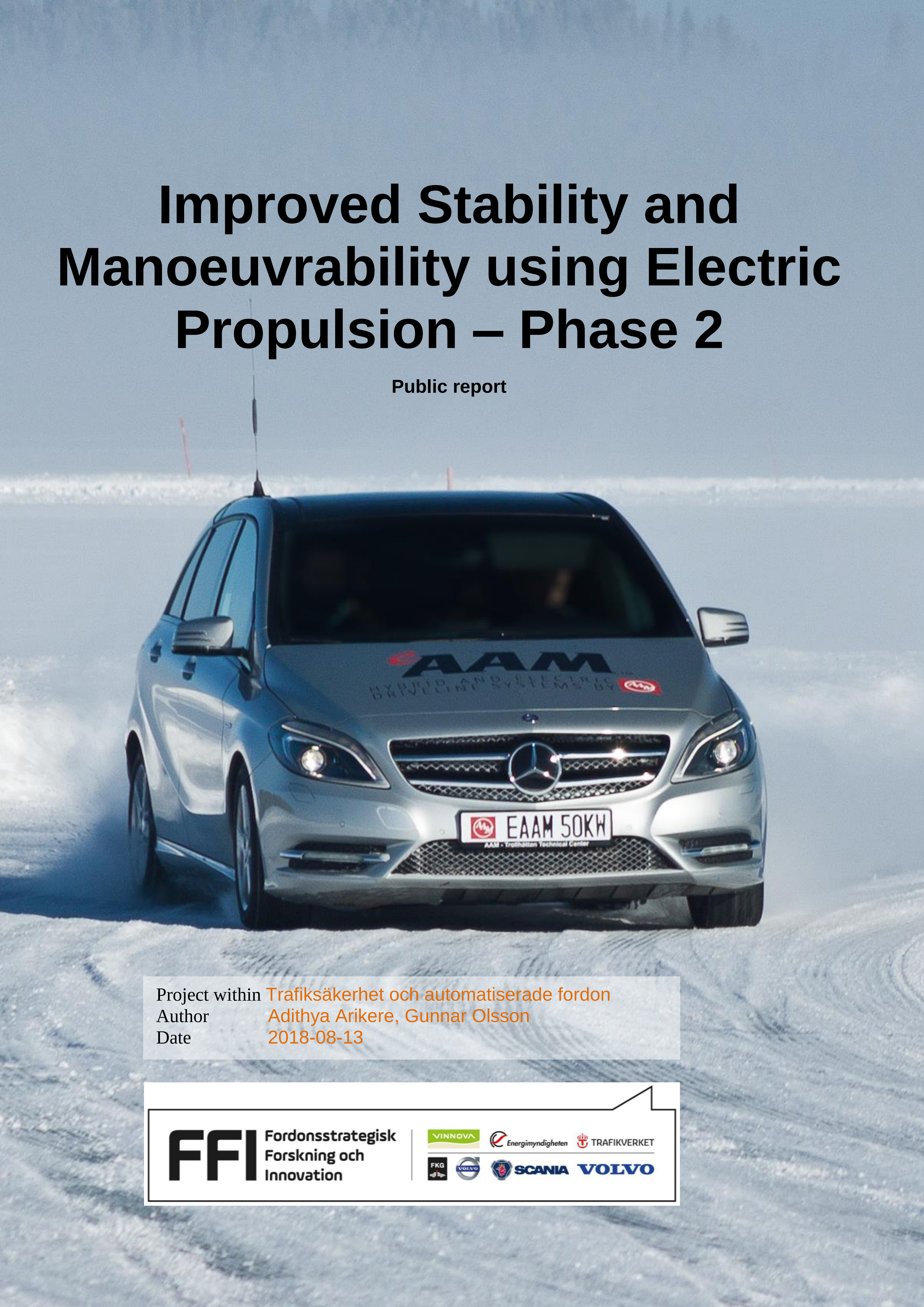

Improved Stability and Manoeuvrability using Electric Propulsion – Phase 2

Public report

Project within Trafiksäkerhet och automatiserade fordon
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FFI Fordonsstrategisk Forskning och Innovation

Content

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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 about €40 is governmental funding.

