Torque Sensing for Vehicle State Estimation

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Project within FFI - Electronics, Software and Communication

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Short about FFI

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. SEK 1 billion per year, of which half is governmental funding.

Currently there are five collaboration programs: Energy and Environment, Traffic Safety and Automated Vehicles, Electronics, Software and Communication, Sustainable Production, Efficient and Connected Transport systems. For more information: www.vinnova.se/ffi

1 Executive summary

Electric vehicles have the potential to significantly reduce energy consumption and emissions for personal and commercial road transport and number of electric vehicles is likely to increase in the future due to stricter emission legislations. In order to accelerate market penetration, the competiveness of electric vehicles should increase in comparison to conventional vehicles. Active safety is an area where electric vehicle have a possible advantage over conventional vehicle and that could reduce the number of fatalities and injuries in road traffic accidents.

However, the performance of active safety systems today is limited by the knowledge of vehicle state estimates and vehicle parameters, e.g. vehicle speed and the tyre-road friction coefficient. This thesis investigates the potential benefits of using the electric motor as a sensing element to improve state and parameter estimations and thereby also active safety systems. In particular, accurate torque estimation provided by electric propulsion is utilized as an additional source of information. The possibility of using active tyre force excitation for the estimation of the tyre-road friction coefficient is also investigated.

The results show that there is a potential to improve the longitudinal and, in some situations, the lateral tyre force estimation using electric motors. However, the estimates are sensitive to errors in the inertial parameters. A method for estimating the vehicle inertial parameters was therefore proposed. The estimate of the vehicle mass converged to within 3% of the measured value for the evaluated test cases. However, the estimation of the longitudinal centre of gravity position and the yaw inertia of the vehicle is sensitive to measurement errors and disturbances. This is mainly due to the weak link between lateral and longitudinal dynamics in normal driving conditions. An alternative method using the seat belt indicators was therefore proposed. This method improves the estimates of these parameters on average when compared to assuming default values.

A method to estimate the tyre-road friction coefficient with active tyre force excitation was also proposed. This method enables the estimation of the tyre-road friction coefficient when demanded from an active safety system. Electric motors offer several advantages for active tyre force excitation. The fast response and the ability to apply both positive and negative torque can improve the slip control of the wheels, which is crucial for vehicle stability during the intervention.

In summary, the improved wheel torque estimation has the potential to improve the tyre force estimation in both the longitudinal direction directly and in the lateral direction through improved inertial parameter estimation. Furthermore, the electric motor as an actuator provides further opportunities during active tyre force excitation.

Keywords: state estimation, vehicle dynamics, tyre-road friction estimation, electric vehicles, active safety, parameter estimation

2 Background

Vehicles with electric propulsion have several advantages over vehicles with internal combustion engines. The main advantage of electric vehicles is their potential to reduce energy consumption and emissions, both locally and globally, for personal and commercial transports. Environmental issues and their link to transportation systems motivate a shift towards the electrification of vehicles. It is assumed that the number of electric vehicles will increase in the future due to the negative impact that combustion vehicles have on the environment.

In order to decrease the environmental impact of transportation systems, the transition to carbon-dioxide neutral energy sources should be accelerated. This can be partly be achieved by increasing the competiveness and consequently the sales of electric vehicles through the further investigation of their benefits over combustion engines. The transition from conventional vehicles to electric vehicles can thus be accelerated.

One of the main areas where electric motors offer new possibilities is in active safety systems. Improvements in active safety increase the customer value and consequently the competiveness of the vehicles. Investigating these new opportunities further could also benefit individuals and society as a whole due to the potential for reducing the number of traffic related injuries.

The focus of this project was to investigate how active safety systems can be improved for vehicles with electric propulsion. In particular the advantages with electric motors as a sensing element to estimate vital vehicle states and parameters are explored. With better active safety systems the competiveness of electric vehicles can be improved and the market penetration for electric vehicles can thus be accelerated.

