THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN MACHINE AND VEHICLE SYSTEMS

Vehicle Dynamic Opportunities in Electrified Vehicles for Active Safety Interventions

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Abstract

Although the sales of electrified vehicles is growing, studies indicate that the growth is inadequate to sufficiently reduce CO_2 emissions and mitigate global warming. Some form of added incentive is needed to drive electrified vehicle sales. On the other hand, there is an increased need for traffic safety due to the adoption of ambitious goals such as the *Vision Zero*. This thesis attempts to identify vehicle dynamic opportunities to improve vehicle safety that are enhanced or enabled by electrified drivetrains, thereby offering an opportunity to add value to electrified vehicles and make them more attractive to consumers.

As an example of a low hanging fruit, the possibility of accelerating an electrified lead vehicle to mitigate the consequences of, or prevent being struck from behind was investigated. A hypothetical Autonomous Emergency Acceleration (AEA) system (analogous to the Automatic Emergency Braking (AEB) system) was envisioned and the safety benefit due to the same was estimated. It was found that the AEA system offers significant opportunities for preventing or reducing injuries in rear-end collisions.

The possibility of using propulsion to improve safety in an obstacle avoidance scenario in the presence of oncoming traffic was also investigated. In order to better understand the manoeuvre kinematics, a large number of these cases with varying scenario parameters were investigated in an optimal control framework. Analysis of the results showed that, in this scenario, the obstacle length and the ratio of oncoming vehicle to host vehicle velocities were the two most important parameters which determined the extent of benefit that can be achieved with propulsion. Based on this insight, more detailed investigations were then done for fewer, but more extreme cases of the scenario to estimate the safety benefit due to propulsion both with restricted and unrestricted steering. Results showed that while significant benefit can be achieved due to propulsion even with unrestricted steering, its benefit is amplified when the steering is restricted. Finally, simple closed loop wheel force controllers for lateral control were implemented in simulation. Investigations using the same showed that when performing lateral control alone in this scenario, it is beneficial to be able to do so without slowing the vehicle down which can be done with an electrified drivetrain.

In summary, several vehicle dynamic opportunities for improving safety using electrified drivetrains were identified. Detailed investigations of select cases showed that significant safety benefit stands to be gained by appropriate control of electrified drivetrains in the accident scenarios. Consequently, a strong opportunity is seen for adding safety related value to electrified vehicles at little to no extra cost.

Keywords: electrified drivetrain, torque vectoring, speed control, active safety, vehicle dynamics, rear-end collisions, obstacle avoidance with oncoming traffic, driver assistance systems

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Adithya Arikere
Göteborg, May 2015

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A	A. Arikere, C.-N. Boda, J. M. Olafsdottir, M. Dozza, M. Svensson, and M. Lidberg. "On the Potential of Accelerating an Electrified Lead Vehicle to Mitigate Rear-end Collisions". *Proceedings of the 3rd International Symposium on Future Active Safety Technology Toward Zero Traffic Accidents*. FAST-zero '15. (Accepted for publication). Gothenburg, Sweden, Sept. 9, 2015
Paper B	A. Arikere, M. Klomp, M. Lidberg, and G. Olsson. "The Potential Safety Benefit of Propulsion in Obstacle Avoidance Manoeuvres with Oncoming Traffic". *Proceedings of the 12th International Symposium on Advanced Vehicle Control*. AVEC '14. Tokyo, Japan, Sept. 22, 2014, pp. 126–131
Paper C	A. Arikere, M. Lidberg, and G. Olsson. "The trade-off between distance margin and steering effort in obstacle avoidance manoeuvres with oncoming traffic". *Proceedings of the 24th International Symposium on Dynamics of Vehicles on Roads and Tracks*. IAVSD 2015. (Accepted for publication). Graz, Austria, Aug. 17, 2015

Contents

Part I
Extended Summary

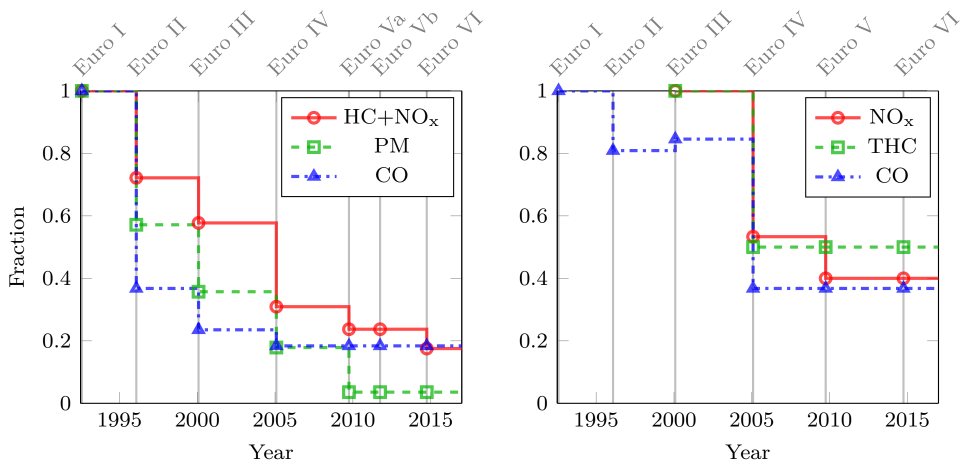
1 Introduction

1.1 Background

1.1.1 The emissions problem

Over the past few decades, there has been increasing awareness regarding pollution, global warming and diminishing oil reserves among people. This has led to an increased pressure from both the public and governments on vehicle manufacturers to make cars that are more environmentally friendly and less dependent on fossil fuels. A consequence of this is that legislation regarding emission and fuel efficiency requirements on new cars have been getting more and more stringent.

In a first-of-its-kind study done by the United Nations (UN), it estimated that air pollution across Europe is costing "a staggering" \$1.6 trillion a year in deaths and diseases, which amounts to nearly one tenth of the region's gross domestic product (GDP) [33]. Approximately 50 % of this pollution (and consequently the damages and cost) is estimated to be caused by road transport [45]. To limit such harmful byproducts of combustion that make the air less fit to breathe, emission norms are imposed on a regional basis and many emission regulations worldwide mandate maximum emission levels of less than 20 % of that allowed in 1993 (for diesels, [34]). As an example, in fig. 1.1, the evolution of European emission norms (Euro I through Euro VI) for passenger cars is illustrated.



(a) *Diesel vehicles* (b) *Gasoline vehicles*

Figure 1.1: *Legislated Euro emission norms for passenger cars as a fraction of the Euro I standard. Note that before Euro III (2000), for gasoline cars, while the total HC+NO$_x$ was restricted there were no individual restrictions on THC or NO$_x$. (HC=hydrocarbons, NO$_x$=nitrous oxides, PM=particulate matters, CO=carbon monoxide, THC=total hydrocarbons). [34]*

Fuel efficiency requirements have been imposed indirectly through restrictions on fleet average carbon dioxide (CO_2) emissions of new cars sold. While the average CO_2 emission has been falling in recent years, the EU has set an ambitious fleet average CO_2 emission target of 95 g/km in 2021. This represents approximately a 40 % reduction over the 2007 emission levels of 158.7 g/km [18]. Figure 1.2 shows the average CO_2 emissions for the passenger car fleet as a whole and for different manufacturers. While manufacturers have largely been able to meet the 2015 target (130 g/km), meeting the 2021 target will likely be a challenge.

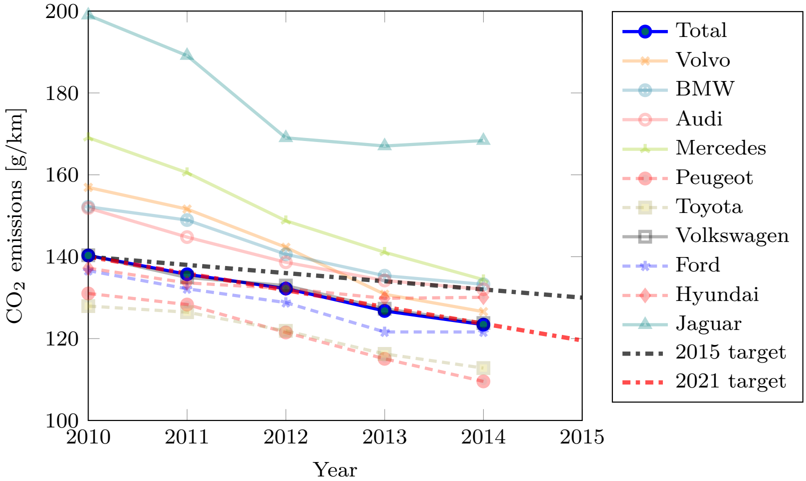


Figure 1.2: *Fleet CO_2 emissions. [29]*

The combination of these stringent emission and efficiency requirements have led to governments and vehicle manufacturers investing large sums of money in research related to alternative fuel sources and in general, ways of reducing energy consumption. One of the methods to reduce energy consumption in vehicles that has been gaining prominence is drivetrain electrification.

While the numerous studies investigating the capabilites of electrified drivetrains suggest a strong potential to reduce greenhouse gas (GHG) emissions [10, 12, 16], electrified cars have not really captured the market due to a variety of reasons. Customers cite numerous reasons including high cost, range anxiety, lack of charging infrastructure, etc. Despite this however, electrification is increasing since it is one of the few promising ways to reduce fuel consumption.

In order to meet GHG emission targets, several governments and organisations have established targets for sales or penetration of electrified vehicles [23, 24] in the vehicle fleet. A study published in 2013 [1] shows that predictions made by several studies regarding the penetration of electrified vehicles in the passenger car fleet are too optimistic compared to reality. Other more limited studies [10, 11, 16, 31], while predicting a significant market penetration of electrified vehicles in different countries, show that we are nowhere near on track to meet the required electrified vehicle fleet penetration for an ultimately stabilizing

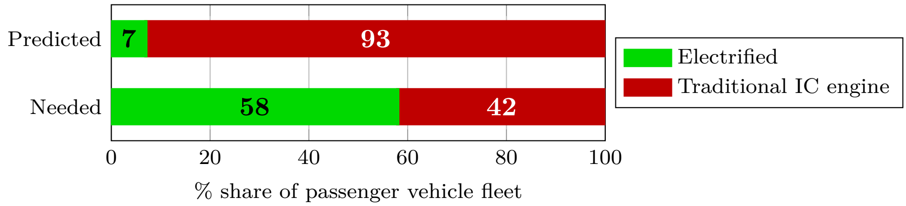


Figure 1.3: *Predicted and needed split of electrified and traditional vehicles in 2030 in the vehicle fleet for a ultimately stabilizing CO_2 concentration of 450 ppm in the atmosphere [24].*

CO_2 concentration in the atmosphere of 450 ppm [23].

It is clear therefore that, to drive the sales of electrified vehicles, some form of added incentive or value is needed. However, "added incentive or value" is a rather broad term. One way to narrow down what sort of "added value" is needed is to look at the "gap areas" with respect to transportation and this leads us to the issue of safety.

1.1.2 The safety problem

Due to urbanisation and increasing mobility of the world population, there are now larger number of motorists in smaller areas. Consequently, along with the increased demand for efficiency, there is also an increasing demand for traffic safety. Several countries and cities have set targets for reducing fatalities in road accidents. For instance, Sweden has the Vision Zero which aims to eliminate fatalities in road accidents completely by 2020 [37] while the UK has similar ambitions [44]. Several cities in the US have also adopted the Vision Zero goal [40–42, 46]. In a 2001 transport white-paper, the European Commission set a target of halving the fatalities on European roads by 2010. The EU failed to meet this target [26]. Furthermore, the road fatality statistics (fig. 1.4) show a vast spread in the performance of different countries in terms of safety.

If we are to achieve the safety targets, it is clear that a lot more needs to be done. Any future approach for improved safety needs to take into account not only the new sensors and sources of information that will be available in the vehicles of the future, but also the capabilites enabled or enhanced by the new actuators available in the cars of tomorrow.