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1. Summary

Climate change and air pollution causing poor air quality are among the most pressing issues facing the world today and the transport sector is a major contributor to both. One way to mitigate both these issues is to switch from purely fossil fuel driven vehicles to fully electric or at least electrified vehicles. However, studies have shown that both the growth in electrified vehicle sales and the pledges and promises that have been made by various governments in terms of combating climate change are far short of what is required to successfully mitigate climate change.

Clearly then, a solution to drive electrified vehicle sales on the open market is needed. One way to achieve this can be to add value to electrified vehicles by implementing functions that exploit the advantages of electric drives over traditional internal combustion engines. And since vehicle safety is another important ``gap area" in the transport sector, adding safety-related value to electrified vehicles could be an effective way to make them more attractive to consumers.

In this thesis, the possibility of implementing active safety functionality that is enabled or enhanced by electric drives is investigated. It was seen that electric drives can be used to perform several enhanced interventions which can in turn be used to perform active safety interventions in a large number of scenarios to improve safety. Three accident scenarios were investigated in detail, in each of which significant safety benefit could be gained with the help of electric drives: i) rear-end collisions, ii) obstacle avoidance with oncoming traffic and iii) intersection accidents.

In summary, this work shows that a strong opportunity exists for adding safety related value to electrified vehicles at little to no extra cost. This in turn could make them more attractive to consumers, help drive electrified vehicle sales and therefore contribute toward mitigating climate change and air pollution.

2. Sammanfattning på svenska

Klimatförändringar och luftföroreningar som orsakar dålig luftkvalitet är bland de viktigaste problemen världen står inför idag och transportsektorn bidrar till en väsentlig del till dessa. Ett sätt att mildra båda dessa problem är att byta från fossilt drivna fordon till helt elektriska eller åtminstone elektrifierade fordon.
Studier har visat att tillväxten i försäljning av elektrifierad fordon är otillräcklig för att tillgodose de behov som gäller för att framgångsrikt mildra klimatförändringen.
Ett sätt att öka försäljningen torde vara att öka kundvärdet hos elektriska fordon med hjälp av ökad aktiv säkerhet genom att implementera funktioner som utnyttjar fördelarna med elektrisk framdrivning.

Syftet med denna studie har varit att undersöka, utveckla och utvärdera nya säkerhetsfunktioner, baserade på fordon med elektrisk framdrivning.

I projektet har den viktiga frågan att besvara varit: ”I vilka trafikscenarier kan det visas att elektrisk framdrivning ger säkerhetsfördelar".

För att kunna svara på denna fråga har uppgiften i projektet varit att utveckla implementerbara algoritmer för de olika fordonsdynamiska regleruppgifter som förekommer i vanlig trafik och sedan verifiera prestandan hos dessa i utvalda trafikscenarier, genom simulering och experiment med riktiga testbilar.

Som exempel på ett trafikscenario undersöktes möjligheten att accelerera ett elektrifierat målfordon för att mildra konsekvenserna av att träffas bakifrån i ett scenario med en hotande bakändeskollision. Ett hypotetiskt automatiskt nödaccelerationssystem (AEA), utvecklades och analyserades. Det visade sig att AEA-systemet erbjuder betydande möjligheter att mildra eller helt förebygga skador vid bakändeskollisioner.

Två andra trafikscenarier som också undersökts i detalj är dels undanväjningsmanövrar i närvaro av mötande trafik och dels korsningsolyckor. Projektet har visat att betydande säkerhetsfördelar kan uppnås med elektriska drivlinor. Ett flertal fordonsdynamiska möjligheter att förbättra trafiksäkerheten har identifierats och därmed en potential att addera säkerhetshöjande kundvärde till elektrifierade fordon.

Utvecklingsarbetet har framförallt fokuserat på utveckling av regleralgoritmer och mjukvara för implementering i bil och att visa förbättringspotentialen både teoretiskt och experimentellt. För den teoretiska analysen har validerade fordonsmodeller från Volvo Cars använts och mjukvaruplattformen har varit IPG CarMaker. Prov i bil av den utvecklade mjukvaran har genomförts vid ett antal tillfällen med en preparerad Volvo XC90 hybridbil. Alla bilprov har genomförts på avlysta banor, Asta Zero eller Hällered.