2.1.1 Environmental aspect

The environmental issues that motivate a shift towards electric vehicles can be split into two different problems, local emissions and global emissions. Local emissions consist of several pollutants including carbon monoxide, soot, hydrocarbon and particulates [1]. In [2] a review of the research regarding the effect of particulate matter (PM) on human health is presented. Previous research has strengthened the evidence that the health effects from particulate matter emissions are biologically plausible. However, the exact mechanisms behind the health effects have to be further investigated. In [3], the economic cost of air pollution in the World Health Organizations (WHO) European region in 2010 was estimated to be US$1.575 trillion. This can be compared to the Swedish GDP of 2010 which was US$ 0.49 trillion [4]. Road transports are estimated to account for around 40% of the total economic costs for air pollution and 50% of the economic cost for ambient air pollutions [3]. This illustrates that local emissions from the transportation industry are not only a problem in developing countries but also a real problem in the European region.

The health issues related to local emission have led to stricter emission legislation for both commercial and passenger vehicles. Furthermore, new legislations aimed at improving the fuel efficiency of new vehicles, limit the fleet average CO_2 emission of passenger cars [5]. The stricter emission legislations forces car manufactures to investigate new solutions for decreasing the fuel consumption and local emissions of their vehicles. Electrification is one of the most promising solutions to this problem as its potential to reduce greenhouse gas emission has been shown in numerous previous studies, especially in combination with future renewable energy sources [6-8].

Despite the fact that electric vehicles are considered by most to be a more environmentally friendly option than conventional vehicles with internal combustion engines, the market penetration is progressing slowly. In 2013, electric vehicles had a new vehicle sales market share for passenger cars of only 1.8% in the European Union [9]. The reasons for not choosing an electric vehicle vary, as shown in a European interview study where the participants were asked to list the most important improvement feature for electric vehicles. The improvements that scored the highest were, range (32%), purchase price (32%), possibility to recharge at home without private garage (25%), and recharge time (9%) [10]. However, with the increasing interest for electric vehicles in the past years the battery price has fallen by around 14% annually from 2007 to 2014 and further reductions are predicted for the future [11]. Increasing the competiveness of electric vehicles would reasonably lead to a larger market penetration and motivating further technological development.

2.1.2 Road traffic safety aspect

Road traffic injuries are the leading cause of death globally for people between 15-29 years old. Furthermore, 59% of global road traffic deaths are accounted for by young adults between 15-44 years. On a global level approximately 1.24 million people die every year on the roads [12]. As a response to the traffic accidents some countries and cities have adopted the Vision Zero Initiative which states that no loss of life due to traffic accidents are acceptable [13]. Reaching this ambitious target requires further research and improvements in infrastructure and in the active and passive safety of the vehicles. Even though the number of fatalities and seriously injured people in traffic accidents in Sweden is decreasing, the total number of injured people has been fairly constant since 1960, see Figures 2.1 and 2.2 [14]. Passive safety is effective in mitigating the severity of the injuries sustained in a crash. However, active safety has the potential to also reduce the overall number of accidents and therefore also the number of injured people. Further improvements in active safety are thus vital to reach the Vision Zero goals. The statistics presented in this section emphasize the amount of work that remains within road traffic safety and consequently the opportunity to increase the competiveness of electric vehicles through improved active safety functions.