1.1.3 At the crossroads between emissions and safety

From the push for more fuel efficient vehicles, it appears that one of the new actuators that will be available in the cars of the future are electric drives. The rise of electrified vehicles seem to be inevitable given the stringent requirements on emissions and efficiency. However as previously mentioned, while electrified vehicles appear to be the future, growth in their sales is too slow to be able to adequately reduce CO_2 emissions.

So, given that some form of added value is needed to drive electrified vehicle sales and that improved traffic safety will likely be an area of need in the future, the question that naturally arises is: *can we add value to electrified vehicles by having new safety related functionality that is enabled or enhanced by electrified drivetrains?*

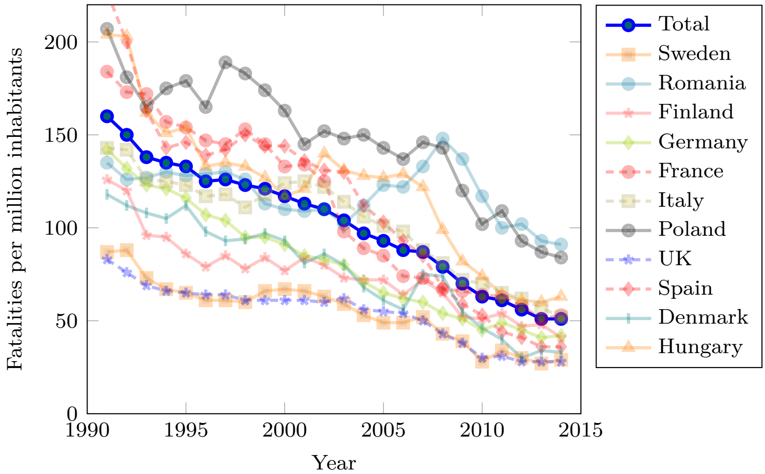


Figure 1.4: *Fatalities per million inhabitants in road accidents. [36]*

Adding such functionality would not only contribute towards the safety targets, but also make electrified vehicles more attractive to both consumers (due to improved safety, possibly lower insurance costs, etc), and to governments (since they now contribute to their safety goals) which might in turn incentivize the sales of such cars.

1.2 Electric drive advantages

Before trying to determine how electrified drivetrains can be used to enhance safety, it might be useful first to review some of the advantages or benefits offered by electric drives over the internal combustion engine (ICE).

Provided below is an overview of some of those benefits both from a customer and a technical standpoint.

- **Energy efficiency**
  The most common reason for using electric drives in the first place are that they are much more energy efficient compared to ICEs. While ICEs typically have average efficiencies of 18 to 20 % [25], electric drivelines can often have efficiencies (including inverter and gear reduction losses) of 76 to 80 % [3].

- **Quick response**
  Electric drives are very quick to respond and have a response time (depending on the type of drive used) in the order of tens of milliseconds [22]. On the other hand, in traditional ICEs, more than 200 ms may be required just to open the throttle actuator. Additionally, due to stringent emission norms, modern cars are adopting downsized turbocharged ICEs [12] which are known to have poor transient response [14]. The almost instantaneous response of the electric drive results in improved

response of the vehicle itself which in turn can be used to improve drivability, safety or handling.

Note that while other factors such as the tyres, compliance in the drive shafts, etc. might increase the response time of the system as a whole, vehicles with electrified drivetrains are still likely to be much faster to respond as a whole.

- **Controllability**
They can be controlled much more precisely and accurately compared to ICEs. This can be used to perform significantly better slip and traction control which improves safety and comfort for the user. In [30], the authors estimate that upto 7 % reduction in braking distances can be achieved due to faster anti-lock braking (ABS) actuation alone. It also opens up new possibilities to perform interventions with a high degree of robustness and accuracy. For e.g., control of vehicle position is difficult with ICEs and brakes (but not impossible, especially at low speeds), but can be done much more easily even at high speeds using electric drives.

- **Bi-directional**
The ability of electric drives to apply both driving and braking torques is of great benefit for performing robust interventions as it allows the possibility to correct for imperfect interventions, drift or other disturbances. It also makes it easy to perform simple corrections and obviates the need to manage the cooperation of multiple imperfect actuators to produce smooth actuation. For instance, in order to perform traction control during hard acceleration, it is necessary to combine the operation of the ICE and the brakes. However, due to their slow response, performing smooth traction control is difficult and typically results in jarring interventions. With electric drives however, such interventions can be made very smoothly.

- **Continous operation**
They can be operated continuously while providing propulsion or braking torque. While ICEs can be operated continously, they cannot be used effectively for braking. Mechanical brakes on the other hand cannot be used continously. This means that there are now many more possibilities to perform continous interventions in order to improve handling, drivability or safety. With brakes, in order not to overuse them, it is necessary to wait until a pre-determined safety criterion is satisfied before interventions are performed. This means that, most often it is necessary to wait for a safety critical scenario to develop before any action is taken (e.g., ABS, ESC). With electrified drivetrains on the other hand, since interventions can be performed continously, it could be possible to continously modify the dynamics of the vehicle so as to prevent an unsafe scenario from even emerging.

- **Sensing ability**
They can also act as very good sensors since they can measure speed and torque very well. ICEs on the other hand have a limited ability to sense either quantity whereas brakes most often can detect speed but not torque (using additional sensors that are usually included with the brakes). This enhanced sensing ability can be of significant use in vehicle state and parameter estimation as shown in [2] and also in any vehicle dynamic controllers.

- **Noise, Vibrations and Harshness (NVH)**
Due to the their relatively simple construction and the fact that they have fewer moving parts, they have nearly no vibrations and are near silent during operation. Consequently, this leads to a much quieter, smoother and more comfortable ride in the vehicle.

- **Torque characteristics**
Electric drives typically deliver their peak torques at low speeds which makes them very suitable for use in ordinary driving. Furthermore, since they are power limited in a large part of their operational range, typically, there is no need for multi-speed gearboxes. This further reduces the complexity of electric drivetrains.

- **Cost savings**
As previously mentioned, electric drives are much more energy efficient compared to ICEs. While ICE only based drivetrains typically have Tank-To-Wheel (TTW) energy efficiencies of between 16 % to 28 %, electric drivelines can often have a TTW efficiencies of up to 90 % [21]. This translates to reduced energy consumption, reduced greenhouse gas emissions and significant cost savings for the user [4].

- **Smooth power delivery (drivability, torque fill)**
The power and torque characteristics of the electric drive offer a smooth, consistent and predictable power delivery. With hybrid drivetrains, the electric drives can be used for “torque fill” wherein the electric motor supports the IC engine by adding or removing torque to make for a smoother, more predictable response. This is especially useful during gear changes or when the turbo (if equipped) spools up when typically, there is a loss of power from the ICE.

- **Fully autonomous low speed manoeuvring**
Since most IC engine based drivetrains have a gearbox which needs to be manually shifted at least between forward, reverse and park, at least a minimal amount of human involvement is required. Since electric drives are typically connected to the wheels by a single speed gearbox, the gear shift in such cases is a software affair. This allows for a fully autonomous low speed manoeuvring with no driver intervention whatsoever. With such capability, one could envision fully autonomous parking functions wherein the driver need not even be in the car as the car finds a parking spot and parks itself.

- **Local emissions**
As previously mentioned, increasing urbanisation and mobility have led to high vehicular density in urban areas. This in turn has exacerbated the issue of pollution which makes the air unfit to breathe and leads to various respiratory related issues and illnesses. For instance, air pollution in Beijing soared to hazardous levels in early 2015 reaching 20 times the level recommended by the World Health Organisation [13]. Electrified vehicles can completely eliminate (fully electric vehicles) or atleast reduce local emissions significantly (hybrids) leading to better air quality and therefore fewer health concerns.

- **Energy source agnostic**
  One of the advantages of electrified vehicles is that since they use electricity, which is a medium of energy transfer rather than a source, they are much more robust to changes in energy sources. For instance, due to our near exclusive dependence on pure IC engine vehicles at the moment, if oil production were to drop or its price to go up significantly, it would result in strong repurcussions not only for vehicle users but also for the economy. Instead, if the vehicle fleet were to be largely electric, it would be easier to adapt to fluctuation in oil prices by reducing energy production from the same and increasing power production from other sources at the power plants.

- **Modularity**
  Compared to IC engine based drivetrains, electrified ones are more modular. This allows a greater amount of flexibility while designing and developing drivetrains where significantly different drivetrains can be obtained with different combinations of the same modules. It also allows for greater sharing of component and modules across various drivetrain configurations. For instance, electrified vehicles with different power and range ratings can be obtained by just using different battery packs of varying energy capacities. Doing the same in an IC engined drivetrain would require a essentially a new drivetrain.

- **Multiple actuators**
  It is possible and even easy to have multiple independent electric drive actuators in a vehicle, whereas driving a vehicle using multiple independent ICEs is infeasible. Vehicles with multiple independent motors are already available on the market from several manufacturers, for e.g., the Model S P85D variant from Tesla, hybrid vehicles from Honda with the super-handling All Wheel Drive (SH-AWD) package, etc. While such vehicles have been primarily focused on enhanced performance, the same can be exploited to improve safety as well.

1.3 Research question

From the advantages of electric drives listed above, barring those pertaining to efficiency or emissions, it can be seen that electric drives offer several advantages which can be used for improved vehicle dynamics (for e.g., quick response, controllability, etc). And based on the fact that a large portion of safety improvements in recent years have come about due to modern vehicle dynamics based active safety functions, the research questions that arise are ass follows:

- *How can the electric drive be used to improve vehicle dynamics?*

- *What are the traffic and/or accident scenarios in which the improved vehicle dynamics could be used for improved safety?*

- *How should the electric drive be used (in select scenarios) to improve safety?*

1.4 Limitations

Several topics, although closely related or required for final realisation of functions described in this work are not investigated here. The ability of the electric drive to improve safety has been studied mainly from a vehicle dynamics point of view.

Idealising assumptions regarding actuator performance have been made in some cases and are mentioned where relevant. The environment sensing aspect (detection problem), although briefly discussed in some cases, has not been studied in detail. The decision making problem (which one of several possible interventions to perform) has been considered only to the extent required in different papers. The driver interaction and driver acceptance questions have also not been adressed in detail. The legal aspect of how to perform interventions while respecting the driver's wishes has not been discussed.

Lastly, this work assumes that an electric drive is already available in the vehicle (can be fully electric vehicle, plugin hybrid or normal hybrid). This project does not make a case for electrifying drivetrains in order to improve safety, but rather identifies opportunities for increasing safety given that an electric drive is already available.

1.5 Thesis outline

This thesis is structured as follows:

- Chapter 1 provides the background for the project and outlines the motivations and the research questions.
- Chapter 2 outlines some of the vehicle dynamic opportunities provided by electrified drivetrains.
- Chapter 3 summarizes some of the control intervention opportunities that are enhanced or enabled by the improved vehicle dynamics due to drivetrain electrification.
- Chapter 4 provides some examples of use cases where electrified drivetrains can potentially be used for improved safety.
- Chapters 5 and 6 briefly introduce the two accident scenarios (rear end collision and obstacle avoidance with oncoming traffic) which are dealt with in the appended publications.
- Chapter 7 provide some discussion of the assumptions made and results presented in the thesis and chapter 8 concludes this thesis and outlines future work to be performed.

2 Vehicle dynamic opportunities

This chapter captures some of the advantages offered by electric motors in comparison to its traditional counterparts (IC engines and brakes) from a vehicle dynamic standpoint and how they can be used in active safety interventions.