Sammanfattningsvis har de utvecklade funktionernas säkerhetsförbättringspotential kunnat verifieras. Detta har gjorts med hjälp av simulering och prov i bil. Projektet har också utvecklat och visat på tekniska lösningar.

Projektet har utvecklat och spridit kunskap inom det undersökta teknikområdet bl a genom vetenskapliga rapporter och deltagande i konferenser samt bidragit till ett utökat kontaktnät för parterna.

3. Background

Over the past few decades, general awareness regarding issues surrounding the use of fossil fuels such as climate change and pollution have been increasing among the general public. As a result, there have been increasing calls both from the public and the governments on vehicle manufacturers to make cars that are more environmentally friendly and less dependent on fossil fuels. One of the side-effects of this is that legislation regarding emission and fuel efficiency requirements on new cars have been getting more and more stringent.

The United Nations (UN) estimated in a recent study that air pollution across Europe costs $1.6 trillion a year in deaths and diseases, which amounts to nearly one tenth of the region's gross domestic product (GDP). Approximately 50% of this pollution (and consequently the damages and cost) is estimated to be caused by road transport. In an effort to combat such pollution, 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, Euro emission norms).

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. Figure 1 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.

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.

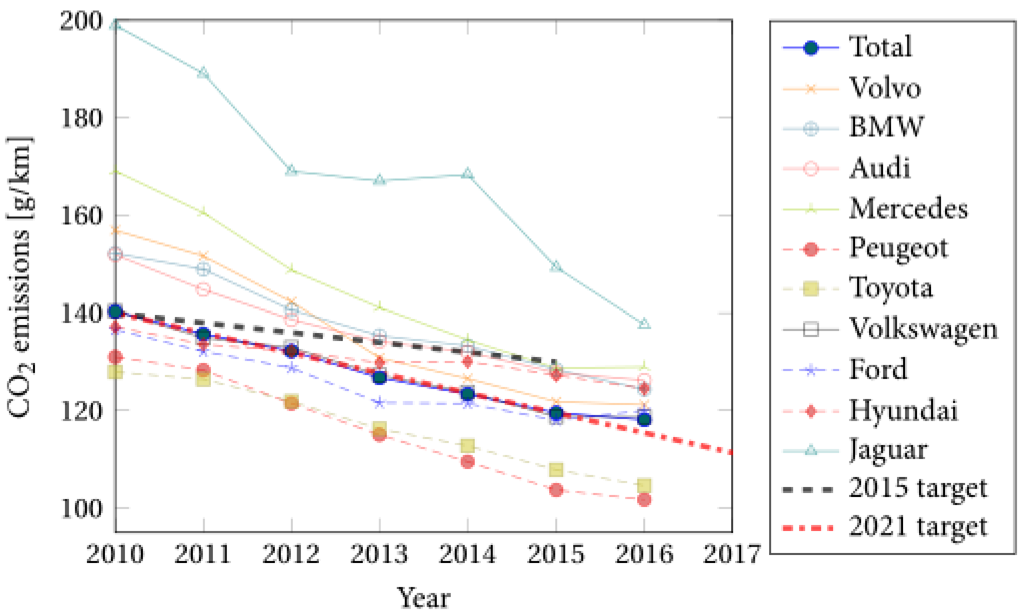

Figure 1 Fleet CO_2 emissions.

While the numerous studies investigating the capabilities of electrified drivetrains suggest a strong potential to reduce greenhouse gas (GHG) emissions, 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 in the vehicle fleet. However, several studies have been done on the expected growth in electrified vehicle sales and market penetration which show that while significant sales and market penetration can be expected, we are nowhere near on track to meet the required electrified vehicle sales or fleet penetration to successfully mitigate global warming. Figure 2 shows predictions of electric vehicle stock in the year 2030 done by the International Energy Agency (IEA). Here, RTS refers to the Reference Technology Scenario which represents projections based on policies that have been announced or are currently under consideration, 2DS refers to a scenario with a 50% chance of limiting expected global average temperature increase to 2^{o}C and B2DS refers to a scenario with a 50% chance of limiting expected global average temperature increase to 1.75^{o}C.