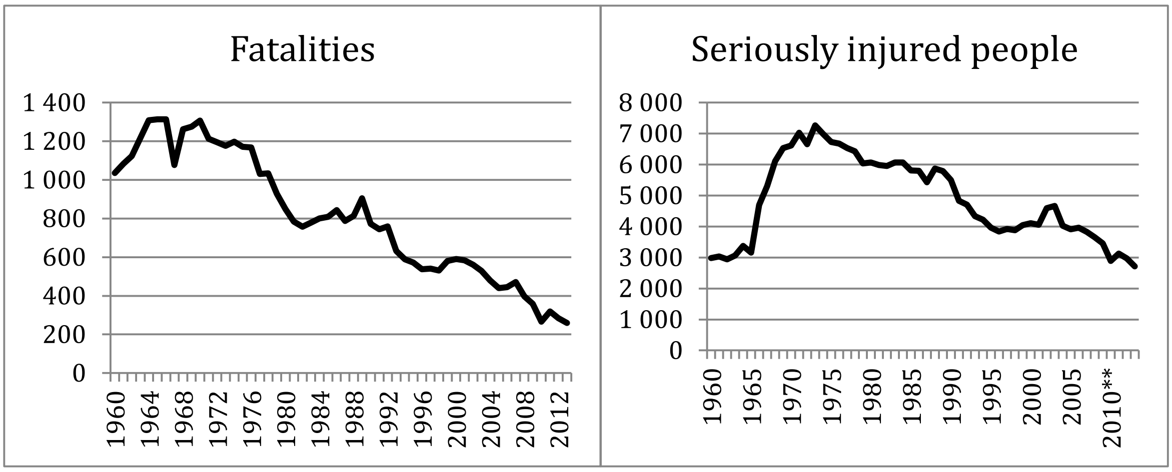

Figure 2.1, Number of fatalities and seriously injured people in Sweden annually due to road traffic accidents from police reports 1960-2013, data taken from [14]

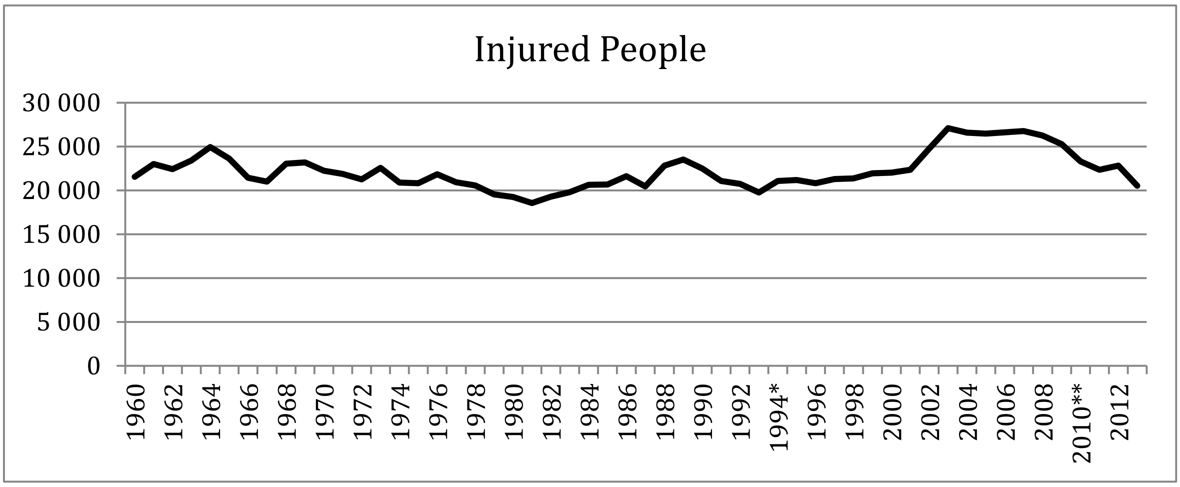

Figure 2.2, Number of injured people in Sweden annually due to road traffic accidents from police reports 1960-2013, data taken from [14]

2.2 Benefits of electric propulsion on a vehicle level

The major benefits of electric motors from a societal perspective are the prospect of reducing emissions in the transportation sector and the possibility of improving vehicle safety. On the vehicle level there are a number of benefits within electric propulsion. Connected to the environmental aspect are the fuel efficiency and local emissions. As a wheel torque actuator, the electric motor offers several benefits that can be utilized to improve active safety functions.

