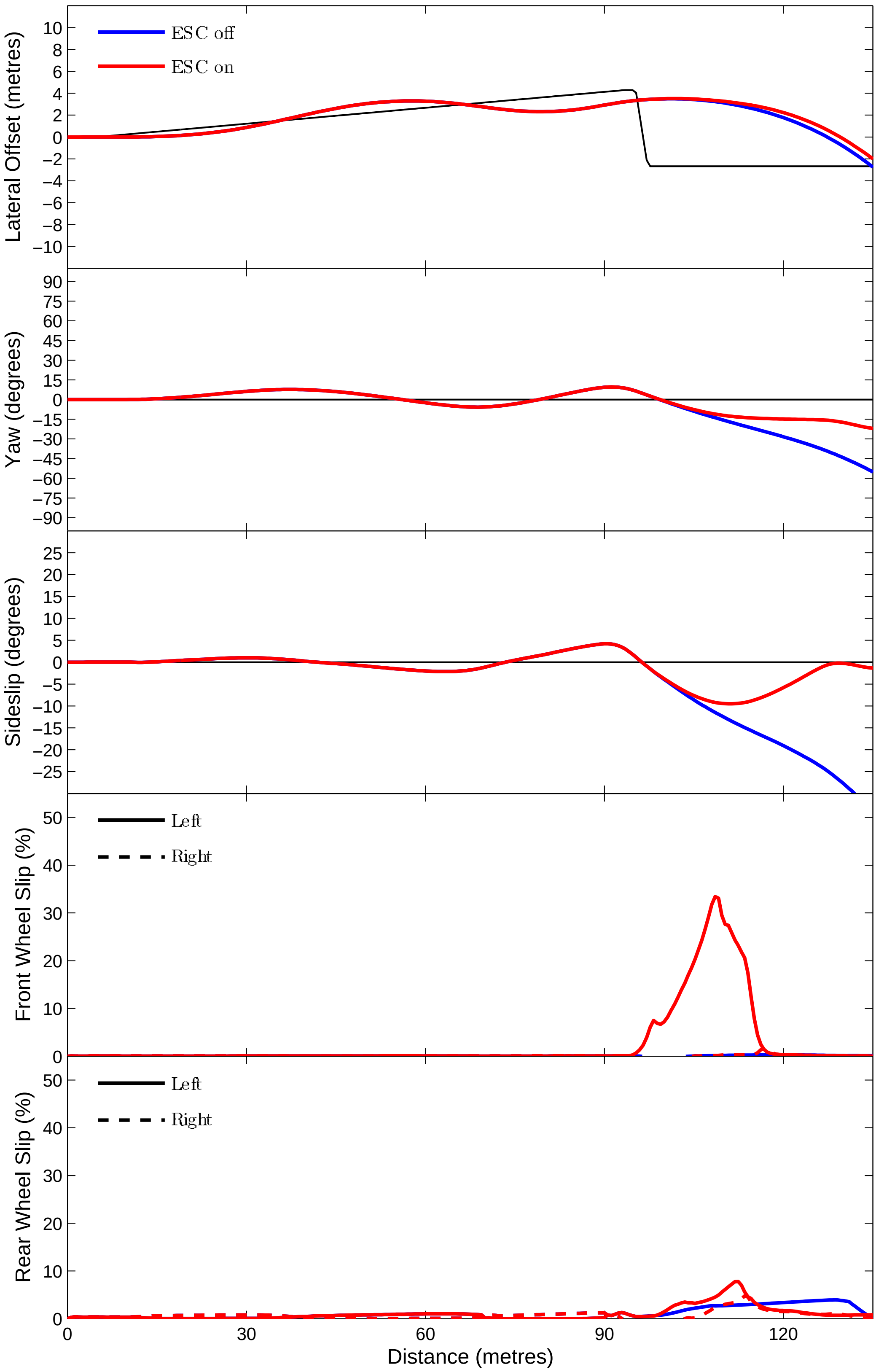


Fig. C.25: Effect of ESC with an initial speed 5 km/h lower (representative value set 1, scenario 8)