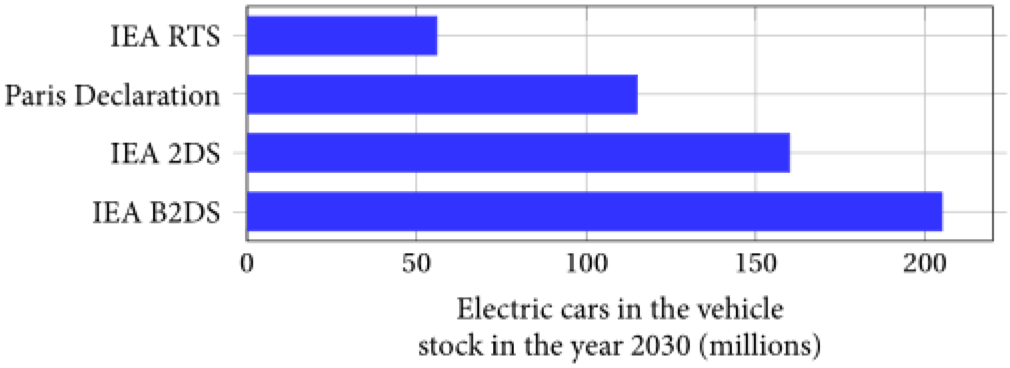

Figure 2 Deployment scenarios for the stock of electric cars to the year 2030. RTS=Reference Technology Scenario (similar to reference scenario in fig. 1.3), 2DS= 2^{o}C scenario, B2DS=Beyond 2^{o}C scenario.

It is clear therefore that, to drive the sales of electrified vehicles, purely relying on legislative reform or government intervention is insufficient. Some form of added incentive or value is needed that would help drive electrified vehicle sales in the free market. 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.

Due to urbanisation and the increasing mobility of the world population, there are now larger numbers of motorists in smaller areas. This increased traffic density not only exacerbates the emissions problem but also results in increased traffic conflicts and hence leads to higher number of accidents. Consequently, along with the increased demand for efficiency, there is also an increasing demand for traffic safety. Several countries and cities have therefor set targets for reducing fatalities in road accidents. For instance, Sweden has the *Vision Zero* goal which aims to eliminate fatalities in road accidents completely by 2020 while the UK has similar ambitions. 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. Furthermore, the road fatality statistics (Figure 3) show a vast spread in the performance of different countries in terms of safety and worryingly, have begun to stagnate over the last three years.

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.

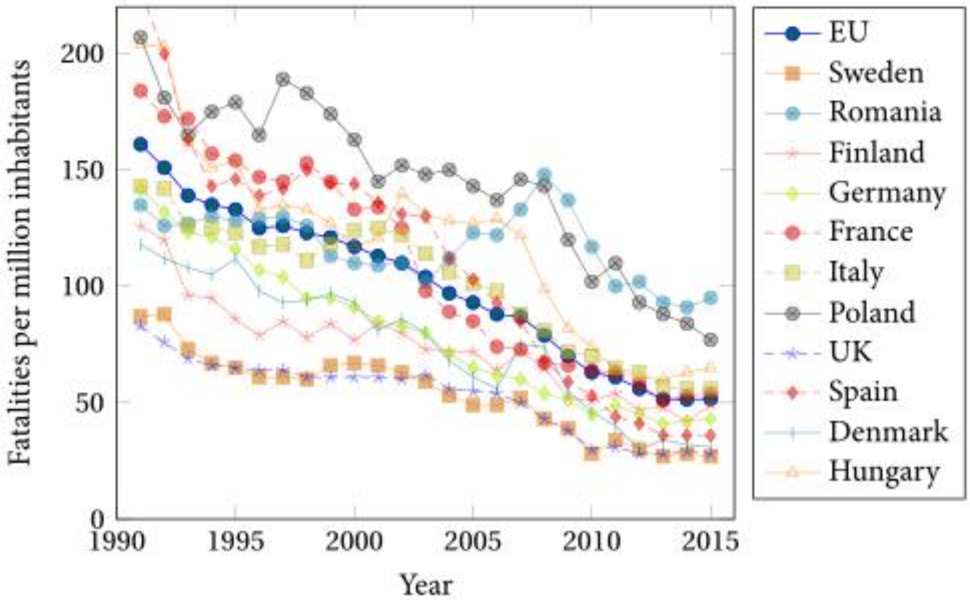

Figure 3 Fatalities per million inhabitants in road accidents.