Electric vehicles are more efficient than conventional vehicles with internal combustion engines. According to [15] around 75-80% electric driveline efficiency can be achieved (including inverter, motor and reduction gear) for rural and highway driving cycles with regenerative braking. This does not include losses in battery and battery charger. With a battery efficiency and battery charger efficiency of 90% each [16], the total efficiency from plug-to-wheels is around 60-65%. In comparison, US light-duty vehicle powertrains had an estimated efficiency of 14-20% for a city driving cycle and 21-30% for a highway driving cycle [17].

Fully electric vehicles do not produce any local emissions from the propulsion system. Even plug-in hybrids reduce local emissions since the internal combustion engine is used less compared to a conventional vehicle. However, it should be mentioned that local emissions

may be emitted close to the power plants depending on how the electricity is produced. The electricity production should therefore move towards renewable or carbon-dioxide neutral methods in order to reduce the overall emissions caused by electric vehicles. The noise emissions from electric motors are also lower compared to conventional vehicles with combustion engines, especially at low velocities where the engine is the main source of noise.
The response time of an electric motor is several milliseconds or 10-100 times faster than internal combustion engines and hydraulic brakes. The torque from electric motors is also more straightforward to estimate accurately compared the torque from internal combustion engines [18]. Due to the fast response and the accurate torque estimation, electric motors have good controllability properties which can be utilized to improve active safety systems. Electric motors can generate both positive and negative torque. This enables efficient torque vectoring systems that can apply opposite torque on the two sides of the vehicle. Torque vectoring can be used not only for vehicle stability systems but also to improve vehicle performance. The possibility to apply a negative wheel torque enables the use of regenerative braking which increases the energy efficiency of the vehicle. Furthermore, electric motors can generate torque at zero motor speed. This means that electric vehicles do not need starting devices (clutches) and do not require multiple gear ratios to operate in a wide velocity range (gearboxes), thus reducing the system complexity. Electric motors have a high specific power that, in combination with the absence of gearboxes and clutches, allows for wheel or axle individual propulsion without any mechanical connections between the different motors.

2.2.1 The electric motor as an actuator to improve active safety

One way to improve the active safety functions utilizing electric motors is to study the benefits of the electric motor as an actuator. The main benefits from this perspective are the improved response, controllability, and the possibility to add both positive and negative wheel torque. Electric motors allows for faster, more accurate interventions without large actuator delays. These benefits have been previously investigated in [19].

2.2.2 The electric motor as a sensing element to improve active safety

In an estimation context, the accurate torque estimation from electric motors provides one of the largest benefits. Accurate information about the current propulsion torque on the wheels provides information about the current longitudinal tyre forces. This fact has been used in [20] to detect excessive wheel slip and improve longitudinal velocity and road slope estimation. With accurate wheel torque estimation, vehicle and tyre parameters that are, or could be, used in active safety systems can be estimated with higher accuracy online and the performance of active safety systems can therefore be improved. The estimate of the applied wheel torque and the benefits of the electric motor as an actuator also enable vehicle force neutral active tyre excitation that can be used to identify the tyre characteristics.

3 Objectives

The competiveness of electric vehicles should be increased in order to accelerate their market penetration and the shift towards a carbon-dioxide neutral transportation system. An area where electric vehicles have possible advantages over vehicles with combustion engines is active safety. The active safety and vehicle dynamics control functions of today are limited by the quality of the vehicle state and parameter estimates. States are defined here as time varying quantities that are affected by the time history of the system. Parameters are defined here as the quantities needed to describe how different states of interest affect each other. Parameters can be viewed as constants or slowly varying in time. However, depending on the application and the point of view, certain quantities can sometimes be regarded as states and sometimes as parameters. This project investigated

the possibilities of utilizing the electric motor as a sensing element to improve current and future active safety and vehicle dynamics control functions. The prospect of estimating vehicle states and parameters that are vital to these control functions with information from the electric motor was also explored. More specifically, the possible benefits of using the accurate wheel torque estimation from the electric motor were examined.
The main focus of the project explored which vehicle states and parameter estimates that could be improved by utilizing the electric propulsion as a sensing element and how the corresponding estimators should be designed to use the information from the electric motors. The vehicle functions that can be enhanced with improved vehicle state and parameter estimation and the requirements these functions put on the estimate in terms of accuracy are also discussed in the report. Furthermore, the project investigated the possibility of using active tyre force excitation to identify the tyre characteristics online during normal driving.