2.1 Longitudinal dynamics

The (simplified) longitudinal dynamics of the vehicle can be modelled using a point mass as:

$$m\ddot{X} = F_x \tag{2.1}$$

where, F_x is the drive force from the propulsion actuator which in turn can be modelled using a first order filter with a characterisic time constant T_s over the driver acceleration demand a_d. This can be represented in *Laplace form* as:

$$ms^2X = \frac{ma_d}{T_s s + 1} \tag{2.2}$$

The same can be represented as a state space model as follows:

$$\begin{aligned} \dot{\boldsymbol{x}} &= A\boldsymbol{x} + B\boldsymbol{u} \\ \boldsymbol{y} &= C\boldsymbol{x} + D\boldsymbol{u} \end{aligned} \tag{2.3}$$

where,

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1/T_s \end{bmatrix} \tag{2.4}$$

$$B = \begin{bmatrix} 0 & 0 & 1/T_s \end{bmatrix}^T \tag{2.5}$$

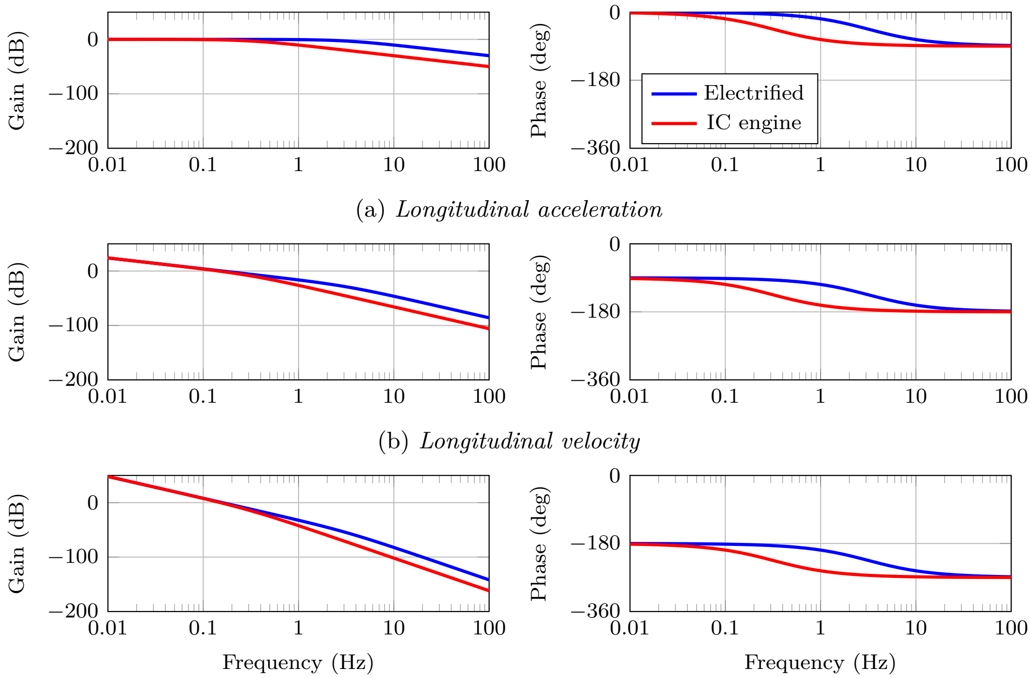
$$C = \operatorname{diag}\begin{pmatrix} 1 & 1 & 1 \end{pmatrix} \tag{2.6}$$

$$D = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix} \tag{2.7}$$

$$\boldsymbol{x} = \begin{bmatrix} X & \dot{X} & \ddot{X} \end{bmatrix}^T \tag{2.8}$$

$$\boldsymbol{u} = a_d \tag{2.9}$$

The *Bode plots* of the transfer functions for the vehicle acceleration, velocity and position from the point mass model above are shown in fig. 2.1 for the electrified and traditional IC engine drivetrains. Characteristic time constants of 50 ms and 500 ms have been assumed for the electrified and traditional IC engine drivetrains respectively. As can be seen, with electrified drivetrains, not only is the bandwidth improved, but the phase shift is reduced for all three transfer functions. The reduced phase shift is very useful from a control standpoint as it allows high frequency control interventions to be



(a) *Longitudinal acceleration*

(b) *Longitudinal velocity*

(c) *Longitudinal position*

Figure 2.1: *Bode plots for electrified and the IC engine based drivetrains*

performed and prevents hysteresis in the response. It is also worth noting that at higher frequencies, the gain of the electrified drivetrain in all three cases is roughly 20 dB more than the IC engine counterpart. This translates to a gain for the electrified drivetrain that is *10 times* that of the IC engine drivetrain at higher frequencies.

This increased bandwidth and the reduced phase shift of the longitudinal dynamic transfer functions due to the electrified drivetrain can lead to several higher level advantages including:

- **Accelerator response**
  The near instant response of motors combined with their torque characteristics leads to electrified drivetrains having very good throttle response. This enhanced throttle response is useful not only from a driver's point of view but also for active safety interventions involving the propulsion actuator. The short reponse time improves the controllability of the motor at the limit (which is mostly the case with active safety interventions) and allows significant benefit to be achieved even when the interventions are initiated at the last moment. Typically, when interventions are done at the last moment with brakes or other actuators, a significant portion of the intervention time is wasted as the actuators get up to their steady state performance levels. With electric drives, this time is reduced and hence allows significant benefit to be achieved even with late interventions.

- **Control of vehicle longitudinal position**
  Due to the enhanced controllability of electric drives, their short response times and their bi-directional nature, accurate vehicle position control is now feasible even at speed. With IC engines, this is difficult not only due to their poor response times, but when errors have to be corrected for (which is likely due to the difficulty in controlling them) the brakes have to be used which once again are difficult to control. With electric drives on the other hand, the same actuator can be used to perform and correct interventions leading to accurate and robust control of vehicle position.

- **Improved slip and traction control**
  As mentioned previously in section 1.2, the quick response of the electric drives can be exploited to perform much finer slip and traction control which can have a direct safety benefit. For instance, as identified in [30], faster ABS actuation with electrified drivetrains can result in shorter braking distances. Since most safety interventions involve pushing the vehicle (and the tyres) to the limit of their capabilities, improved slip control during such interventions can significantly contribute towards safety.

2.2 Yaw dynamics

Using the propulsion actuator, yaw moments can be applied on the vehicle (by using differential brakes and propulsion) in order to influence the yaw motion of the vehicle. The impact of such an action can be investigated using a linear bicycle model as shown in fig. 2.2.

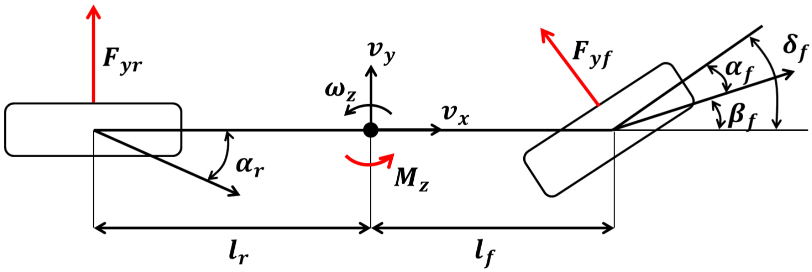


Figure 2.2: *Linear bicycle model*

The linear bicycle model is a common method for evaluating basic lateral dynamic properties of a vehicle in the linear range of its tyres. Here, the vehicle is assumed to be symmetric about its longitudinal axis and consequently, the vehicle is collapsed into a simpler bicycle model where each of its axles have the combined properties of both the wheels on the corresponding axle. The tyres are linearized and small angle assumptions are made to represent the tyres as follows:

$$F_{yf} = C_f \alpha_f \tag{2.10}$$
$$F_{yr} = C_r \alpha_r \tag{2.11}$$
$$\alpha_f = \delta_f - \left(\frac{v_y + \omega_z l_f}{v_x} \right) \tag{2.12}$$
$$\alpha_r = - \left(\frac{v_y - \omega_z l_r}{v_x} \right) \tag{2.13}$$

where, C_f and C_r are the combined cornering stiffnesses of the front and rear axles respectively. The force and moment balance equations for the model can be written as:

$$m(\dot{v_y} + v_x \omega_z) = F_{yf} + F_{yr} \tag{2.14}$$
$$I_{zz} \dot{\omega}_z = F_{yf} l_f - F_{yr} l_r + M_z \tag{2.15}$$

The linear tyre model equations combined with the force balance equations yield a simple vehicle model which is used for further analysis in this section.

For the analysis itself, we consider three cases: the traditional front wheel steer (FWS) setup as a reference, a direct yaw control (DYC) setup which applies a yaw moment to control the vehicle and a yaw response control (YRC) which adds a yaw moment to the FWS setup in order to improve the yaw response but leave the steady state yaw gain unchanged.

The same can once again be represented as a *State space* model as in eq. (2.3). The states and the outputs are the same for each case.

$$\boldsymbol{x} = \begin{bmatrix} v_y & \omega_z \end{bmatrix}^T \tag{2.16}$$
$$\boldsymbol{y} = \begin{bmatrix} v_y & \omega_z & a_y \end{bmatrix}^T \tag{2.17}$$

For the traditional FWS setup, the state matrices are as follows:

$$A^{FWS} = -\begin{bmatrix} \dfrac{C_f + C_r}{mv_x} & \dfrac{C_f l_f - C_r l_r}{mv_x} + v_x \\ \dfrac{C_f l_f - C_r l_r}{I_{zz} v_x} & \dfrac{C_f l_f^2 + C_r l_r^2}{I_{zz} v_x} \end{bmatrix} \tag{2.18}$$

$$B^{FWS} = \begin{bmatrix} \dfrac{C_f}{m} & \dfrac{C_f l_f}{I_{zz}} \end{bmatrix}^T \tag{2.19}$$

$$\boldsymbol{u}^{FWS} = \delta_f \tag{2.20}$$

Similarly, the state matrices for the DYC system can be written as follows (note that to enable easy comparison between FWS and DYC, the yaw moment has been multiplied by $C_f l_f$ so as to apply equal yaw moments on the vehicle for unit inputs):

$$A^{DYC} = A^{FWS} \tag{2.21}$$

$$B^{DYC} = \begin{bmatrix} 0 & \dfrac{C_f l_f}{I_{zz}} \end{bmatrix}^T \tag{2.22}$$

$$\boldsymbol{u}^{DYC} = M_z \tag{2.23}$$

For yaw response improvement, a simple controller can be written which uses the estimated steady state yaw rate and the current actual yaw rate to apply a yaw moment on the vehicle. In a practical implementation, the current yaw rate can be from an inverse plant model running inside the controller which would make the control open loop.

$$M_z = \frac{I_{zz}}{T_{s,tgt}} \left(\frac{\delta v_x}{l + K_u v_x^2} - \omega_z \right) \tag{2.24}$$

where, $T_{s,tgt}$ is the target yaw response time for the vehicle.

The state matrices for the system for FWS with YRC can then be written as:

$$A^{YRC} = -\begin{bmatrix} \dfrac{C_f + C_r}{mv_x} & \dfrac{C_f l_f - C_r l_r}{mv_x} + v_x \\ \dfrac{C_f l_f - C_r l_r}{I_{zz} v_x} & \dfrac{C_f l_f^2 + C_r l_r^2}{I_{zz} v_x} - \dfrac{1}{T_{s,tgt}} \end{bmatrix} \tag{2.25}$$