4. Purpose, research questions and method

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 in the near future.

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.

Given that the electric drives are completely different actuators based on an entirely different technology, they can also be expected (and are known to) have different and superior characteristics and behaviour. These superior characteristics can potentially be exploited to enhance or implement novel functions that cannot be achieved with traditional internal combustion engine drivetrains. 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 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?

5. Objective

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.

The project also addresses scenarios where the driver is out of control and where autonomous functions are needed.

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 driveability 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. Results and deliverables

The main results and deliverables of this work and their contribution to the project goals are as follows:

1. A non-exhaustive list of traffic scenarios where electric drives can potentially be expected to provide a safety benefit have been identified and listed. Also provided along with each scenario is a list of the types of control interventions that can be expected to be of use.
2. In the rear-end collision scenario, a decision making algorithm for autonomous lead vehicle acceleration for collision mitigation has been formulated and presented. The potential safety benefit that can be expected in terms of velocity reductions from such interventions has been evaluated and quantified.
3. The manoeuvre dynamics in the obstacle avoidance with oncoming traffic scenario has been analysed in detail and characteristic parameters that correlate strongly to the safety benefit potential that can be achieved with electrified drivetrains have been identified. These findings are also verified using open-loop driver-controlled real vehicle experiments.
4. The potential safety benefit that can be expected with different actuator setups in the presence of restricted steering in the obstacle avoidance with oncoming traffic scenario has been evaluated and quantified.
5. An integrated motion controller (controlling longitudinal and lateral or yaw dynamics) for mitigating the risk of collision with oncoming vehicles during evasive manoeuvres has been formulated and validated in simulations.
6. The potential safety benefit that can be expected from two different variants of the integrated controller in evasive manoeuvres with oncoming traffic in the presence of restricted steering has been evaluated and quantified in simulation.
7. A real-time closed-loop longitudinal acceleration controller for collision mitigation with oncoming vehicles during evasive manoeuvres has been implemented, tested and validated in experiments.
8. Collision avoidance at the “Left Turn Across Path - Opposite Direction” intersection accident scenario has been analysed and optimal acceleration manoeuvres for collision avoidance at the same have been derived through an analytical optimal control framework. An integrated controller that uses the optimal control result has been implemented in simulation and validated.

All the above results contribute towards the project’s safety goals and towards a vehicle industry in Sweden that continues to be competitive. Since all the results are pertain to improving safety in various real-world accident scenarios, their contribution towards the safety goal is immediately apparent. And since vehicle electrification is a major area of interest for all automotive manufacturers across the world (both due to customer demand and regulatory needs) and all the results concern using electric to achieve novel or improved functions, they contribute to making the automotive industry in Sweden competitive as well.

Results 3, 5 and 8 in particular also “strive to secure national supplies of competence and to establish R&D with competitive strength on an international level” since novel or state-of-the-art techniques are applied here to problems that have hitherto not been addressed before.

Lastly, results 5-8 are the outcome of close cooperation between team members from AAM, ÅF, Volvo Cars and Chalmers and thereby “supports environments for innovation and collaboration”. In particular, result 7 was achieved by performing experiments with an experimental vehicle that was jointly prepared by the team members and used to perform experiments.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Licentiate and doctoral thesis, 3 journal papers and 6 conference papers. Networking among partners and other players.
Be passed on to other advanced technological development projects	X	Modular Electric Drive Systems (MEDS) project. New project at Volvo Cars that uses electric drives
Be passed on to product development projects	X	Result of MEDS project will be a new e-Drive unit for which some of the load cases used for design are the scenarios generated in this work.
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

