FFI

Improved Stability and Manoeuvrability using electric propulsion

Project within: Vehicle and Traffic Safety
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Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

For more information: www.vinnova.se/ffi

1. Executive summary

Although the sales of electrified vehicles are 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 project 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, the possibility of accelerating an electrified lead vehicle to mitigate the consequences of, or prevent being struck from behind has been investigated. In this use case, 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.

In a second use case, 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 showing increased safety benefit.

In summary, several vehicle dynamic opportunities for improving safety using electrified drivetrains have been identified. Detailed investigations of a few selected accident scenarios showed that significant safety benefit can 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.

2. Background

The emissions problem

Over the past few decades, there has been increasing awareness regarding pollution, global warming and diminishing oil reserves among people. 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 [1], approximately half of which is estimated to be caused by road transport [2]. To limit such harmful by-products 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, [3]).

Fuel efficiency requirements have also been imposed indirectly through restrictions on fleet average carbon dioxide (CO_2) emissions of new cars sold. The EU has set an ambitious fleet average CO_2 emission target of 95g/km in 2021 which represents approximately a 40% reduction over the 2007 emission levels of 158.7g/km [4].

The combination of these stringent emission and efficiency requirements has led to an increased interest in electrified vehicles. While electrified vehicles have been shown to have a strong potential to reduce greenhouse gas (GHG) emissions [5, 6, 7], they have not really captured the market due to a variety of reasons. Customers cite numerous reasons including high cost, low range, lack of charging infrastructure, etc. A study done in 2009 [8] shows that we are nowhere near on track to meet the required electrified vehicle fleet penetration for an ultimately stabilizing CO_2 concentration in the atmosphere of 450ppm.

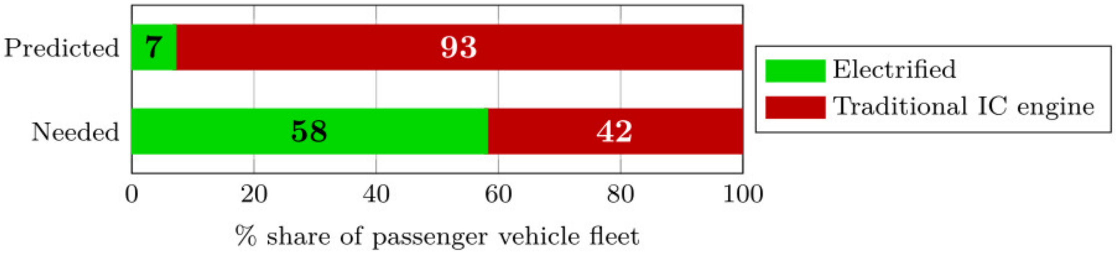


Figure 1: Predicted and needed split of electrified and traditional vehicles in 2030 in the vehicle fleet for an ultimately stabilizing CO2 concentration of 450 ppm in the atmosphere [8]

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.

The safety problem

Due to urbanisation and increasing mobility of the world population, there are now larger numbers 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 [9]. 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 [10].

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 capabilities enabled or enhanced by the new actuators available in the cars of tomorrow.

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. 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?

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.

3. Objective

Given 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 as 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?

4. Project realization

First, an analysis of capabilities of the electrified drivetrain is done to identify the vehicle dynamic advantages offered by electric drives over traditional IC engines. This is then followed by a study of various accident scenarios to identify cases where the advantages of electrified drivetrains so identified can be used to enhance safety. Resulting from this analysis is a so called “map of scenarios” which is presented briefly later on and detail in the licentiate thesis. This map briefly lists the different accident scenarios where electrified drivetrains can be used to improve safety and the type of intervention that will need to be performed for the same.

As an example of a low-hanging fruit, the rear-end collision scenario is then analysed in detail. Paper A (see section 6.2) analyses the potential safety benefit from autonomous acceleration of an electrified lead vehicle to mitigate or prevent being struck from behind. Safety benefit was estimated based on the expected reduction in relative velocity at impact in combination with injury risk curves. Simple kinematic analysis is done to estimate the velocity reductions that can be achieved. Potential issues and safety concerns with the operation and implementation of such a system in the real world are discussed from engineering and human factors stand point. In particular, the effect of the pre-collision acceleration in reducing whiplash injury risk due to change in head posture and reduction of crash severity is also discussed.

Next, the more complicated scenario of obstacle avoidance with oncoming traffic is analysed. Since this scenario requires relatively more complex interventions, first a kinematic analysis of the manoeuvre is done to understand the influence of various parameters on the manoeuvre and to identify the ones that most affect the benefit that can be achieved with electrified drivetrains. 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 (see section 6.2) for more details.