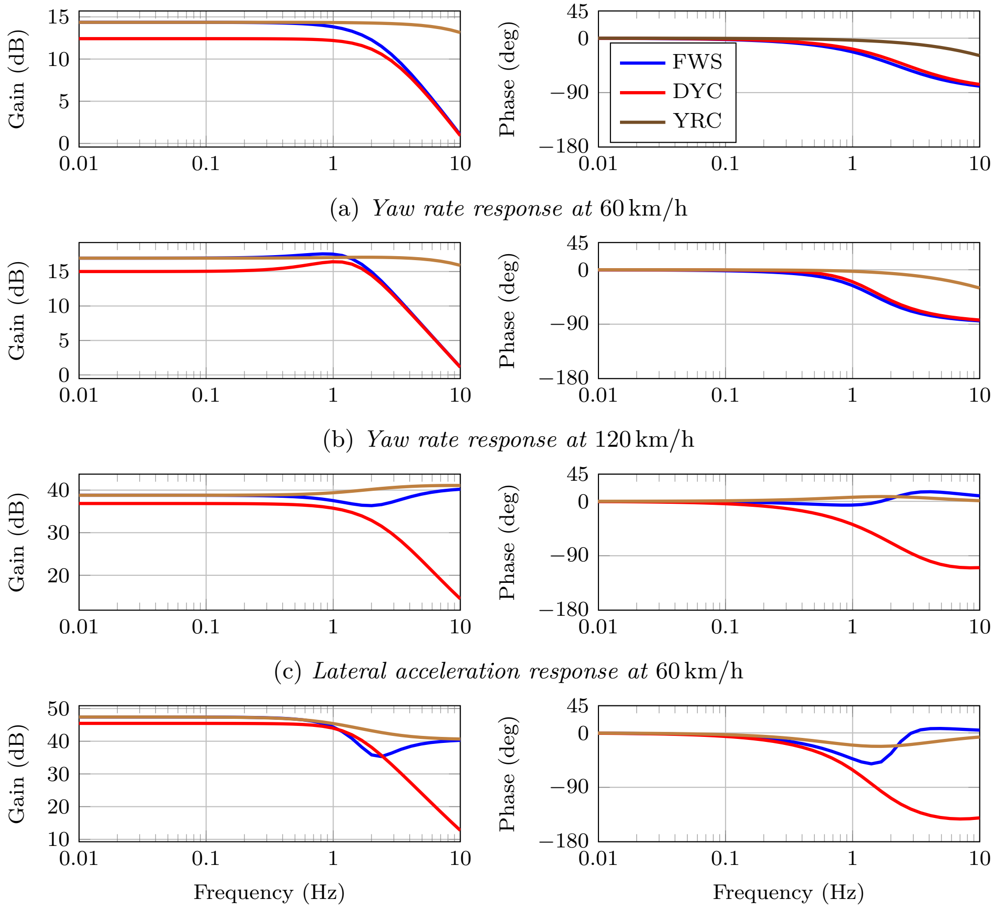
$$B^{YRC} = \begin{bmatrix} \dfrac{C_f}{m} & \dfrac{C_f l_f}{I_{zz}} + \dfrac{1}{T_{s,tgt}} \dfrac{v_x}{l + K_u v_x^2} \end{bmatrix}^T \tag{2.26}$$

$$\boldsymbol{u}^{YRC} = \delta_f \tag{2.27}$$

Since the output and the states are the same in all cases, the output matrices can be written in terms of the states and the state matrices as follows:

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ A(1,1) & A(1,2) + v_x \end{bmatrix} \tag{2.28}$$

$$D = \begin{bmatrix} 0 & 0 & B(1) \end{bmatrix}^T \tag{2.29}$$



(a) *Yaw rate response at* 60 km/h

(b) *Yaw rate response at* 120 km/h

(c) *Lateral acceleration response at* 60 km/h

(d) *Lateral acceleration response at* 120 km/h

Figure 2.3: *Bode plots for yaw rate and lateral acceleration*

where, A and B are the respective state matrices in each case.

Shown in fig. 2.3 are the *Bode plots* for the yaw rate and lateral acceleration transfer functions for the three cases at two different speeds. For the FWS and DYC systems, it can be seen that their yaw rate gain and phase shift are very similar to each other. As for their lateral acceleration gains, while the FWS gain is uneven and is sensitive even at high frequencies, the DYC shows much more even behaviour whose gain tapers off at higher frequencies. This makes the DYC robust to noise and due to its similar gain and phase shift properties at lower frequencies, makes it suitable as a redundancy for the steering actuator. Additionally, as shown, yaw response control (YRC) results not only in much higher bandwidth (both yaw rate and lateral acceleration), but also in much more consistent response (flatter gain curve) and a much lower phase shift as well. Consequently, when FWS and DYC are used together appropriately (i.e., YRC), they can be used to significantly expand the dynamic limits of the vehicle which can in turn be used for improved safety.

These improved yaw dynamic capabilities can be used for several higher driver level advantages and/or functionality including:

- **Yaw response improvement**
  Electrified drivetrains offer significant opportunities for yaw response improvement either on demand or continously depending on the layout of the electrified drivetrains. If only a single electric drive is available for traction only, it can be used in combination with differential brakes to improve yaw response on demand. When multiple electric drives are available on the same axle, they can be used for continuous yaw response improvement. An alternative could be to use a switchable electric drive system such as [38] which uses a single motor that can switch between traction and torque vectoring modes.

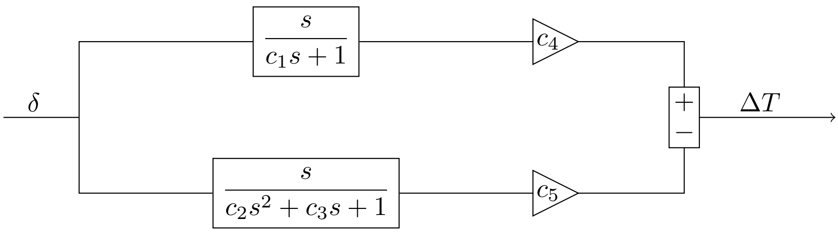
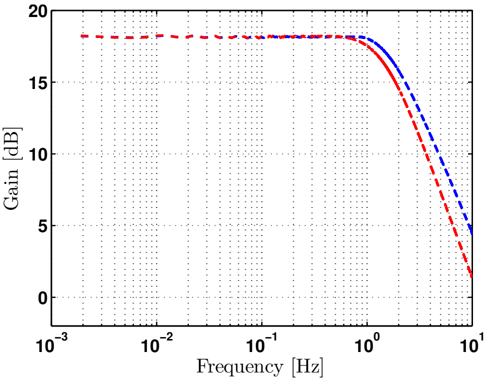


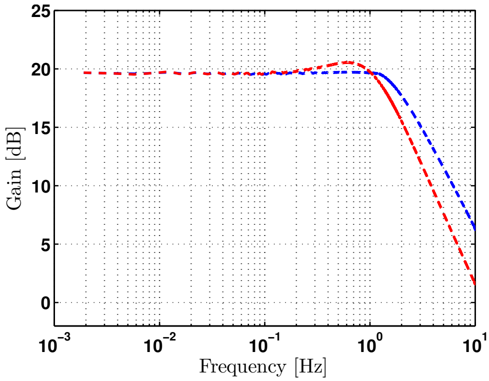
Figure 2.4: *Schematic of the empirical yaw response controller. (See [5])*

The case of using multiple independent actuators to enhance yaw response is considered (among others) and evaluated in [5]. A simple empirical yaw response controller is designed as shown in fig. 2.4 with the aim of improving the transient yaw response of the vehicle but leave the steady state response unchanged. The parameters for the same were determined through global optimisation with an objective that maximises the transient response of the vehicle for a given set of steering inputs.

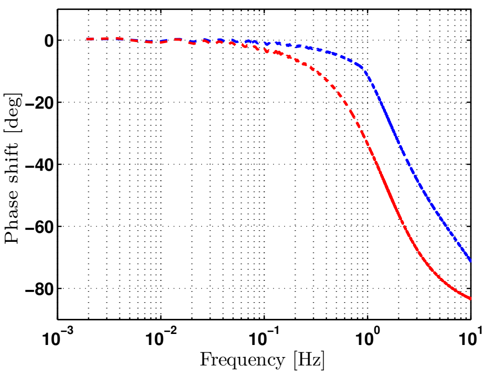
The effect of using even such a simple controller on the yaw response of the vehicle is illustrated in the frequency response plots shown in fig. 2.5. It can be seen that



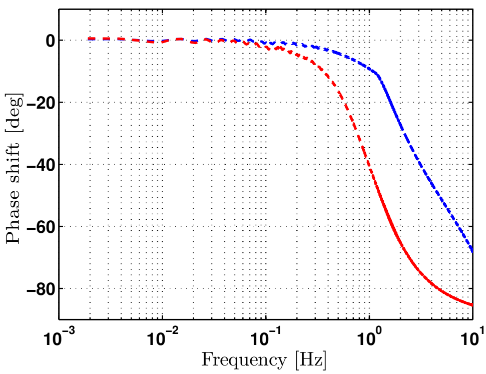
(a) *Freq. resp. at* 100 km/h



(b) *Freq. resp. at* 150 km/h



(c) *Phase shift at* 100 km/h



(d) *Phase shift at* 150 km/h

Figure 2.5: *Frequency response and phase shift plots the vehicle yaw rate at* $a_y = 4\,\mathrm{m/s^2}$. *(Plots from [5])*

the steady state yaw response of the vehicle remains identical whereas the yaw bandwidth is slightly increased and flattened creating a more consistent response. More importantly however as seen in figs. 2.5c and 2.5d, the phase lag of the yaw response is reduced significantly. This leads to a much more immediate yaw response and lends the vehicle a sense of sportiness.

- **Decoupling of yaw and longitudinal dynamics**
  Electrified drivetrains offer the capability to quickly and reliably provide longitudinal force to the vehicle in either direction (braking or propulsion). This, in combination with differential braking allows for the application of pure yaw moments on the vehicle by applying net zero longitudinal forces on the wheels of an axle. Effectively, this means that yaw moment control can be done on the vehicle with little to no impact on the longitudinal dynamics. This capability offers vast vehicle dynamic opportunities that are useful not only for handling enhancement but also in safety critical scenarios as shown in Paper B and Paper C.

  This decoupling of londitudinal and yaw dynamics also allows for more effective torque vectoring to be performed. Torque vectoring allows for individually varying the torque supplied to each wheel. This in turn allows complex vehicle dynamic interventions to be performed. For instance, vehicle dynamic interventions during cornering need to take into account that applying wheel torques can potentially reduce the lateral capacity of that tyre. With torque vectoring, this trade-off can be better managed and allows for improved vehicle dynamic performance.

- **Continuous vehicle dynamic improvements**
  While IC engines are very difficult to control for vehicle dynamic interventions (fast response needed), brakes on the other hand cannot be used continuously or even frequently since they can burn up. Furthermore, when differential braking is used for interventions, as a side effect, it slows the vehicle down which may not always be desirable. On the other hand, electric drives have the immediate response that is so useful and can be operated continously making them suitable for continuous interventions. If multiple electric drives are available on the same axle or if there is a possiblity of continuously performing torque vectoring, it allows for changing both the steady state and transient dynamic behaviour of the vehicle. This can be very useful from a safety point of view as suitable continuous interventions can be used to prevent unsafe situations from even emerging as opposed to the current method of waiting for the situation to become unsafe before performing an intervention.

2.3 Global vehicle force

The possibility of applying positive tractive force on the wheels opens up additional ways of distributing longitudinal forces. This additional freedom could be useful in achieving an improved trade-off between global vehicle forces. To understand this statement better, first the concept of friction ellipse needs to be introduced.

The friction ellipse is a concept used to visualise the traction force capabilities of a tyre for a given normal load. Shown in fig. 2.6 is an example of the same with two tyre force vectors at the limit of the tyre's friction limit. In this case, if we assume that the longitudinal forces (F_{x1}, F_{x2}) are demanded and applied on a tyre by the controller, then the lateral forces (F_{y1}, F_{y2}) can be interpreted as the maximum tyre lateral force available at the driver or the controller's disposal. However, as can be seen, due to the digressive nature of the relationship between longitudinal and lateral force, the rate of loss of lateral force capacity ($\{F_{y,max} - F_{y1}\}$ and $\{F_{y,max} - F_{y2}\}$) increases as the longitudinal force is increased (F_{x1} and F_{x2}). This means that if the longitudinal force applied is doubled, the loss in lateral force capacity is *more than doubled*.

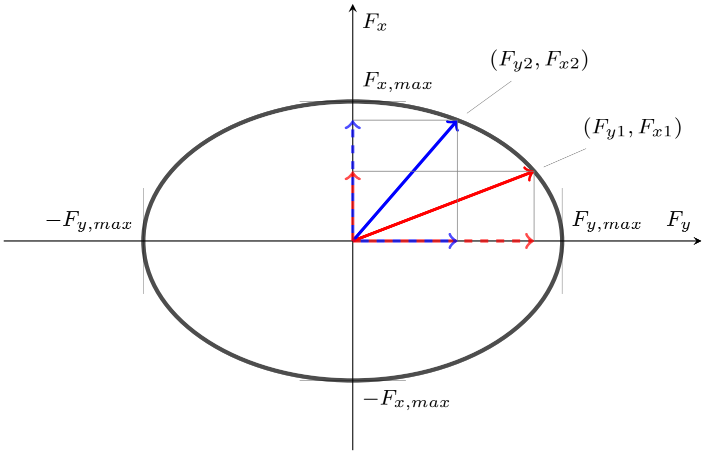


Figure 2.6: *Friction ellipse with two sample tyre traction force vectors*

This has some strong implications for the distribution of longitudinal forces. For instance, consider the task of generating a yaw moment on the vehicle by applying longitudinal forces on the wheels of an axle. With differential braking, all the longitudinal force would have to be applied on one wheel whereas when propulsion is used as well, the forces can be distributed between both wheels leading to smaller longitudinal force magnitudes. And as seen from the friction ellipse and digressive nature of tyre forces, distributing the forces between the wheels results in a smaller loss in lateral force capacity of the axle. Effectively, this means that when propulsion is available, not only are greater torque vectoring magnitudes possible, but also more of the lateral force capacity of the tyres are available when interventions are performed.