[1] Arikere, Adithya, Matthijs Klomp, Mathias Lidberg, and Gunnar Olsson. "The Potential Safety Benefit of Propulsion in Obstacle Avoidance Manoeuvres with Oncoming Traffic." In *Proceedings of the 12th International Symposium on Advanced Vehicle Control*, 126–31. Tokyo, Japan, 2014.
[2] Arikere, Adithya, Mathias Lidberg, and Gunnar Olsson. "The Trade-off between Distance Margin and Steering Effort in Obstacle Avoidance Manoeuvres with Oncoming Traffic." In *Proceedings of the 24th International Symposium on Dynamics of Vehicles on Roads and Tracks*. Graz, Austria, 2015.
[3] Arikere, Adithya, Christian-Nils Boda, Jona Marin Olafsdottir, Marco Dozza, Mats Y. Svensson, and Mathias Lidberg. "On the Potential of Accelerating an Electrified Lead Vehicle to Mitigate Rear-End Collisions." In *Proceedings of the 3rd International Symposium on Future Active Safety Technology Towards Zero Traffic Accidents, 2015*, 377–384. Göteborg, Sweden, 2015. https://research.chalmers.se/publication/217156.
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[5] Arikere, Adithya, and Anders Tysk. "Added Value for Electrified Vehicles through Enhanced Active Safety." *World Electric Vehicle Journal* 8, no. 3 (2016): 621–32.
[6] Arikere, Adithya, Derong Yang, Matthijs Klomp, and Mathias Lidberg. "Integrated Evasive Manoeuvre Assist for Collision Mitigation with Oncoming

Vehicles.” *Vehicle System Dynamics*, January 12, 2018, 1–27. https://doi.org/10.1080/00423114.2017.1423091.
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[8] Arikere, Adithya, Derong Yang, and Matthijs Klomp. “Optimal Motion Control for Collision Avoidance at Left Turn Across Path/Opposite Direction Intersection Scenarios Using Electric Propulsion.” *Vehicle System Dynamics*, May 29, 2018, 1–28. https://doi.org/10.1080/00423114.2018.1478107.
[9] Arikere, Adithya, Derong Yang, Matthijs Klomp, and Bengt J H Jacobson. “Evaluating the Robustness of Integrated Control for Collision Mitigation with Oncoming Vehicles with Respect to Steering Effort.” *International Journal of Driving Science* Submitted (December 5, 2017).
[10] Arikere, Adithya. “Vehicle Dynamic Opportunities in Electrified Vehicles for Active Safety Interventions.” Licentiate thesis, Chalmers University of Technology, 2015. http://publications.lib.chalmers.se/publication/217153-vehicle-dynamic-opportunities-in-electrified-vehicles-for-active-safety-interventions.
[11] Arikere, Adithya. “Vehicle Dynamics Control for Active Safety Functions Using Electrified Drivelines.” Chalmers University of Technology, 2018. https://research.chalmers.se/publication/501005.

8. Conclusions and future research

Adding customer value to electrified vehicles through enhanced or novel active safety functions that cannot be achieved with traditional IC engines could be a major way not only to make electrified vehicles more attractive to consumers, but also to governments and regulatory agencies trying to reduce traffic accidents. However, there are many open questions around the possibility, feasibility and the extent to which such functionalities can be achieved. This work aims to answer some of these questions. Three accident scenarios, namely the rear-end collision, the obstacle avoidance with oncoming traffic and the intersection accident scenario have been investigated in detail and the safety potential that can be expected with electrified drivetrains (in vehicle dynamic terms) in each of these scenarios have been quantified.

In [3], the rear-end collision, one of the most common types of accidents, is analysed in detail. An analysis of the accident statistics shows that rear-end collisions predominantly involve stationary or low lead vehicle speeds, low impact speeds and small speed differences which make electric drives well suited for interventions here, since they deliver their peak torque at low speeds. A decision making scheme to determine when to accelerate was then formulated based on similar principles as those used for Automatic Emergency Braking (AEB). Simulations with simplified models using this decision making scheme showed that acceleration alone could reduce the impact speeds by up to 15 km/h and when combined with braking on the following vehicle, impact speed reductions of up to 75 km/h could be achieved. Another intervention was also designed which involved displacing the lead vehicle forward and coming back to rest at the end of intervention. Evaluation of this intervention showed that speed reduction improvements of up to 20 km/h could be achieved.