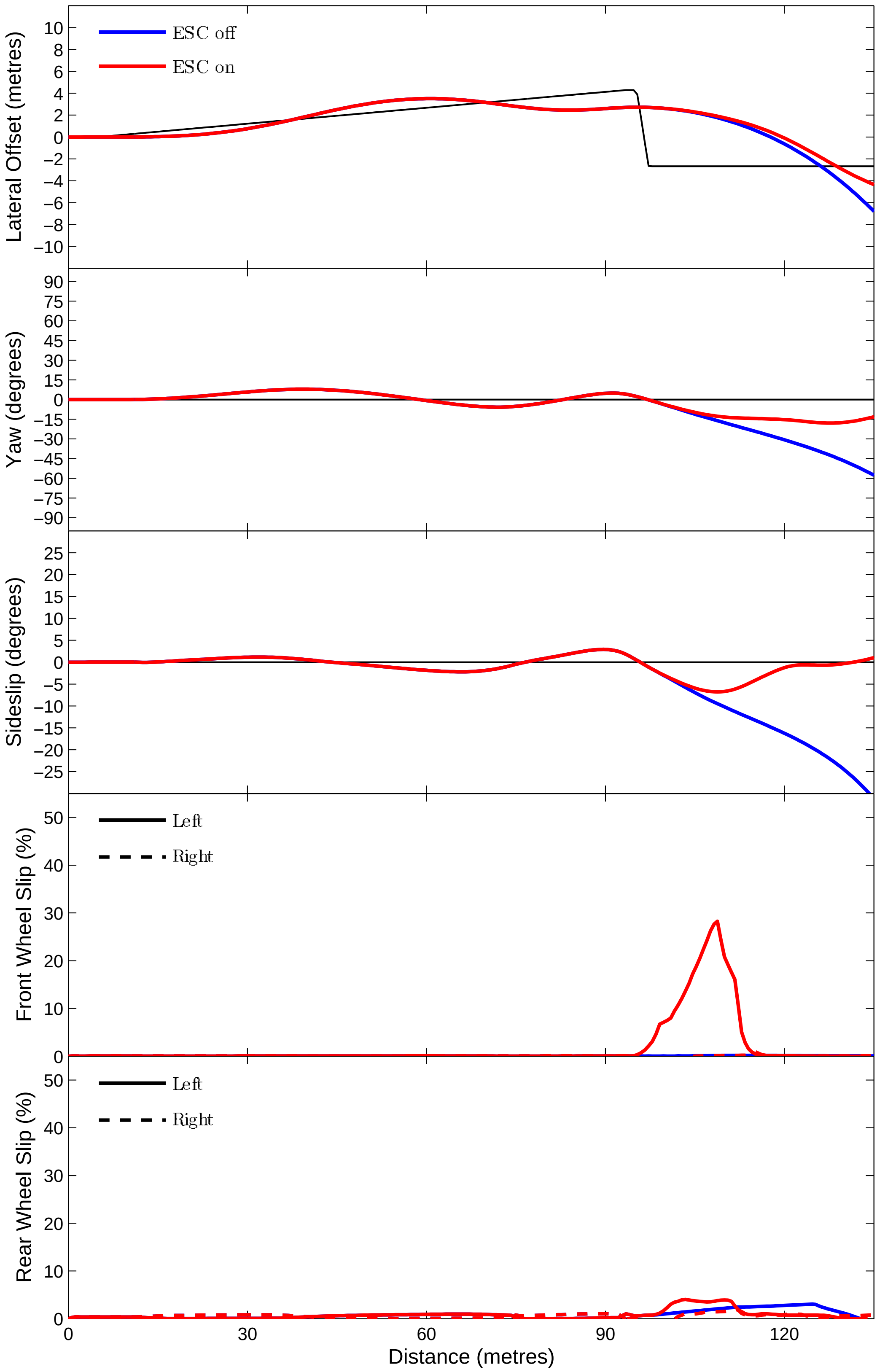


Fig. C.26: Effect of ESC with a sealed shoulder (representative value set 1, scenario 8)