The friction ellipse is also useful to visualise the capability of an actuator in terms of the area of the friction ellipse that it can reach. For instance, using the steering and the brakes, only the bottom half of the friction ellipse is reachable. When propulsion is added, the top half of the friction ellipse can also be reached to different extents depending on the magnitude of the driving force that it can deliver.

These tyre force capabilities can also be translated into vehicle global force capabilities. The vehicle global forces are simply the net sum of the tyre forces and moments acting on the vehicle. Since these are the forces which ultimately control the motion of the vehicle, an analysis of different actuator capabilities in this context could be useful.

Ignoring pitch, roll and heave motions, the global vehicle force in terms of the tyre forces can be written as:

$$\boldsymbol{f}^g = AT\boldsymbol{f} \tag{2.30}$$

where $\boldsymbol{f}^g$ is the vector of global forces, A the geometry matrix, T the transformation matrix to convert tyre forces from the wheel reference frame to the vehicle reference frame and $\boldsymbol{f}$ the vector of tyre forces.

The tyre and the global forces can be expressed as follows:

$$\boldsymbol{f}^g = \begin{bmatrix} F_x^g & F_y^g & M_z^g \end{bmatrix}^T \tag{2.31}$$

$$\boldsymbol{f} = \begin{bmatrix} F_{x1} & F_{y1} & F_{x2} & F_{y2} & F_{x3} & F_{y3} & F_{x4} & F_{y4} \end{bmatrix}^T \tag{2.32}$$

The transformation matrix T can be written as:

$$T = \operatorname{diag}\begin{pmatrix} T_1 & T_2 & T_3 & T_4 \end{pmatrix} \tag{2.33}$$

where,

$$T_i = \begin{bmatrix} \cos\delta_i & -\sin\delta_i \\ \sin\delta_i & \cos\delta_i \end{bmatrix} \tag{2.34}$$

Here, δ_i is the steering angle on wheel i.

Finally, the geometry matrix can be written as:

$$A = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ -w_f & l_f & w_f & l_f & -w_r & -l_r & w_r & -l_r \end{bmatrix} \tag{2.35}$$

where, w_f and w_r are the half track widths at the front and rear and l_f and l_r are the distance of the front and rear axles from the centre of gravity.

These equations can be used to investigate the imapct of different actuator setups on the global force plane. For comparison, we consider three different actuator setups for generating longitudinal forces on the tyres as shown in table 2.1.

Name	Constraints	Comment
Brk	$-F_{x,max} \leq F_{x,i} \leq 0$	Brakes only.
SEM	$-F_{x,max} \leq F_{x,i} \leq F_{x,max}/2$	**S**mall **E**lectric **M**otor + brakes
LEM	$-F_{x,max} \leq F_{x,i} \leq F_{x,max}$	**L**arge **E**lectric **M**otor + brakes

Table 2.1: Actuator setups and constraints

The *Brk* setup, as the name implies, has only brakes and consequently can only generate negative longitudinal forces on the tyres. The *SEM* setup has a small electric motor capable of delivering forces to utilise upto half the maximum longitudinal traction available on the tyres. The *LEM* setup on the other hand is assumed to be capable of utilising all the available longitudinal traction on the tyres. Note also that for the *SEM* and *LEM* setups, all-wheel drive is assumed, i.e., the motor is able to drive all four wheels.

Additionally, for this analysis a few other assumptions are made. The steering angle is assumed to be zero (or small) and that it is not accessible by the controller. Consequently, the lateral slip of the tyres are fixed and cannot be influenced by the controller. We also assume a friction circle which is a simplification of the friction ellipse concept.

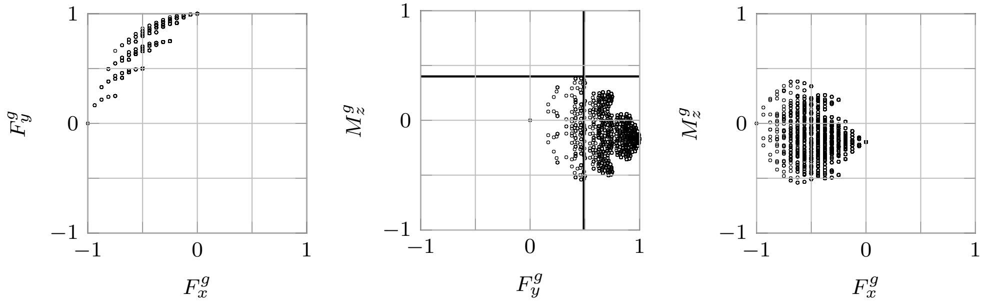
Shown in fig. 2.7 are the global force capabilities of the three actuator setups for a case when the vehicle is cornering hard and the tyre lateral slips are saturated. Note that the global force and moments have been normalized with the maximum forces and moments achievable.

As can be seen, when propulsion is available, the global force capabilities of the vehicle are much larger as expected. More importantly, it can be seen that when propulsion is available, the tradeoff between lateral force and yaw moment is much better.

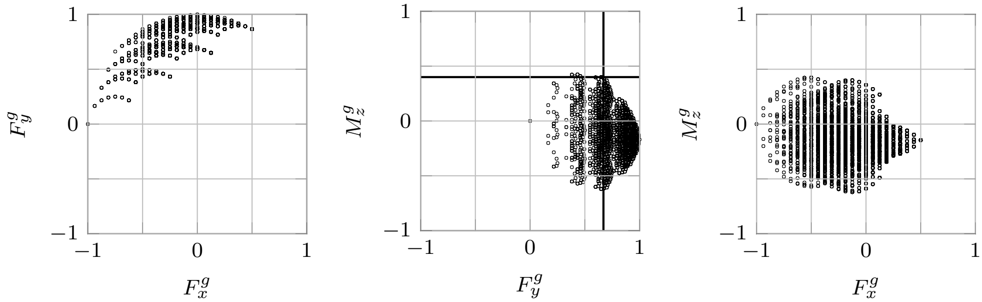
For instance, consider the case of applying a yaw moment on the vehicle while hard cornering. Marked in the M_z^g vs F_y^g plots of fig. 2.7 are the points corresponding to applying a moment of 0.4 on the vehicle. As can be seen, when only the brakes are used, it results in the global lateral force being reduced by half. When the electric motors are used on the other hand, only approximately 30 % of the lateral force is lost. This means that when electric motors are used, not only are greater yaw moments possible, but the vehicle's lateral dynamic performance is not hampered when interventions are performed. It is also worth noting that the *SEM* setup achieves a trade-off that is nearly as good as that of the *LEM* setup. Hence, even with a relatively small electric drive, significantly improved trade-off can be achieved with the global vehicle forces.

A similar effect can be seen in the trade-off between M_z^g and F_x^g. It can be seen that near $F_x^g = 0$, the *Brk* setup has nearly no ability to apply a yaw moment. In contrast, the *SEM* setup has a fair yaw moment capability while the *LEM* has a large yaw moment capability. And, of course, the peak yaw moment magnitudes that they can deliver is larger when an electric drive is added into the mix.

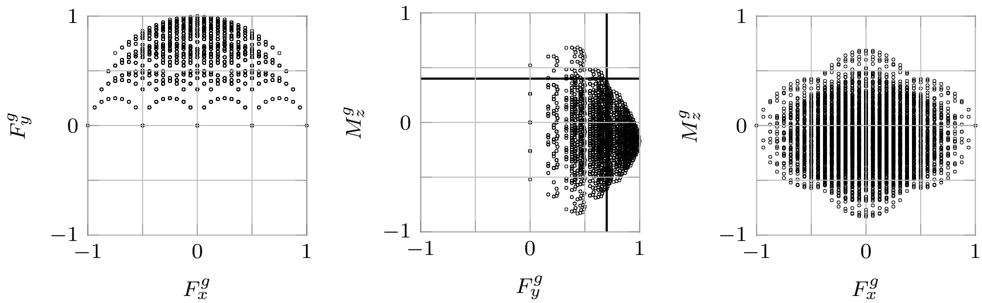
These improved global force trade-offs can be of large benefit in terms of safety. Since lots of active safety functions involve controlling the vehicle at the limits of its dynamic abilities, expanding the same can result in better vehicle dynamic performance and therefore better performance of the active safety functions.



(a) *Global force potential for the* Brk *setup*



(b) *Global force potential for the* SEM *setup*



(c) *Global force potential for the* LEM *setup*

Figure 2.7: *Global vehicle forces*

3 Control opportunities

In this section, some of the major types of control interventions that can be performed with electrified drivetrains which are expected to be useful in safety critical scenarios are detailed. These control interventions can either be used independently or together as required in different accident scenarios to improve safety. Note also that each intervention type has been assigned a color coded abbrieviation which is used in the following chapter to signify the control interventions expected to be of use in each accident scenario.

3.1 Longitudinal speed control [SPD]

In this type of control intervention, the primary control objective is the longitudinal speed of the vehicle. While longitudinal speed can be effectively controlled using traditional IC engine based drivetrains as well (as is the case with cruise control for example), it cannot be done well enough for use in active safety interventions. This is due to the fact that the time window of opportunity for most active safety interventions can be under a second which is too short a duration for traditional drivetrains to be able to reliably deliver a requested torque.

Speed control can be used to improve safety in several ways: for e.g., reducing the relative speed at impact (possibly by acceleration), controlling speed so as to adjust the duration of a manoeuvre or event, reducing speed to prevent or mitigate understeer, etc.

3.2 Longitudinal position control [XPC]

Control of vehicle longitudinal position is the primary goal here. This control task is performed by translating the vehicle longitudinal position based objective to a lower level vehicle speed based objective. Due to this, once again, traditional IC engine based drivetrains are difficult to use in such interventions.

In some cases, longitudinal position control can help avoid collisions completely (.e.g., intersection accidents) while in others, it can help reduce the severity of an impact by providing more room for the bullet vehicle to perform interventions (e.g., rear-end collisions).

3.3 Occupant posture control [OPC]

Here, the goal is to use an appropriately timed acceleration pulse to help adjust the posture of the occupants to reduce injury risk in an imminent collision. For instance, a quick burst of forward acceleration before an imminent rear end collision could potentially push the head back into the headrest thereby reducing the risk of whiplash injury.

Since electric motors can generate torques several times that of their rated torques for brief periods of time and can do so very quickly, they are well suited for this purpose. Furthermore, in this control task, not only the magnitude of acceleration, but also the timing, duration of the pulse and the jerk may be very important. Consequently, traditional IC engine based drivetrains are unsuitable for this purpose.

3.4 Yaw moment control [YAW]

In this case, the goal is to control the yaw motion of the vehicle, which could either be to control the yaw acceleration, yaw rate or rarely, the yaw angle of the vehicle. Yaw rate and yaw angle control is mostly done by translating it to a lower level yaw acceleration control task. While this task can be accomplished by differential brakes, they necessarily slow the vehicle down as a side effect, which may not always be desirable. Furthermore, differential brakes have significant response times which make them unsuitable for improving vehicle response in emergency manoeuvres.

Some of the ways this can help improve safety include: by enhancing the vehicle yaw response and/or stability during severe steering manoeuvres, by controlling the vehicle's yaw motion to improve the driver's control of the vehicle (understeer/oversteer), etc. For instance, during an evasive steering manoeuvre to avoid an obstacle, the vehicle's initial turn in response could be improved to help avoid the obstacle whereas immediately after the avoidance, the vehicle's yaw motion could be damped in order to improve stability and prevent the vehicle from spinning out. Primarily, this control task is done with the aim of assisting the driver and consequently interventions involving such control tasks are typically driver assist interventions rather than autonomous ones and typically require much less environmental information.