For the next step, the steering is assumed to be restricted and a similar analysis is done as before to estimate the benefit of electrified drivetrains in such a case. In Paper C (see section 6.2), 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.

5. Results and deliverables

Enhanced intervention opportunities

In this subsection, some of the major types of interventions which are enabled or enhanced by electrified drivetrains and are expected to be useful in safety critical scenarios are listed. Note also that each intervention type has been assigned a colour coded abbreviation which is used in the accident scenarios to signify the control interventions expected to be of use in each accident scenario.

Longitudinal speed control [SPD]

In this type of control intervention, the primary control objective is the longitudinal speed of the vehicle. Due to the fact that the time window of opportunity for most active safety interventions can be under a second, traditional IC engine based drivetrains cannot be used here and an electrified drivetrain is required for reliable interventions.

Longitudinal position control [XPC]

Control of vehicle longitudinal position is the primary goal here. Once again, traditional IC engine based drivetrains are too slow and difficult to use in such interventions.

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. 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 can generate large accelerations and jerks which make them well suited for this purpose.

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. Electric drives in combination with differential brakes can perform effective yaw moment control without slowing down the vehicle (which is a major drawback of using differential brakes alone).

Lateral position control [YPC]

The goal here is to control the lateral position of the vehicle in the scenario. Only high speed applications are considered here. 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.

Longitudinal slip control [SLP]

The control task is here to manage the tyre longitudinal slips so as to keep them within certain levels. The quicker response time of electric drives can be used to enhance this intervention.

Use cases for enhanced interventions

A map of different use cases for enhanced interventions using an electrified drivetrain is given here. In the corresponding illustrations accompanying each use case, the types of control interventions that are expected to be beneficial are marked using the color-coded abbreviations introduced in the previous subsection. In the following use cases, 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.

Evasive steering to avoid frontal collision

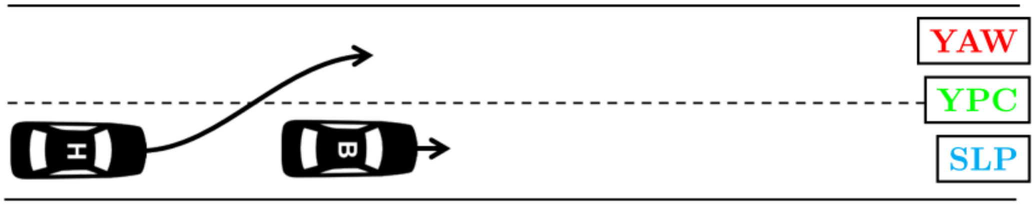


Figure 2: Evasive steering to avoid frontal collision

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

Accelerate to avoid rear-end collision

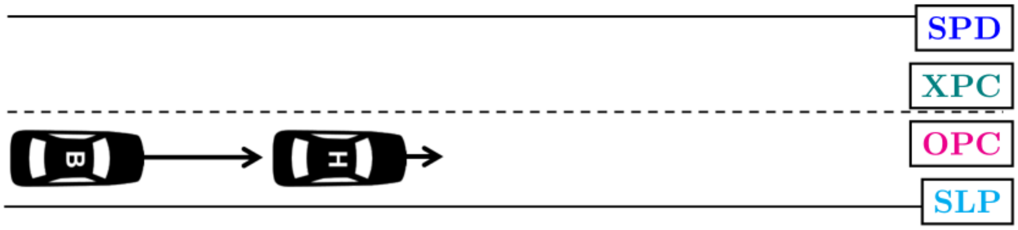


Figure 3: Accelerate to avoid rear end collision

The case of a rear-end collision with an electrified lead vehicle (host) is shown in fig. 3. 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. The electric drive can also 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. (See Paper A for more details)

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. (See Papers B and C for more details)