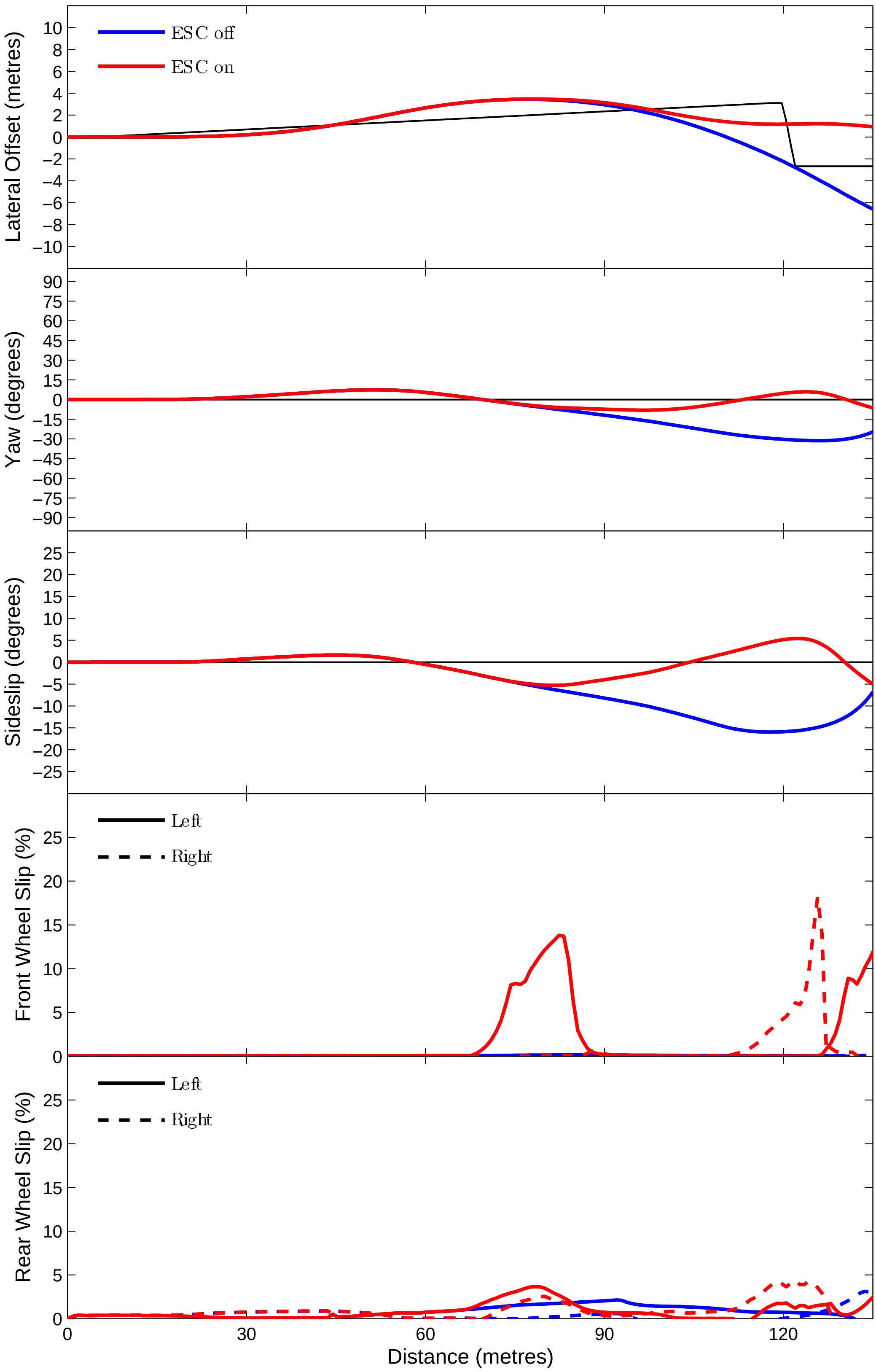


Fig. C.27: Effect of ESC with an initial speed 5 km/h lower (representative value set 2, scenario 8)