3.5 Lateral position control [YPC]

While the vehicle's lateral position cannot be controlled directly, it can be controlled indirectly by controlling its yaw motion and in some cases, its longitudinal speed as well. At high speeds, control of the vehicle's lateral position can be done by translating the task to a lower level yaw moment control task. At low speeds, both yaw moment and the vehicle longitudinal speed might need to be controlled. Lateral control at low speed is complicated by the fact that other effects such as scrubbing of the tyres, steering geometry, etc. become important which are difficult to account for. In this thesis, with regards to lateral position control, only high speed applications are dealt with. As in the case of yaw moment control, while this control task can be achieved with differential brakes, they are not very suitable for this purpose. Furthermore, since lateral position control typically requires precise and extensive actuation (as lateral position is a third order function of the applied yaw moment), they result in even more deceleration.

Just like in the case of longitudinal position control, lateral position control can also help avoid collisions or at least provide more room for the striking vehicle to perform manoeuvres. For instance, this can be used to avoid small overlap collisions without significantly affecting the steering wheel if required. It can also be used to assist the steering in avoidance if the driver intervention is insufficient or lacking in any way. This control task takes away control from the driver to a certain extent and hence care needs to be taken while performing this intervention.

3.6 Longitudinal slip control [SLP]

The control task is here to manage the tyre longitudinal slips so as to keep them within certain levels. Excessive longitudinal slip could lead to the tyre saturating in the longitudinal direction and losing lateral grip which could in turn lead to loss of control. Excessive slip also, in general, reduces the forces generated by the tyres and as result decreases vehicle performance (both braking and cornering).

While slip control can be effectively done with brakes alone, it has been shown that using electric drives for the same lead to significant improvements [30]. Furthermore, in traditional drivetrains, when slip control is done while accelerating, it typically results in jarring and inefficient interventions due to the slow response time of the ICE. Normally, this is only a comfort problem. However, with electrified drivetrains, since acceleration can also be used for safety, controlling slip well during such interventions also becomes important. Additionally, since most active safety interventions involve pushing the vehicle (and therefore the tyres) to their limits, improved slip control will not only reduce distance and duration of manoeuvres, but also enhance stability during these events. Slip control is a control task that is performed almost always with any type of intervention.

4 Use cases for enhanced interventions

In this chapter, a map of different use cases for enhanced interventions using an electrified drivetrain has been provided. Before proceeding further, definitions (in the context of this thesis) of some important, commonly used terms are in order.

- **Accident scenario:** *An outline of the scene which characterizes a potential accident.*
- **Manoeuvre:** *The motion history of the vehicle in the accident scenario.*

  This term is mostly used with reference to the host vehicle.
- **Intervention:** *Any sort of action performed or input to the vehicle deviating from the initial condition or steady state.*

  Can be performed by the driver, a controller or a combination of both.
  - **Driver intervention:** *An intervention performed by the driver.*

    For e.g., braking and/or steering to avoid an obstacle. Does not necessarily have to contribute towards improved safety.
  - **Control intervention:** *An intervention performed by a controller.*

    The interventions outlined in chapter 3 are examples of control interventions. These interventions have relatively low level control objectives (for e.g., control speed, control yaw rate, etc.) and are not specific to the accident scenario at hand.
- **Use case:** *A combination of an accident scenario and a corresponding intervention which is expected to avoid or mitigate the collision in each case.*
- **Function:** *A strategic combination of one or more control interventions performed with the goal of improving safety in a certain accident scenario.*

  Note that a function is a just an idea or strategy of how to perform interventions to improve safety and does not include the hardware or the specific implementation. For e.g., the concept of ABS (not the actual sensors, actuators, etc. that form the ABS) to control slip under severe braking is an example of a function.
- **System:** *The practical realisation of a function including the hardware.*

  For e.g., the ABS function along with the sensors, actuators and any other hardware form the ABS system.

Each use case is briefly described in this chapter along with how an electrified drivetrain can enhance or enable an intervention to improve safety in each case. In the corresponding illustrations accompanying each use case (or a set of them if several use cases are very similar), the types of control interventions that are expected to be beneficial are marked using the color-coded abbreviations introduced in the previous chapter.

In the following sections, the ***host vehicle*** represents the vehicle of interest that has the electrified drivetrain whereas the ***bullet vehicle*** represents the threat which the host vehicle aims to avoid.

4.1 Braking to avoid frontal collision

This use case concerns the rear-end collision scenario which is one of the most common types of traffic accidents. In this case, the intervention to prevent or mitigate the accident consists simply of braking until the collision is avoided or mitigated. While the Automatic Emergency Braking (AEB) system does exactly that, since it relies on traditional brakes which have significant delays and response times, the AEB system can be enhanced by electrified drivetrains.

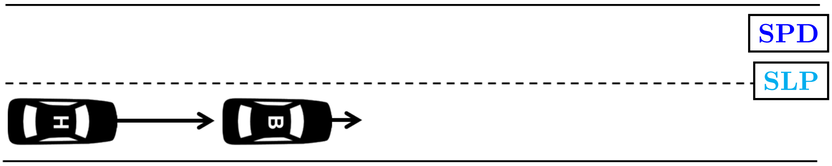


Figure 4.1: *Braking to avoid frontal collision*

As noted in [15] and as shown from real world tests of AEB systems in [19], the brakes can take upto 0.7 s to reach their peak performance. This delay can be dramatically cut short when electrified drives are used for braking as well. Furthermore, improved ABS actuation and slip control can, as shown in [30], reduce braking distances significantly which can in turn improve safety.

4.2 Evasive steering to avoid frontal collision

In this case, an evasive steering manoeuvre is performed either by the driver or an active safety system in order to avoid a collision with a slow moving lead vehicle. Here, the electric drive, in combination with differential braking can be used to perform torque vectoring which can both enhance the yaw response of the vehicle at the initiation of the manoeuvre and also stabilize the vehicle at the end leading to improved safety. The availability of electric drive is advantageous since it allows for higher torque vectoring magnitudes to be achieved by allowing for positive longitudinal forces to be applied on the wheels as well.

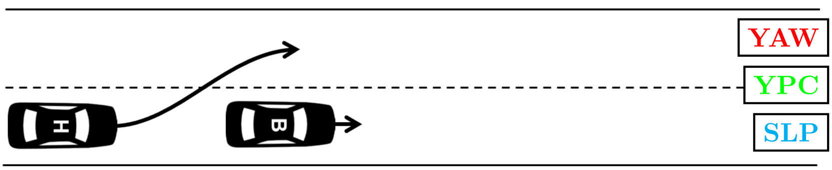


Figure 4.2: *Evasive steering to avoid frontal collision*

Alternatively, if multiple electric drives are available on an axle or if they natively allow for torque vectoring (e.g., [38]), even higher safety improvement is possible since the electric torque vectoring solution would have shorter response times which are critical in such an emergency manoeuvre.

In this scenario, yaw moment control (to enhance yaw response and stability) and slip control interventions would help improve safety.

4.3 Accelerate to avoid rear-end collision

The case of a rear-end collision with an electrified lead vehicle (host) is shown in fig. 4.3. The availability of an electric drive in the lead vehicle opens up several intervention opportunities to improve safety in this scenario.

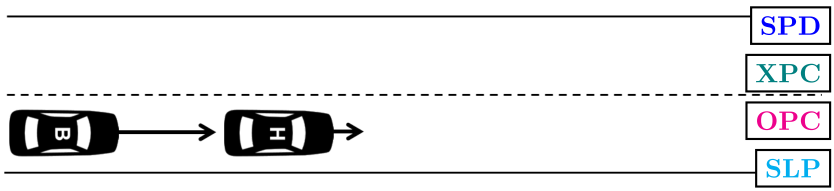


Figure 4.3: *Accelerate to avoid rear end collision*

One of the possible ways to mitigate or even prevent the accident could be to accelerate the lead vehicle and thereby reduce the relative speed at impact. A beneficial side-effect of this is that it also provides more room for the bullet vehicle to brake and thereby amplifies the safety benefit. One could then envision a limited version of this intervention wherein the host vehicle is moved forward precisely by accelerating and then braking so that the vehicle speed is not increased at the end of this manoeuvre. This intervention may be useful, for instance, when the lead vehicle is stationary at a junction with a certain amount of usable free space in front of it.

Alternatively, the electric drive can be used to deliver a short but sharp burst of acceleration with high jerk but with little increase in speed or displacement as this alone could reduce the risk of whiplash injuries for the occupants. The reason for this safety benefit is that the sudden and sharp acceleration pulse can potentially cause the heads of the occupants to be pushed back into the head rests and this improvement in posture can lead to a reduced whiplash injury risk.

In all cases, slip control can enhance the effectiveness of the respective intervention. The interventions can also be combined in different ways to create enhanced versions of the same.

A similar case is considered and analysed in more detail in Paper A.

4.4 Evasive steering for frontal collision avoidance in the presence of oncoming traffic

When evasive steering is performed by the driver in order to avoid a frontal collision, there is a risk of collision with any oncoming vehicles. In such a case, this risk can be reduced by appropriately performing yaw moment control to assist the steering while also controlling the speed to reduce the distance travelled as well as the time taken to complete the manoeuvre.

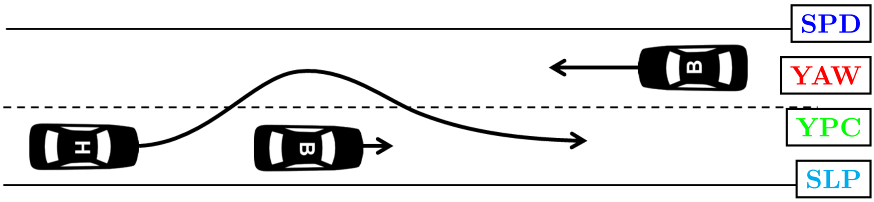


Figure 4.4: *Evasive steering for frontal collision avoidance in the presence of oncoming traffic*

A specific case of this accident scenario has been considered and analysed in detail in Paper B and Paper C.

4.5 Evasive steering and acceleration for rear-end collision avoidance in the presence of obstacle ahead

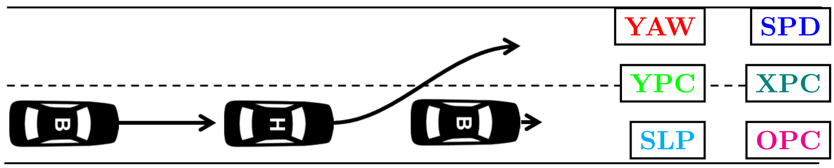
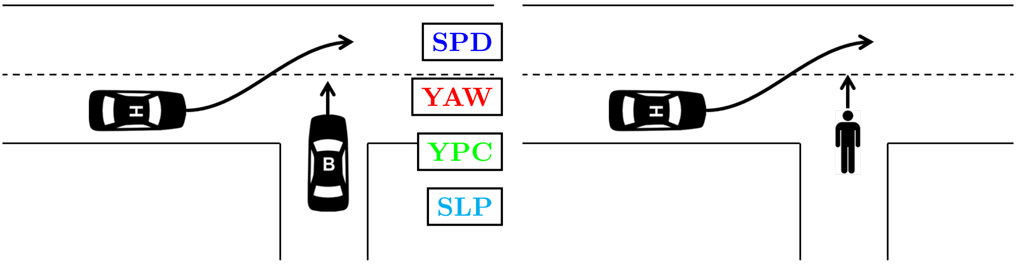


Figure 4.5: *Evasive steering and acceleration to avoid rear-end collision in the presence of an obstacle ahead of the host vehicle.*

An example of an accident scenario in which all of the identified control interventions can be used is the case when a host vehicle is about to be struck from behind while there is also an obstacle ahead of the host vehicle. The presence of the obstacle in front prevents the possibility of performing speed control alone without lateral intervention. And the presence of the bullet vehicle behind means that just lateral control might not be sufficient. It might be necessary to speed up while also steering away from the obstacle ahead. When collision avoidance is not possible in this case, the longitudinal position control and the occupant posture control interventions might be of use to mitigate the severity of the crash and reduce the injury risk.