3.1 Research Limitations

The project only considers on-road driving where the vehicle instrumentation is limited and the manoeuvres cannot be selected freely in time and space. The scope is thus limited to using electric propulsion as an addition to standard vehicle sensors and actuators that can be expected in a premium production vehicle of the year 2020. See Table 3.1 for signal sources that were used in the estimators in this project. It is reasonable to assume that vehicle state information through image processing will be available in the year 2020. However, this additional information is not considered in the present work since it is considered as a parallel research and development track. Although not used in the estimators presented in this project report, Electric Power Assisted Steering (EPAS) has sensors that enable the estimation of the aligning torque of the tyres. This information can be used for friction estimation [21]. EPAS is common in production vehicles today but has not been utilized in the research so far.
It is assumed that the estimate of the electric motor torque is available to the estimator. Hence, no investigation of how the torque estimation from the electric motors can be improved has been done. The proposed methods should not depend on vehicle or tyre parameters that are not feasible to know for a production vehicle. The project does not consider the implementation of cooperative systems such as car-to-car or car-to-infrastructure communication. However, some of the results can be used to contribute to the information in such cooperative systems.

Table 3-1, Signal sources used for estimation

Sensor/Signal Source	Signals	Notation
Inertial Measurement Unit	Longitudinal Acceleration	a_x
	Lateral Acceleration	a_y
	Vertical Acceleration	a_z
	Roll rate	ω_x
	Pitch rate	ω_y
	Yaw Rate	ω_z
Wheel speed sensors	Wheel speed on each wheel	ω_{wi}
Steering wheel angle sensor	Steering wheel angle	δ_{SWA}
GPS (1Hz)	Position	X, Y
	Velocity	V
	Heading Angle	ϕ_z
Electric Motor	Estimated Torque	T_{EM}
	Motor Speed	ω_{EM}
Internal Combustion Engine & Powertrain	Estimated Propulsion Torque	T_{ICE}
	Engine Speed	ω_{ICE}

4 Goals

The goals of the project are captured by the research questions below.

1. What vehicle functionality can be achieved and/or improved by improved vehicle states such as tire to road friction and vehicle speed? What kind of requirement does that imply in terms of accuracy and precision on the estimate? A case study example will be torque vectoring for regenerative braking.

2. How should the vehicle state estimator be designed? During which operations (propulsion, braking and/or steering) should data collection be done? Which information should be used (information from electric motors, friction brake system, steering system, body inertial sensing, …)? How advanced models of wheel suspension need to be used as base for estimator? Which estimation signal processing techniques (existing or new developed) are most suitable? What does this imply in terms of requirements on the sensors and communication?

3. How can the quality of the estimated variables be formulated in a generic manner, useful for different functions and applicable for vehicles with different sensor configurations? Which information exchange should there be between different estimator parts and functions?

4. How should a potential force extraction be performed such that;
    a. the possibility to estimate at all, alternatively more accurate
    b. without negative influence of the ride and handling experience
    c. without jeopardizing the handling safety of the vehicle
    d. tire wear, wear of the vehicle etc. is minimized

Generally the project was first based on the idea to go from the requirements on the vehicle functionality to requirements on the estimator and all the way down to sensor requirements. During the project the focus shifted towards finding out what accuracy that was possible to achieve for different estimates. The reason for this shift was the broad range of applications that could benefit from improved state estimation. Hence, limiting the investigation to a single active safety systems could potentially make the scope of the project too narrow. Hence, goal 1-3 was shifted somewhat towards an inverse order. The main question in the project was how the state estimates could be improved using electric propulsion and how the state estimator should be designed. Point 1 was down prioritized regarding research, input from the different project partners involved in the project and findings from a literature survey was summarized in publication E. The focus of Point 3 was redirected towards defining the required excitation to achieve a high quality estimate. In particular, a large focus was put on research question 4 which was treated in publication C,D,F,G. This method showed a great potential to allow for friction estimation during normal driving, something which is not possible today without active tyre force excitation.