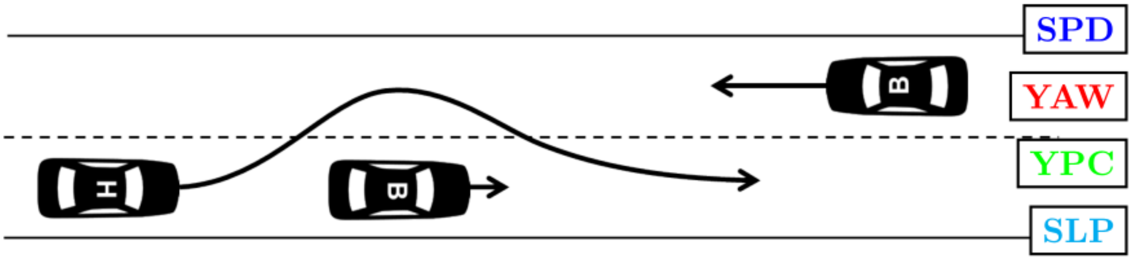
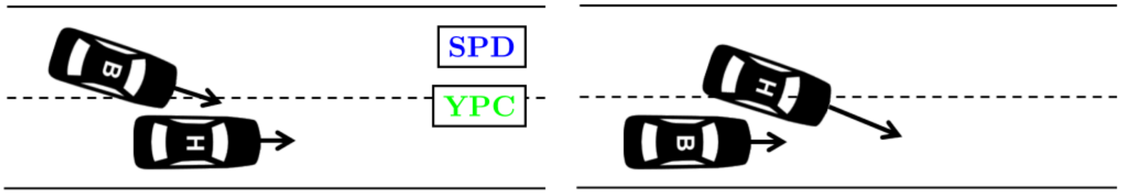


Figure 4: Evasive steering for frontal collision avoidance in the presence of oncoming traffic

Side swipe collisions

Two variations of the side swipe collision are shown in fig. 5. 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.

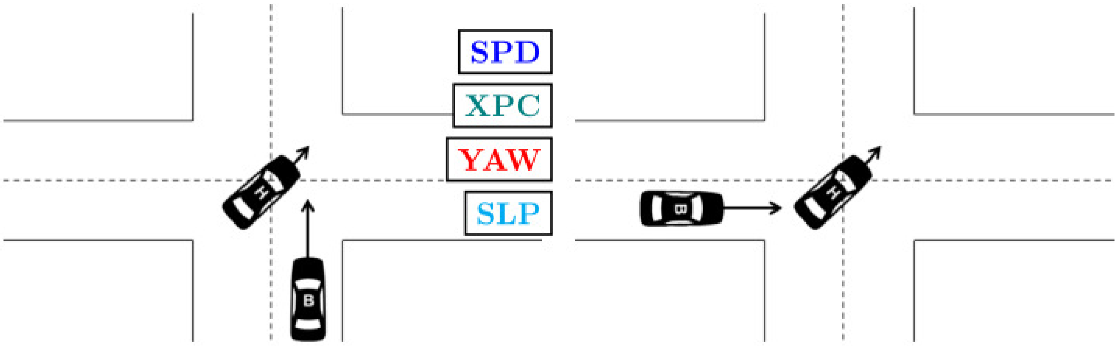


(a) *Bullet vehicle changes lane enroaching into host vehicle space and is about to crash into rear of host vehicle* (b) *Host vehicle changes lane encroaching into bullet vehicle space and is about to crash into front of bullet vehicle*

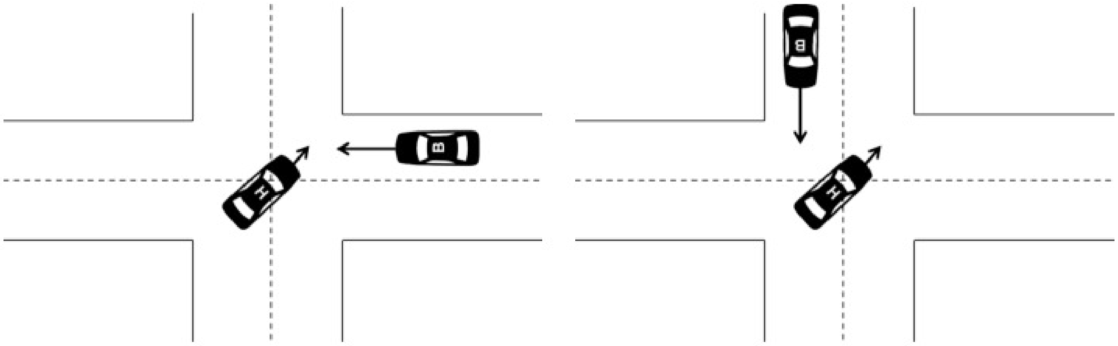
Figure 5: Side swipe collisions

Intersection accidents

A variety of intersection accidents are shown in fig. 6. 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.