4.6 Evasive steering and acceleration for avoiding T-bone collisions/pedestrians



(a) *Avoiding T-bone collisions* (b) *Pedestrain avoidance*

Figure 4.6: *Evasive steering and acceleration to avoid collisions from the lateral direction*

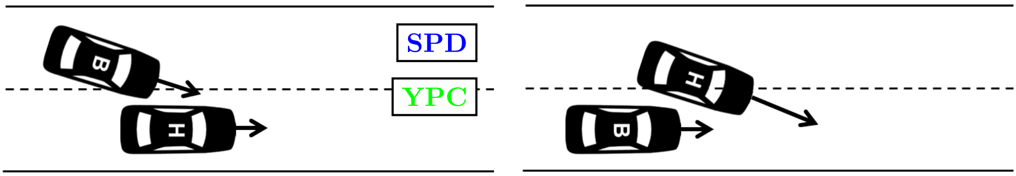
In this scenario, the threat (bullet vehicle or pedestrian) has a constant (assumed) lateral velocity and encroaches on to the host vehicle lane. Assuming braking alone is insufficient to prevent the collision, it may be necessary to perform evasive steering as well. However, since the threat has a lateral velocity, the duration of the evasive manoeuvre becomes important: the longer the manoeuvre takes, larger is the encroachment of the threat into the host vehicle lane, and hence more severe is the evasive manoeuvre required from the host vehicle. Consequently, speed control becomes important in this manoeuvre.

Differential braking to assist the steering could be detrimental in this case since it would slow the vehicle down resulting in it taking a longer time to reach the threat and consequently requiring a more severe intervention. The ability to apply yaw moments without slowing the vehicle down (as can be done with torque vectoring) could be useful here. Control over speed, yaw moment (for stability, responsiveness), lateral position and tyre slips could be useful in this scenario.

4.7 Side swipe collisions

Two variations of the side swipe collision are shown in fig. 4.7. Crucially, in both cases the host vehicle is ahead of the bullet vehicle which means acceleration becomes a reasonable solution.

Simply increasing speed to move the vehicle forward could help prevent the accident in this case. Although the goal here is to achieve an increased longitudinal displacement, accurate control over the same is not required and hence just speed control is sufficient. Lateral position control could also be beneficial in this case. Slip control and yaw moment control may be necessary depending on the severity of the intervention and the steering performed by the driver.



(a) *Bullet vehicle changes lane enroaching into host vehicle space and is about to crash into rear of host vehicle*

(b) *Host vehicle changes lane encroaching into bullet vehicle space and is about to crash into front of bullet vehicle*

Figure 4.7: *Side swipe collisions*

4.8 Intersection accidents

A variety of similar intersection accidents are shown in fig. 4.8. While these cases mostly require the same types of interventions, they show up differently in the accident statistics and hence several variations of the same are shown distinctly here.

In all these cases, yaw moment, speed and slip control are required. While speed control is the crucial part that helps avoid the accident, due to the large curvature of the path being taken, speed control necessarily needs to be combined with yaw moment control and also slip control in order to ensure stability while performing this intervention.

4.9 Exit after give-way/stop sign

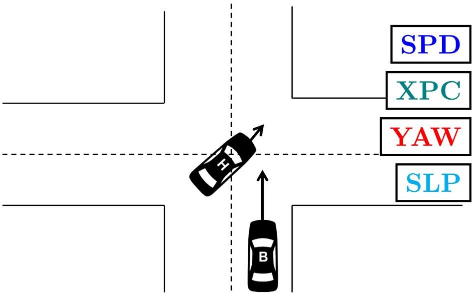
These cases, while similar to intersection accidents in terms of the types of interventions required, show up differently in crash statistics. Furthermore, the speeds involved in these collisions could be different from intersection accidents. The environmental detection aspect is also very different from intersection accidents in these cases.

As in intersection accidents, yaw moment, speed and slip control need to be performed to effectively improve safety in this scenario.

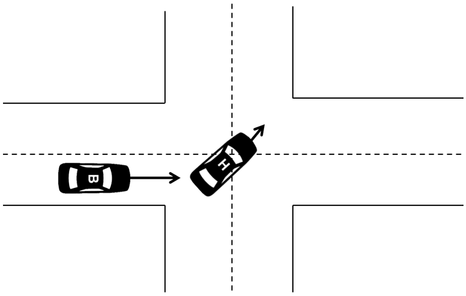
4.10 Loss of control accidents

Loss of control accidents, typically involving understeer or oversteer scenarios are overrepresented in terms of the injuries, loss of life and economic cost. While these accidents can be well dealt with using ESC, due to their severe nature, improved effectiveness in these scenarios are still welcome.

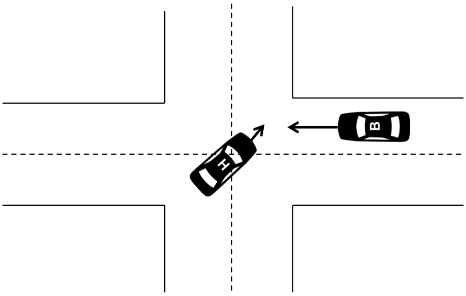
With electrified drivelines, not only are increased yaw moments possible (by also applying positive traction force on one of the wheels), but also more effective slip control (due to shorter response times) is possible leading to higher effectiveness of the ESC system. In some cases, appropriate load transfer can also be generated towards the front



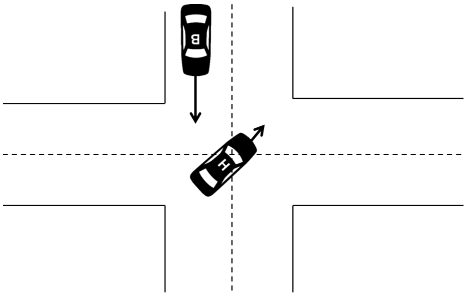
(a) *Intersection accident 1*



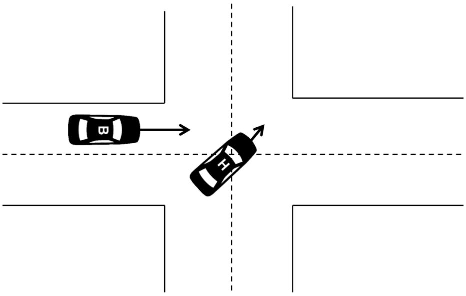
(b) *Intersection accident 2*



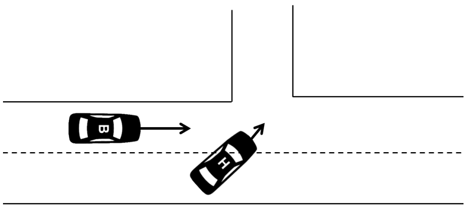
(c) *Intersection accident 3*



(d) *Intersection accident 4*

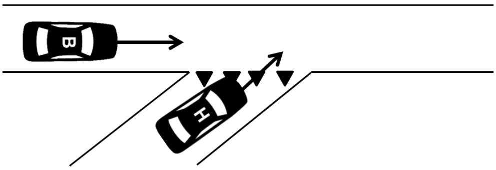


(e) *Intersection accident 5*

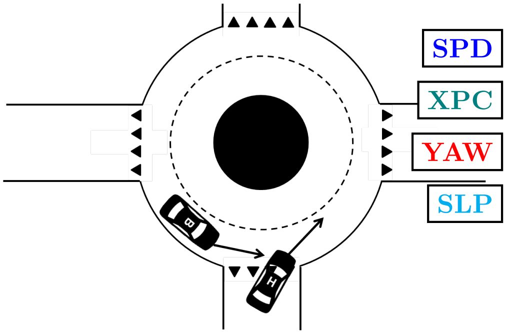


(f) *Intersection accident 6*

Figure 4.8: *Intersection accidents*

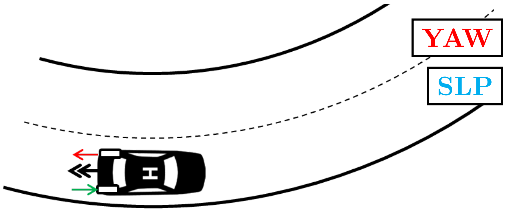


(a) *Host vehicle exits onto main road in front of bullet vehicle with small margin*

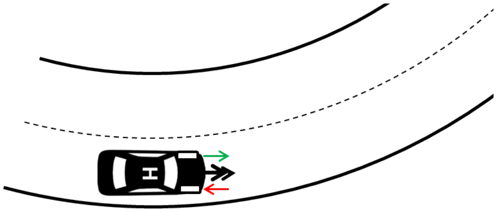


(b) *Host vehicle exits into roundabout in front of bullet vehicle with small margin*

Figure 4.9: *Exit onto road after give-way/stop sign*



(a) *Understeer control*



(b) *Oversteer control*

Figure 4.10: *Loss of control accidents*

or the rear by suitably directed longitudinal acceleration in order to increase the grip at the relevant axle.

Case study I

5 Rear-end collisions: The low hanging fruit

With regards to being able to use electrified drivetrains for active safety interventions, the rear-end collision scenario is one of the simplest and yet most promising accident scenarios. This chapter describes this scenario (same as the one outlined in section 4.3) and the benefits that can be expected from a speed control intervention in this scenario.

The rear-end collision is one of the most accident types that occur in the world accounting for 29.7 % of all accidents in the US in the year 2000. In the same year, approximately 2.2 % of all licensed drivers in the US were involved in rear-end collisions and of those drivers involved in all types of crashes, 36 % were involved in rear-end collisions alone [35]. Similarly, they accounted for 35 % of all traffic fatalities and injuries in Japan in 2005 [43], 24 % of all accidents in Germany [39] and 26 % of all motor crashes resulting in insurance claims in the UK [9].

Due to the high incidence of these accidents, over the years there has been a lot of effort to try and improve safety in this scenario. One of the outcomes of this is the Automatic Emergency Braking (AEB) system that is now available on the market. This system is fitted on the following vehicle and applies the brakes when it detects that a collision with a lead vehicle or obstacle is imminent. Several studies have been done investigating the effectiveness of this system and one such study which used real world crash data in its analysis found that upto 35 % of all rear-end collisions could be avoided completely and 53 % could be mitigated in severity using AEB [32].

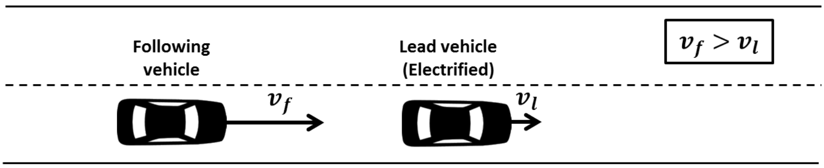


Figure 5.1: *Illustration of a rear-end collision scenario*

However, given that rear-end collisions are one of most frequently occuring accidents, despite the high effectiveness of AEB, the remaining accidents that are not mitigated or prevented by AEB still account for a large number of accidents. These accidents could potentially be improved by a speed control intervention that accelerates the lead vehicle when a collision becomes imminent.

Analysis of accident statistics pertaining to rear-end collisions shows that electric drives are extremely well suited for an intervention in this scenario. In [17], the authors find that approximately 70 % of rear-end collisions involve an impact speed of less than 30 km/h. Less than 15 km/h speed difference is seen in more than 70 % of the cases according to [20]. Between 70-90 % of rear-end collisions involve stationary lead vehicles [27, 28]. In summary, accident data shows that a majority of rear-end collisions involve low lead vehicle speeds and since electric drives deliver their peak torques at low speeds, this makes them suitable in this scenario. Furthermore, the small relative speed in most cases means that only a small speed increase is required in the lead vehicle which makes it easier to achieve and also less risky as an intervention.

Safety benefit can be expected from acceleration not only due to the reduced relative speed at impact, but also by moving the lead vehicle forward, it provides more distance for the following vehicle to brake. Furthermore, since electric vehicles can deliver their torques very quickly and can briefly supply torques several times that of their rated values, the resulting acceleration and jerk can be used to adjust the posture of the occupants' heads to reduce whiplash injury risk.