5 Results and deliverables

5.1 Summary of publications from the project.

5.1.1 Publication A, Tire Force Estimation Utilizing Wheel Torque Measurements and Validation in Simulations and Experiments

Paper A investigated how the tyre force estimation can be improved with accurate knowledge of the applied wheel torque from the propulsion system. This represents using an electric motor for propulsion with accurate torque estimation. The main benefits could be found in the estimation of the longitudinal tyre forces. However, knowledge about the wheel torque distribution between the left and the right wheels is required for an accurate estimation of the lateral axle forces when torque vectoring is used.

Furthermore, a number of issues with tyre force estimation using standard sensors were identified. The main issue highlighted was the need for an online estimation of the vehicle inertial parameters in order to have accurate tyre force estimation. It was also shown that individual lateral tyre force estimation is challenging without adding extra sensors. An approach which is commonly found in literature where the axle lateral force is distributed according to the vertical load was evaluated. This method did not perform as well as expected due to the many assumptions used to derive the method. The estimation of the axle lateral force was found to be robust against large errors in the vertical force estimation. The results also showed that information about the road bank angles is redundant for the estimator since the accelerometer measurements capture the effect of the road banking.

5.1.2 Publication B, Inertial parameters estimation for vehicles with electric propulsion

The main benefit of electric motors for inertial parameter estimation is the accurate torque estimation. One result from this paper shows that it is possible to accurately estimate the mass using the torque estimation from the electric motor. This is done without making any assumption regarding the rolling resistance coefficient or the aerodynamic drag coefficient but requires a certain excitation.

A method to estimate the longitudinal centre of gravity position and the yaw inertia was proposed. The method is based on the planar equations of motions and the electric motor torque estimation. The results showed that this method was not accurate or robust enough to be used in a production vehicle. This is mainly due to uncertain wheel steering angles and the weak interaction between the front lateral tyre forces and the longitudinal acceleration.

A more straightforward approach was also proposed for the estimation of the longitudinal centre of gravity position and the yaw inertia. This method is based on the mass estimate and the seatbelt indicators. The method was shown to perform, on average, better than using default parameter values for an unladen vehicle, provided that the mean values of the passenger and driver weights are known.

This paper illustrates some of the difficulties with estimating the longitudinal centre of gravity position and the yaw inertia using a standard sensor set. In order to have a more accurate estimation of these parameters, extra sensors should be added to the vehicle.

5.1.3 Publication C, Identification of tyre characteristics using active force excitation

Paper C investigates the possibility of using active torque excitation to estimate the tyre-road friction coefficient and the slip stiffness. An intervention, where the propulsion torque on the front axle is increased linearly and the rear brake pressure is controlled to keep a constant velocity, was performed in a test vehicle. An estimation method was then proposed that removes the need to directly measure the longitudinal velocity of the vehicle. This method was compared to a reference model with measured longitudinal velocity.

The main results show that it is possible to estimate the tyre-road friction coefficient during this intervention if the tyre excitation is large enough. The proposed method to estimate the friction coefficient without measuring the longitudinal velocity was found to be more sensitive to measurement noise and disturbances on the wheel speed signal when compared to the reference model. As a result, this method tends to underestimate the friction when the tyre excitation is too low. The tendency to underestimate the friction coefficient was shown to be dependent on the noise level on the wheel speed signals. The estimator performance and the possibility to separate between low and high friction surfaces can therefore be improved by reducing the noise and disturbances on the wheel speed signals. The wheel speed signals were taken directly from the CAN-bus during the experiments.