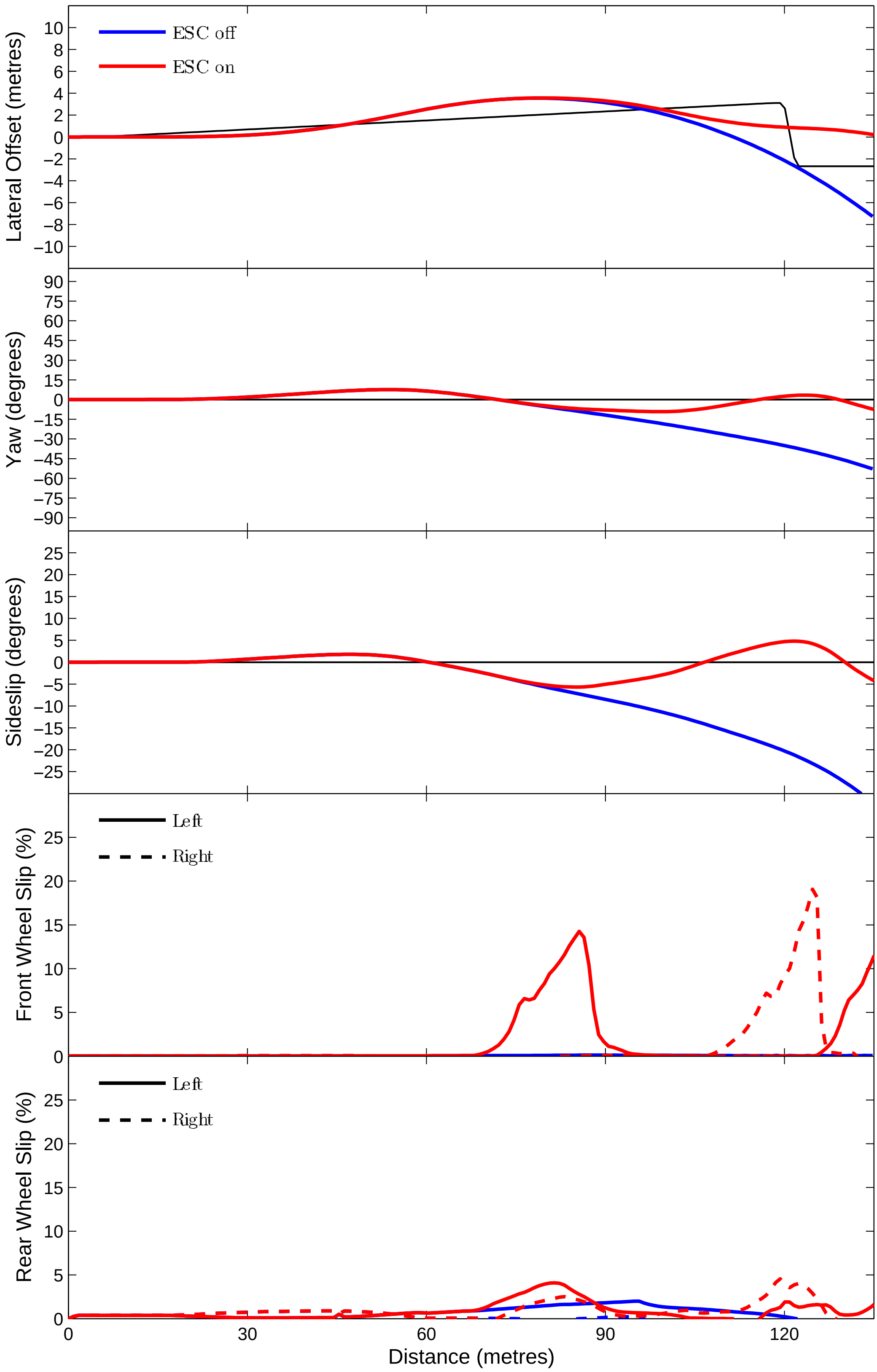


Fig. C.28: Effect of ESC with a sealed shoulder (representative value set 2, scenario 8)

C.9 Scenario 9

The following figures are presented:

- Effect of ESC on representative value set (lower speed)
- Effect of ESC on representative value set (sealed shoulder)