In [8], an analysis of the intersection accident scenario, specifically, the "Left Turn Across Path - Opposite Direction" scenario, is presented. The possibility of assisting the driver in collision avoidance by crossing the intersection ahead of the oncoming vehicle is analysed. Optimal manoeuvres for collision avoidance by crossing the intersection are determined through an analytical particle model optimal control framework. An integrated motion controller is implemented and tested in a high fidelity simulation environment. Simulation results show that the driver can be assisted effectively to avoid the collision with as much as 1.5 m more distance margin when compared to the passive vehicle even in an on-limit case, i.e., the distance margin improvement is achieved mainly through optimisation of the direction of the individual tyre forces and not by increasing the magnitude of the forces themselves. Even more improvement in distance margin can be expected in non-limit scenarios where the tyre force magnitudes can be increased by the controller.

[1, 2, 4] and in particular [6, 9] deal with the obstacle avoidance with oncoming traffic scenario in detail. [6] starts with an analytical study of the accident scenario to identify the important parameters that characterise the manoeuvre. Based on the findings, an integrated controller to assist the driver in collision mitigation with oncoming vehicles while performing evasive manoeuvres is formulated and presented. The integrated controller is then evaluated in a few selected variants of the obstacle avoidance with oncoming traffic scenario and it was seen that distance margin improvements of up to 4 m could be achieved.

In [9], two variants of the integrated controller are considered for evaluation: one where the speed controller is integrated with a traditional ESC and another where it is integrated with a lateral controller designed to assist the driver in performing the evasive manoeuvre. Simulations in a high-fidelity environment showed that both controllers increase the robustness with respect to steering effort over a traditional ESC-only control strategy. Specifically, the variant with the lateral controller performed noticeably better not only in increasing the distance margin but also in the distance it takes to perform the avoidance manoeuvres.

Finally, in [7], a real-time implementation of the integrated controller has been done and tested in experiments with a Volvo XC90 test vehicle. The results show that the integrated controller consistently increased the distance margin compared to a reference case where the driver lifted off the accelerator pedal at the beginning of the manoeuvre (throttle off). The results also indicate that the task of speed control is difficult to perform in such an emergency manoeuvre despite the lack of a "surprise" factor which a real driver would likely face.

In general, the results from the different analyses 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 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 vehicle response and stability in critical scenarios, it can also be used for steering redundancy.

In summary, several vehicle dynamic opportunities for improving safety using electrified drivetrains were identified. Detailed investigations of select cases showed that significant safety benefit potentially 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.

Before the results can be used in production vehicles however, several vehicle dynamic and non vehicle-dynamic aspects need to be investigated and questions answered.

From a vehicle dynamics point of view, several opportunities exist for future work. In the obstacle avoidance with oncoming traffic scenario, the robustness of interventions in the presence of moving obstacles or accelerating or braking bullet vehicles needs to be analysed. Additionally, the integrated controller can be extended to consider such factors as moving obstacles or accelerating bullet vehicles. The benefit that can be expected with different actuator limitations (motor power, torque, front-wheel drive vs. all wheel drive, etc) under different scenario conditions (low friction, high vehicle speed, etc.) needs to be quantified which in turn can be used to derive actuator requirements.

A robustness and sensitivity analysis of the controllers needs to be performed with respect to the accuracy of the data that they use. For instance, the robustness of the controller for the intersection accident to inaccurate tyre data needs to be investigated and quantified. The on-line estimation of different vehicle states and parameters that are used by the controllers is another opportunity for future work.

While a real-time implementation of the integrated controller for collision mitigation with oncoming vehicles while performing evasive manoeuvres has been tested in [7], a more comprehensive validation still needs to be performed where the both the propulsion actuators and the brakes can be controlled simultaneously. Experimental validation of the collision avoidance controller for intersection accidents still needs to be performed.

From a non-vehicle dynamics perspective, numerous aspects needs to be investigated in the future such as the human factors aspect (how would the drivers of the host and bullet vehicles react to acceleration of the host vehicle?), safety systems interaction (would the interaction between automatic emergency braking on the bullet vehicle and the safety system on the host vehicle have a detrimental impact?), decision making (should emergency acceleration, braking or steering be performed at some point during the scenario?), driver interpretation (is the driver intending to brake to halt or steer away from the threat?), etc. Since these aspects involve little vehicle dynamics, they are best performed in collaboration with or entirely by active safety researchers.

9. Participating parties and contact persons

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