(a) *Intersection accident 1* (b) *Intersection accident 2*



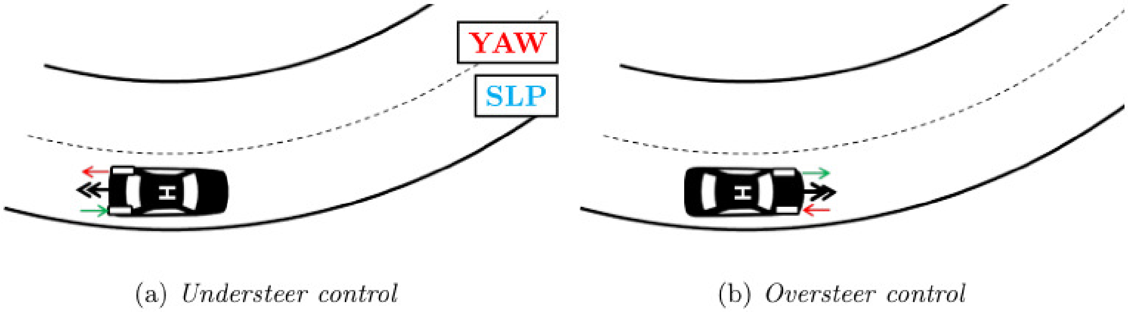
(c) *Intersection accident 3* (d) *Intersection accident 4*

Figure 6: Intersection accidents

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. See the licentiate thesis for more examples and details.



(a) *Understeer control* (b) *Oversteer control*

Figure 7: Loss of control accidents

Use case I: 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.

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.

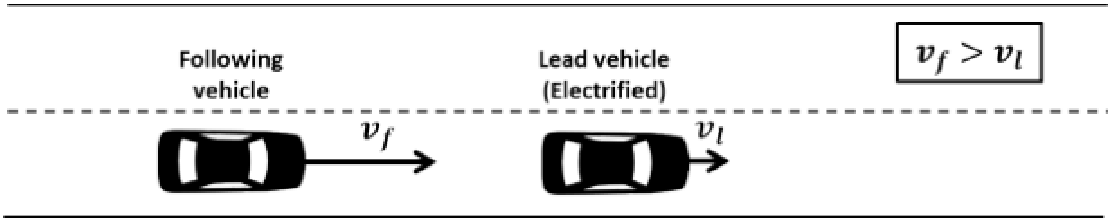


Figure 8: Illustration of a rear-end collision scenario

An analysis on the potential of a hypothetical Autonomous Emergency Acceleration system (AEA) in an electrified lead vehicle to mitigate rear-end collisions is presented in Paper A. It is found that when used in conjunction with Automatic Emergency Braking (AEB), even collisions with high relative speed (up to 75 km/h) can be prevented with low increases in lead vehicle speed and distance travelled (on average ≈15km/h and ≈2m respectively). Significant reductions in relative velocity at impact can be achieved by relatively short lead vehicle displacements without significant increase in lead vehicle speed as well. Given that 30% reduction in fatality risk can be achieved with just 10%

reduction in impact speed, an acceleration based active safety system could have a large safety benefit. See Paper A for more details.

Use case II: Obstacle avoidance with oncoming traffic

This subsection describes the obstacle avoidance with oncoming traffic scenario, how to use the electrified drivetrains to perform safety related interventions in this scenario and the benefit that can be expected from the same.

Understanding the manoeuvre kinematics and expected safety benefit

It was found that the two most important parameters that characterize the manoeuvre and determine the extent of benefit that can be achieved by electrified drivetrain are the obstacle length and the velocity ratio (bullet vehicle to host vehicle velocity). The possibility and potential of using propulsion to reduce the encroachment distance in this scenario is investigated and presented. For short obstacles of length 3 m and less, relatively large velocity ratios of over 1.5 are required to achieve safety benefit of over 2 m and up to a maximum of 8 m. With obstacles of length 15 m or higher, safety benefit of over 1 m can be achieved even with velocity ratios of less than 1. Safety benefit of between 5 to 15 m can be achieved when the velocity ratios are between 1.5 and 2 and up to 45 m when the velocity ratios are even higher. It was found that even with optimal steering control, on average, a safety benefit of approximately 3 m was achieved using torque vectoring capability. This safety benefit is expected to be even more pronounced when a sub-optimal steering profile is used.

Expected safety benefit in the presence of restricted steering

Theoretical investigation done using optimal control showed a clear safety benefit of being able to apply a yaw moment on the vehicle without affecting the speed in the obstacle avoidance with oncoming traffic scenario. Under certain manoeuvre conditions characterized by high velocity ratios and long obstacles, the benefit of torque vectoring is amplified. The high performance of torque vectoring in lateral control tasks even in comparison to optimal steering leads one to conclude that it can be an effective assist or redundancy for the steering actuator.