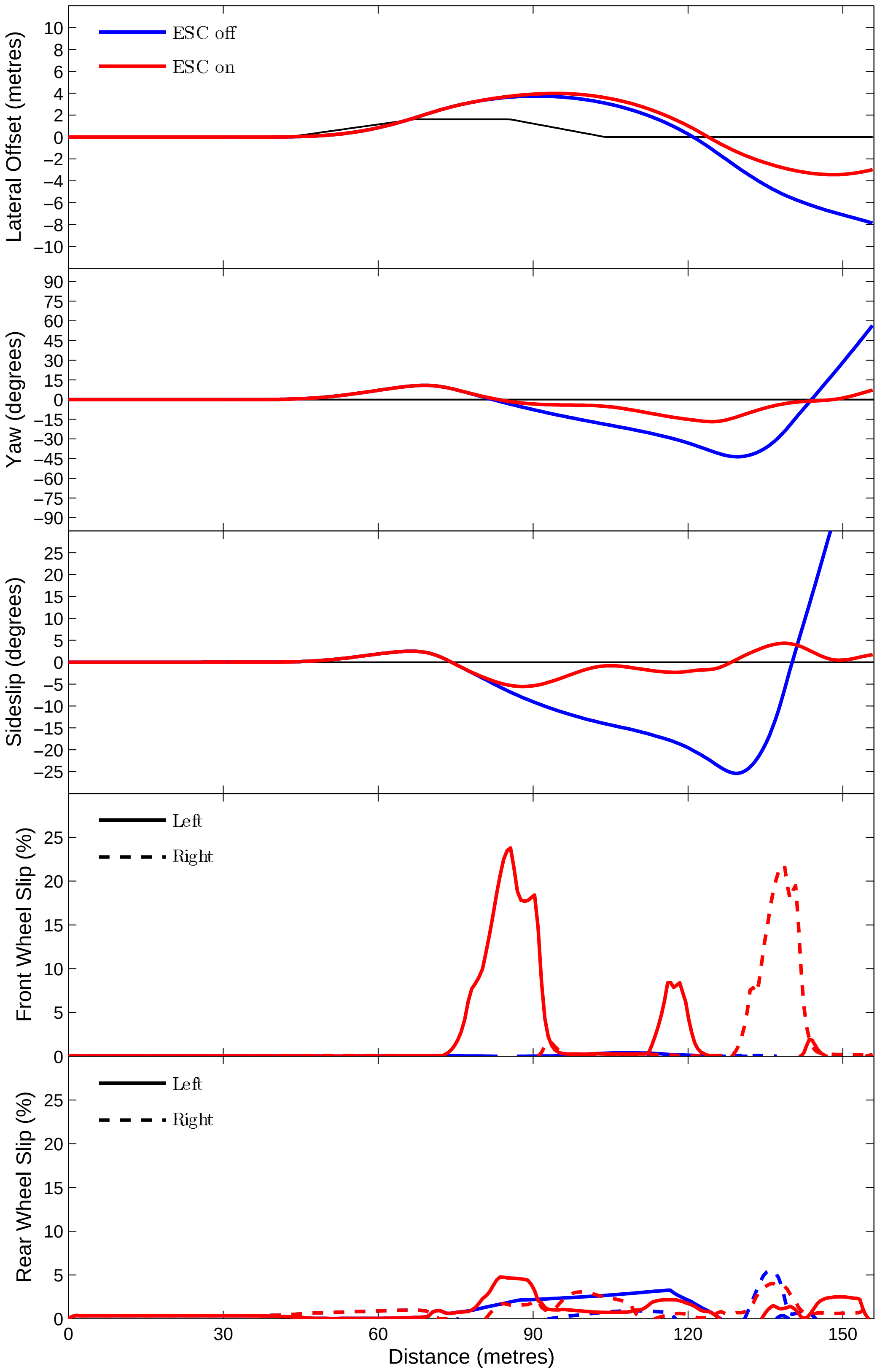


Fig. C.29: Effect of ESC with an initial speed 5 km/h lower (scenario 9)