These concepts and their expected safety benefit in the rear-end collision scenario are explained in more detail in Paper A.

6 Obstacle avoidance with oncoming traffic

This chapter describes the obstacle avoidance with oncoming traffic scenario (similar to the one outlined in section 4.4), how to use the electrified drivetrains to perform safety related interventions in this scenario and the benefit that can be expected from the same.

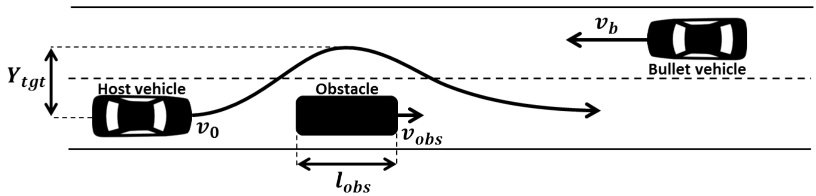


Figure 6.1: *Illustration of an obstacle avoidance with oncoming traffic scenario*

As shown in fig. 6.1, this scenario involves significantly coupled dynamics and hence both longitudinal as well as yaw dynamics need to be controlled.

6.1 Understanding the manoeuvre kinematics and expected safety benefit

Since this scenario requires relatively more complex interventions, it is important to first understand the dynamics of the manoeuvre involved and how the different manoeuvre parameters affect the interventions required. This is done in Paper B where the parameters that characterize the manoeuvre with respect to the safety benefit that can be expected from electrified drivetrains are identified.

Next, using the identified parameters, more detailed investigation is done to estimate the safety benefit that can be expected when electrified drivetrains are used for interventions. These investigations are done in an optimal control framework and in this initial analysis, assume optimal steering. See Paper B for more details.

6.2 Expected safety benefit in the presence of restricted steering

As previously mentioned, this manoeuvre involves significant lateral dynamics and as a result, typically requires a steering intervention as well. However, this steering intervention cannot always be guaranteed to be optimal and hence Paper C investigates the safety benefit that can be expected when the steering intervention is restricted.

In Paper C, the maximum safety benefit that can be expected with different actuator sets in the presence of restricted steering is first estimated using an optimal control framework. Next, closed loop controllers are designed and implemented that try to assist the steering in the lateral control task (but not the longitudinal) and from this, the safety benefit that can be expected from using the different actuator sets for lateral control alone are estimated. Since lateral control is the more essential of the two in this scenario (especially with restricted steering), the ability of different actuator sets to perform this task is of interest. Additionally, performing the lateral control task is relatively easier since it requires lesser environmental information.

More details, results and analysis of these are presented in Paper C.

7 Discussion

The aim of this thesis was to identify the potential of electrified drivetrains from a vehicle dynamics perspective with the aim of using the same to improve safety. Since active safety systems mostly involve performing an intervention on the vehicle by controlling its dynamics, the first step towards envisioning or creating new active safety functions using electrified drivetrains is to understand how they modify the dynamics of the vehicle. Once the potential of electrified drivetrains has been established in various scenarios, decision can be taken as to whether or not it would be worth using electrified drivetrains for active safety interventions based on practical considerations.

In this chapter, the impact of the assumptions made in order to enable this deeper analysis of the vehicle dynamics and the potential applications of the same are detailed.

7.1 Impact of assumptions

Since the focus of this thesis is the vehicle dynamics, several simplifying assumptions have been made and the impact of the same are detailed below.

7.1.1 Sensors and information

Throughout this thesis, all required environmental information from sensors or other sources have been assumed to be readily available. While this may not be true in the current generation of vehicles, due to the advent of advanced active safety, cooperative and autonomous systems, a vast array of sensors and information sources might become available in the cars of the future. Since it is very hard to predict exactly which sensors or information will become available or the properties of that information (accuracy, reliability, etc) we make the simplyfing assumption now of perfect information to establish a basis for what is possible. It would be possible later on to adjust the estimates based on the actual accuracy and reliability of information.

The results presented here regarding the potential of electrified drivetrains in various scenarios can also act as an incentive to add or enhance the fidelity of sensors or information in order to enable or achieve as much of the safety benefit as possible. The results can also be used to establish requirements on sensor and information sources for use in such safety interventions.

7.1.2 Actuator performance

Reasonable assumptions have been made regarding actuator performance in Paper A with most values pertaining to the same having been taken from other scholarly or state-of-the-art papers. In Paper B and Paper C, most actuators are assumed to have optimal or high performance and this assumption is highly unfair to the electric drive since the other actuators have significantly worse performance in reality. The assumptions have been made however to ensure that the results are robust to any possible advancement in the respective technologies which may increase the actuator performance in the future.

Additionally, the use of idealising assumptions allows us to use the results to generate requirements on the actuator performance.

In the rest of the thesis, the assumptions made and their impact are mentioned where relevant. In general, improvement in actuator performance would reduce the benefit offered by electrified drivetrains over traditional ones. However, IC engine performance is unlikely to improve to an extent so as to be usable in an active safety intervention in the future. This is largely due to the downsizing trend which involves turbocharging and while this reduces emissions, it also increases their response times. Brakes on the other hand could improve in performance over time; however electric drives are still likely to be faster and have the advantage of being able to supply driving torques as well.

7.1.3 Human factors

The human factors issue has mostly not been addressed in this thesis even though it is an important part of active safety functions. While this definitely needs to be adressed in any active safety function, these are not deal-breakers by themselves. Instead they put restrictions on the how the results presented in this thesis can be used.

For instance, for an Autonomous Acceleration System (AEA) presented in Paper A, a warning system similar to those used in AEB systems would be unsuitable. Since the threat is now behind the host vehicle, the new warning system would need to be designed to help lead the driver's attention to the rear-view mirror. This can have a significant effect on the driver's response time and change the effectiveness of the warning, but the vehicle dynamics in this scenario remain unchanged. Consequently, autonomous systems which would need little to no interaction with the system would be unaffected, whereas driver assist systems would be a little affected and warning systems would be heavily affected by the human factors issue.

7.2 Applications

The potential applications for the predominantly vehicle dynamic results and analysis presented in this thesis are detailed below.

7.2.1 Driver interaction

One of the very important factors that affect the quality of driver interaction is the delay between the driver making a request and that request being satisfied. Due to the nearly instant response of electric drives, they offer a strong opportunity for enhancement of driver interaction. Since most current generation differential brakes have significant response times, their ability to enhance the driver interaction is limited. The unwanted deceleration side-effect of differential brakes make them further unsuitable for driver interaction enhancement and relegates them for use only in extreme situations. When coupled with an electrified drivetrain however, which can compensate for the deceleration, the two can be used effectively to enhance driver-vehicle interaction and also to improve safety.

The possibility of controlling or influencing the driver vehicle interaction opens up new possibilities with regards to guiding the driver towards safer behaviour when necessary. The same can be used during handover situations - for instance, when an autonomous function hands over control of the vehicle to the driver, it might be necessary to control the driver interaction to let the driver gradually get back in control of the vehicle.

7.2.2 Warning systems

New driver warning systems can be envisioned which use the results presented in this work to estimate when the vehicle approaches a point beyond which the actuator set available in the vehicle would be unable to help and use that to issue warnings and adjust their timings.

For instance, for forward collision warning at high speeds, typically the system needs to wait until evasive steering is no longer a viable option for collision avoidance before a warning is issued. Such systems typically do not account for the possibility that there may be an oncoming vehicle in the adjacent lane which would limit the possibility of performing evasive steering. However, if an oncoming vehicle were to be detected, using the results presented in Paper B regarding the manoeuvre kinematics in the obstacle avoidance with oncoming traffic scenario, the risk of collision with the oncoming vehicle can be estimated. Using this estimate, decisions can then be made regarding the viablity of an evasive steering manoeuvre. If it can be determined that there is a high risk of collision with an oncoming vehicle if the host vehicle moves to the adjacent lane, there would no longer be any need to wait for evasive steering to become unviable anymore and the warning can be given earlier.

7.2.3 Assistance systems

The same factors mentioned in section 7.2.2 can be used for assistance systems as well since most assistance interventions are preceded by a warning phase. The driver interaction aspects mentioned in section 7.2.1 can also be used in the assistance phase to enhance the effectiveness of the intervention. Additionally, estimates regarding collision risk can be used to determine the extent and type of assistance to be delivered and also to determine if an intervention by the driver is in fact a collision avoidance intervention and how the intervention needs to be supported.

For instance, in the obstacle avoidance with oncoming traffic scenario, an estimate of the risk of collision with an oncoming vehicle can be used to determine whether to assist the driver in overtaking the obstacle by maintaining or increasing speed (if demanded by the driver) or to mitigate a possible collision with an oncoming vehicle by reducing speed.

7.2.4 Autonomous systems

Once again, the applications mentioned in sections 7.2.2 and 7.2.3 can be applied for active safety systems as well. The applications for this research have been largely captured in chapter 4 and in Paper A, Paper B and Paper C. However, the intervention opportunities identified in chapter 3 can still be used in other accident scenarios as necessary to improve safety. Based on the improved potential of electrified drivetrains as shown, further novel intervention opportunities can be envisioned for use in safety scenarios.

7.2.5 Cooperative systems

Although electrified drivetrains expand the dynamic capabilities of the vehicle, the very same factor could make it difficult to implement active safety systems since these now have to account for the increased opportunities that are available not only to the host vehicle but also possibly to the bullet vehicle. With cooperative systems however, such concerns could be laid to rest since the vehicles would then be able to exchange relevant information and synchronize their interventions to maximise safety. Cooperative systems also mitigate the issue of sensors and information captured in section 7.1.1 and reduce the requirements on sensors.

8 Conclusions and future work

8.1 Conclusions

The advantages offered by electrified drivetrains in terms of expanded vehicle dynamic capabilities (chapter 2) and how they can be used for novel or improved interventions for safety have been shown (chapter 4). Two accident scenarios, namely the rear-end collision and the obstacle avoidance with oncoming traffic scenario have been investigated in detail and the safety benefit that can be expected with electrified drivetrains in these scenarios have been estimated.

The results from the analysis show that electrified drivetrains offer a strong opportunity to improve safety in these scenarios. The results also highlight the importance of being able to control the speed or at least not affect it (if not demanded by the driver) in safety critical scenarios. Another feature highlighted in the results is the importance of being able to decouple the yaw and longitudinal control interventions. When yaw moment interventions can be done without affecting the longitudinal dynamics, not only can it be used to improve the vehicle response and stability in critical scenarios, it can also be used for steering redundancy.

Before the results can be used in production vehicles however, several non vehicle-dynamic aspects need to be investigated. The human factors aspect, i.e., how would the drivers of the host and bullet vehicles react to acceleration of the host vehicle, needs to be considered. The decision making and the interpretation of driver input (is the driver trying to make an avoidance manoeuvre or just performing lane keeping?) is another important aspect which will need to be solved. Investigation also needs to be done using accident statistics to estimate the proportion of accidents in which the envisioned control strategies or functions can be of use.

In summary, several vehicle dynamic opportunities for improving safety using electrified drivetrains were identified. Detailed investigations of select cases showed that significant safety benefit stands to be gained by appropriate control of electrified drivetrains in the accident scenarios. Consequently, a strong opportunity is seen for adding safety related value to electrified vehicles at little to no extra cost.

8.2 Future work

From a vehicle dynamics point of view, several opportunities exist for future work. In the obstacle avoidance with oncoming traffic scenario, the benefit of speed control with closed loop controllers need to be investigated. The robustness of such interventions in the presence of moving obstacles or accelerating bullet vehicles needs to be analysed. The benefit that can be expected with realistic limitations (low performance actuators, limited environmental information, etc) needs to be quantified. In case of the rear-end collision scenario, more detailed investigation regarding the interaction of an acceleration system on the lead vehicle with active safety systems on the following vehicle (like the AEB) needs to be done.

In both cases, closed loop controllers need to be implemented in test vehicles and experiments need to be carried out in order to validate the results. Experimental testing would also lead to more robust, pragmatic and efficient controllers which would also need to handle unforseen circumstances.

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Part II
Appended Papers