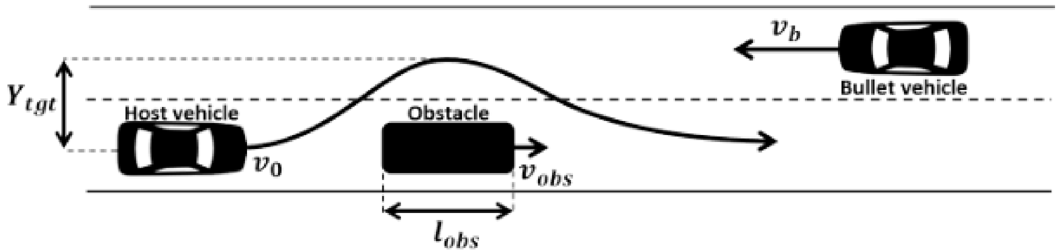


Figure 9: Illustration of an obstacle avoidance with oncoming traffic scenario

Simulations using a simple closed loop controller and a more realistic steering intervention highlight the importance of speed control, especially in the presence of limited actuator capability. Simply being able to assist the steering in the lateral control task without causing a speed penalty significantly improves the safety. While differential braking can be useful in the scenario under some conditions it significantly reduces safety in others. Torque vectoring ability is seen to be useful not only in improving safety but also in being able to do so reliably with much less environmental information.

5.1 Delivery to FFI-goals

Safety targets
The main target is improved traffic safety by implementation of new active safety functions. The project primarily addresses accidents where the driver tries to avoid the accident but fails, due to non-optimal use of road friction. Hence, the project would like to offer better vehicle controllability to the driver.

Industrial competitiveness targets
The project contributes especially to the following 3 targets:

- **Target:** ***"strive to secure national supplies of competence and to establish R&D with competitive strength on an international level"*** The project contributes by showing how electric propulsion systems can add value in safety and drive-ability on top of energy efficiency.
- **Target:** ***"contribute towards a vehicle industry in Sweden that continues to be competitive"*** Electrification of vehicle is of highest priority in the global automotive industry. The project contributes to the competitiveness by exploiting systems for energy saving for improving safety.
- **Target:** ***"support environments for innovation and collaboration"*** The project contributes by cooperation between parties from all three groups: OEMs, suppliers and academy.

6. Dissemination and publications

6.1 Knowledge and results dissemination

Results of the PhD project and/or papers were made at the following events/conferences as part of the project:

- Transportation Initiative Seminar, Gothenburg – 2013-09-12
- 12th International Symposium on Advanced Vehicle Control (AVEC '14), Tokyo, 2014-09-22 – 26
- Elektronik i Fordon, Gothenburg – 2014-04-24
- 24th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD '15) – Graz, 2015-08-17 - 21
- Future Active Safety Technology Towards zero traffic accidents (FastZero '15) – Gothenburg, 2015-09-09 - 11

6.2 Publications

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. 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. Graz, Austria, Aug. 17, 2015

Lic thesis - A. Arikere, “Vehicle Dynamic Opportunities in Electrified Vehicles for Active Safety Interventions,” Licentiate, Chalmers University of Technology, Göteborg, 2015.

7. Conclusions, applications and future research

Conclusions

The advantages offered by electrified drivetrains in terms of expanded vehicle dynamic capabilities and how they can be used for novel or improved interventions for safety have been shown. 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.

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.

Potential applications

Autonomous emergency acceleration system for rear end collision avoidance

The research done in Paper A could be used to develop the motion control and the decision making modules for an autonomous emergency acceleration system for rear-end collision avoidance and/or mitigation. Considering that rear-end collisions are one of the most common types of accidents and that the sensors required for this function will become available in cars of the future (due to advanced driver assist and autonomous functions), this function offers a strong opportunity to add safety at little to no extra cost.

Evasive steering assist

The research presented in Paper C could be used to perform evasive steering assist in terms of controlling the trade-off between steering intrusiveness reduction and safety (avoiding obstacle and/or oncoming vehicle). Using this method, steering assistance systems could be devised that not only help the driver avoid a collision but do the same with less steering intrusiveness. This in turn is less likely to startle the driver and therefore help the driver perform better in such critical scenarios.

Overtaking assist

The research presented in Papers B and C can be used in active safety functions that assist the driver in performing an overtaking maneuver by either controlling the speed or assisting in lateral control of the vehicle or in achieving a suitable trade-off between the two.

Decision making applications

The vehicle dynamics results derived in Papers A, B and C can be used to power the decision making algorithms in active safety functions. For instance, results from paper B and C can be used to make a decision whether to initiate, terminate or continue an overtaking manoeuvre.

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.

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