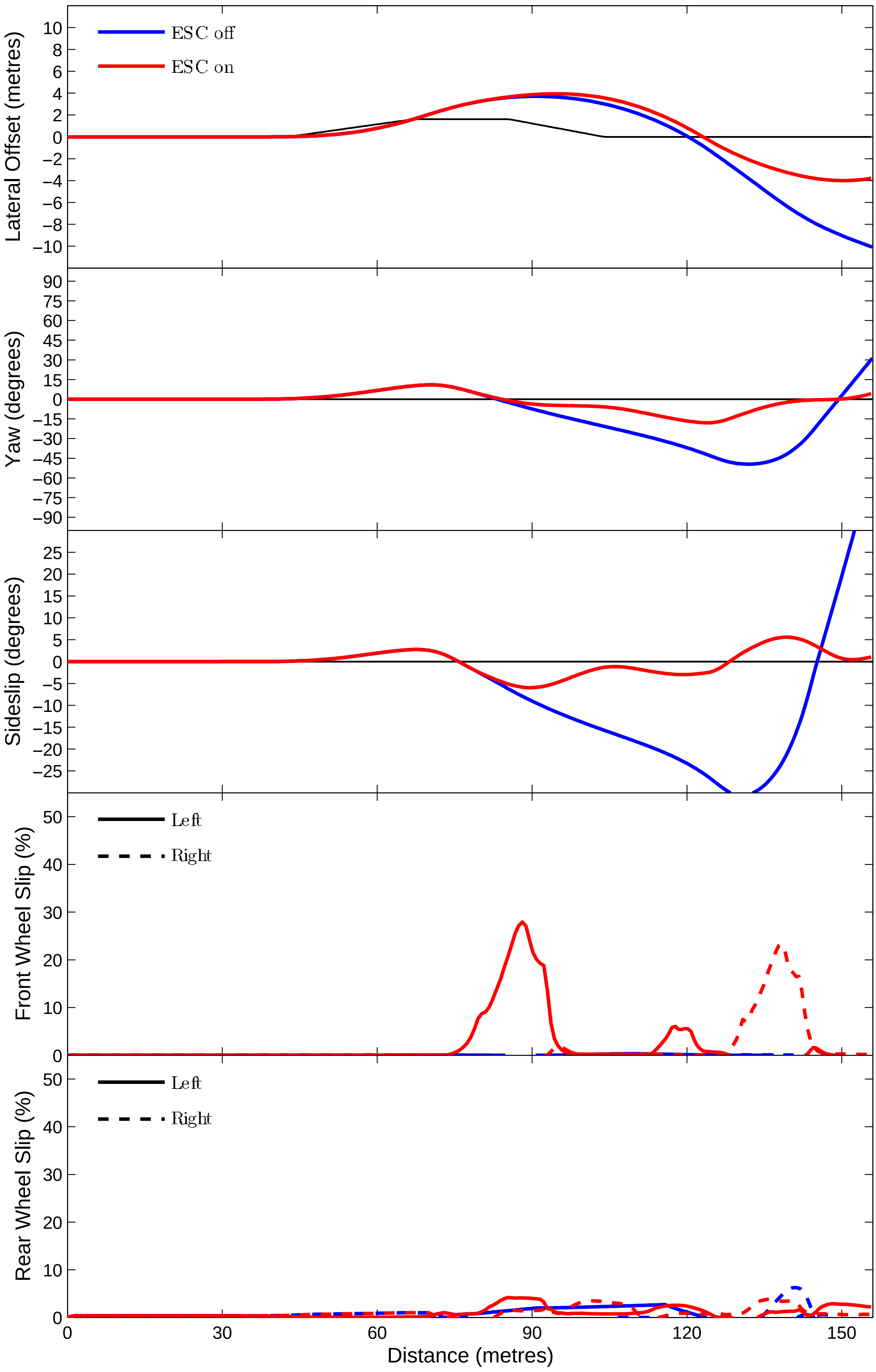


Fig. C.30: Effect of ESC with a sealed shoulder (scenario 9)

C.10 Scenario 10

The following figures are presented:

- Effect of ESC on representative value set (lower speed)
- Effect of ESC on representative value set (sealed shoulder)

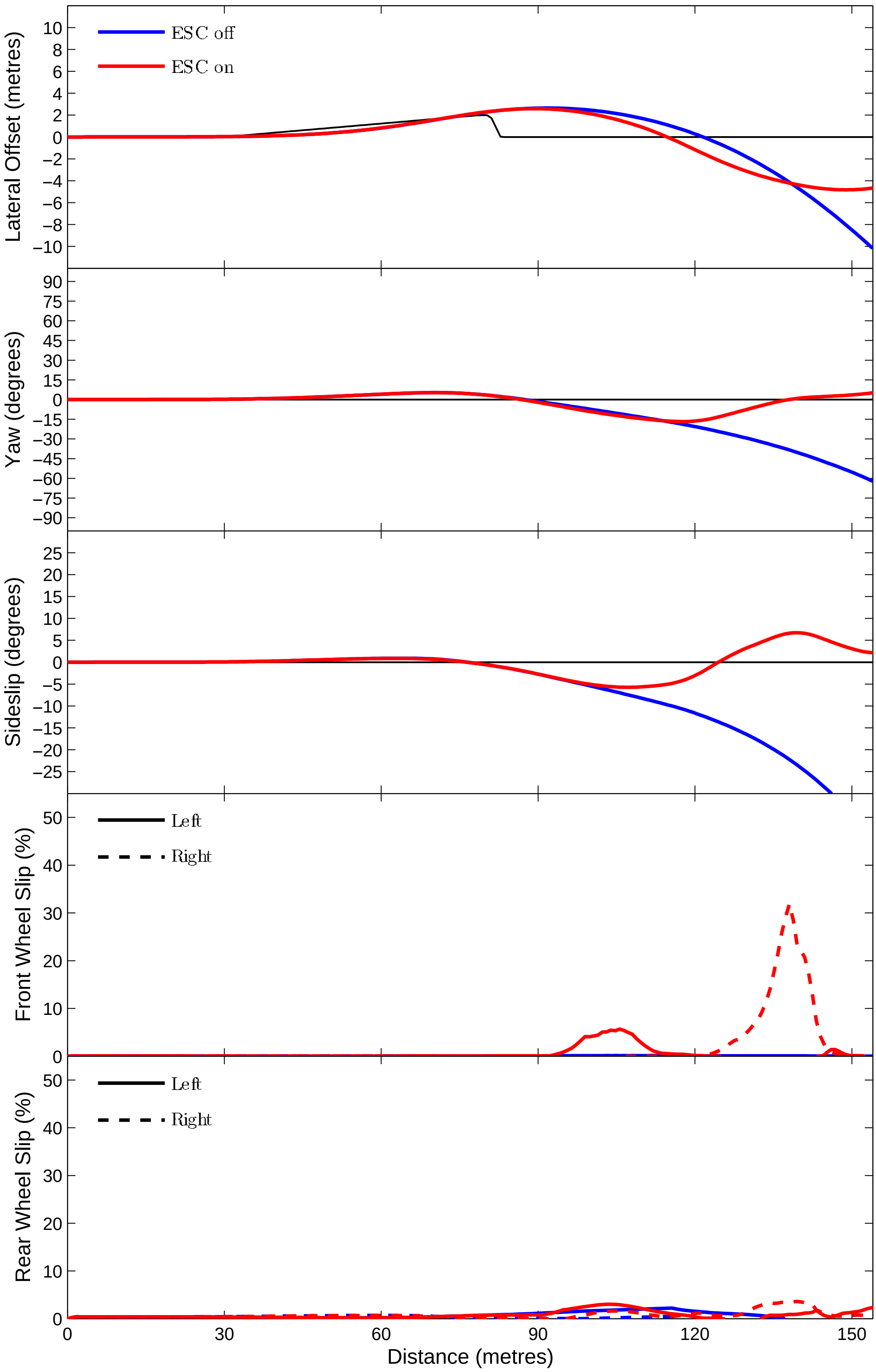


Fig. C.31: Effect of ESC with an initial speed 5 km/h lower (scenario 10)

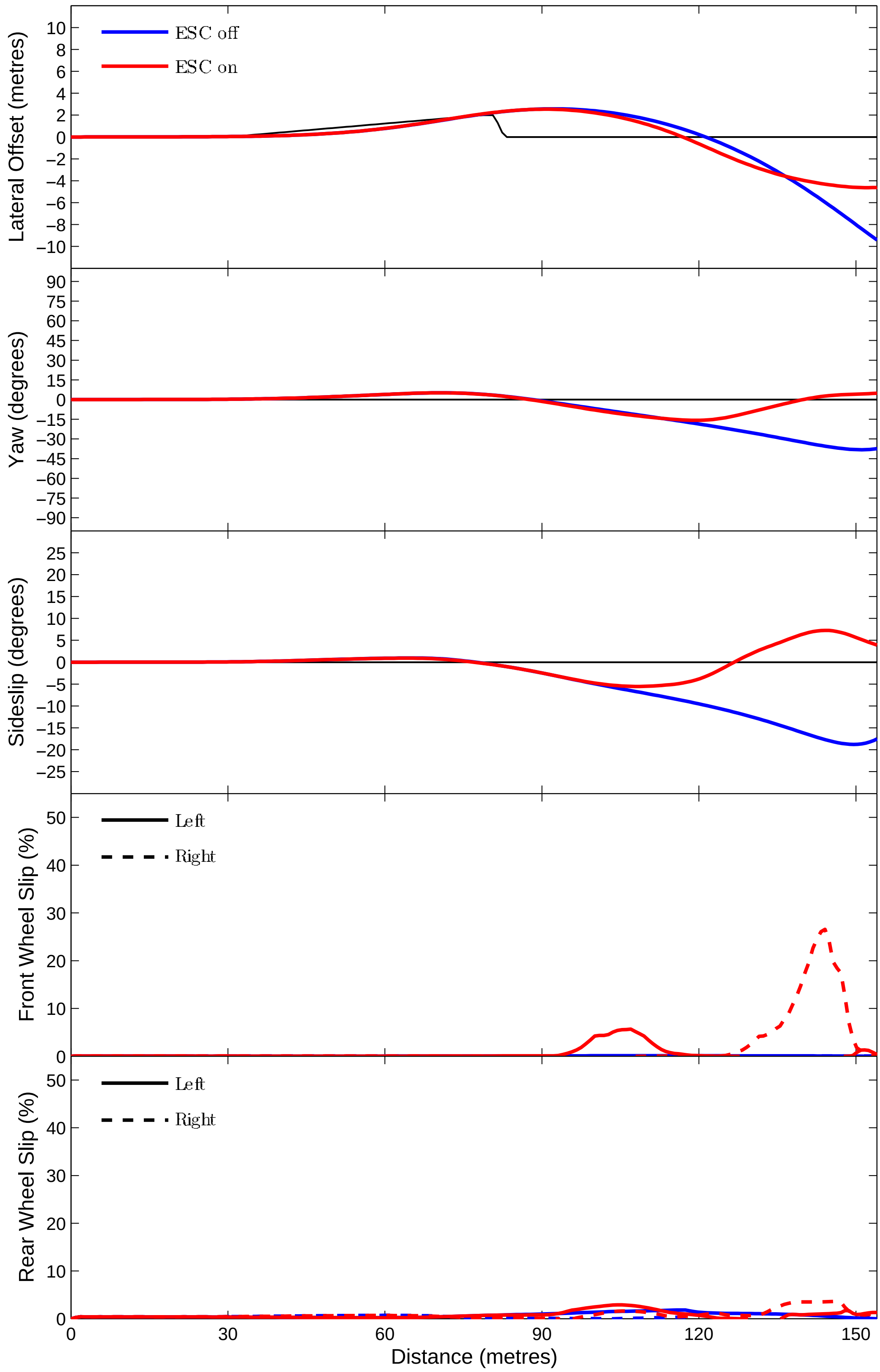


Fig. C.32: Effect of ESC with a sealed shoulder (scenario 10)

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