These experiments were performed without any electric propulsion. However, adding electric propulsion to the rear axle would have several advantages. Firstly, the accurate torque estimation improves the longitudinal tyre force estimation since the disturbances from the accelerometer is avoided. Furthermore, the controllability of the rear axle torque gives new possibilities for a more advanced torque profile during the excitation and allows for better slip control. Furthermore, if electric propulsion is used instead of the friction brake to apply a negative torque to the rear axle, the energy consumption during the intervention can be reduced by regenerating some of the energy.

5.1.4 Publication D, Tyre to road friction estimation arrangement by exiting wheel torques

Patent regarding the method described in Publication C, Identification of tyre characteristics using active force excitation. The main difference from the method proposed in Publication C is that the vehicle speed is not kept constant. Instead the drivers intended acceleration is followed.

5.1.5 Publication F, Friction Utilization for Tyre-Road Friction Estimation on Snow: An Experimental Study

Friction estimation using effect-based approaches are challenging during normal driving due to the large tyre excitation needed for an accurate estimate. The required excitation level varies for different tyres, road surfaces, road conditions and tyre models used in the estimator. Previous research has shown the required friction utilization on different surfaces. However, due to the small sample sizes it is hard to draw any general conclusions. This paper investigates the tyre excitation required to estimate the tyre-road friction coefficient with a generic estimator for 76 different tyres on snow for five different tyre models and for different levels of measurement noise. The results indicate that the brush model with parabolic pressure distribution, although commonly used, are not the best option for friction estimation on snow.

5.1.6 Publication G, Design of Tyre Force Excitation for Tyre-Road Friction Estimation

This publication investigates how the excitation should be designed to minimize the friction estimation errors for three different tyre models on wet asphalt and gravel. The results show that a simple force ramp is a good option to use for the magic formula tyre model while a fast ramp is more efficient for the Dugoff tyre model and the Brush model. Furthermore, the magic formula has a lower estimation error in general compared to the other two models. The results shows that the excitation should be chosen both with regards to the complexity of the tyre model but also depending on the noise level.

5.2 Connection to FFI goals

The overall goals of the FFI program are:

1. Reduce the environmental impact of road transportation
2. Reduce the number of traffic related injuries and fatalities
3. Increase the international competiveness

The project has contributed to the first goal by showing a number of advantages with electric vehicles compared to conventional vehicles with internal combustion engines. Hence, the competiveness of electric vehicles is demonstrate within the project.

The investigation of the estimator design and performance is related to the second overall goal for the FFI program and relates to active safety. The findings within this project can be used to improve state estimates and thus improve the performance of active safety systems. Furthermore, the knowledge of the current friction coefficient is important for autonomous vehicles that has to adapt the vehicle velocity depending on the prevailing environmental conditions.
The third goal has been achieved by increasing the knowledge about active tyre force excitation for friction estimation, mass estimation and tyre force estimation. Furthermore, a patent application has been submitted which can secure that the intellectual property rights for this technology stays within the Swedish automotive industry.

The connection to the targets of the FFI subprogram "Fordonsutveckling" is presented below:
 Target: ***"undertake development initiatives of relevance to industry"*** The project contributes by showing how electric propulsion systems can add value as sensing elements to safety on top of energy efficiency.

 Target: ***"lead to industrial technology and competence development"*** 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 of results

6.1 Utilization of results.

The project has resulted in a Licentiate degree at Chalmers, and a number of publications that have increased the knowledge within the area. Experimental trial during the project have resulted in an increased practical understanding of the associated problems and issues. The knowledge gained during the problem have been successfully transferred from Chalmers to the two industrial partners. Volvo cars have taken the project results as input an internal project to industrialize friction estimation based on active force excitation, with the aim of a customer function in the future.

6.2 Publications

Publication A
Albinsson, A., Bruzelius, F., Jacobson, B., & Jonasson, M. (2014). Tire Force Estimation Utilizing Wheel Torque Measurements and Validation in Simulations and Experiments. In *The 12th International Symposium on Advanced Vehicle Control,(AVEC'14), Tokyo, Japan*.

Publication B
Albinsson, A., Bruzelius, F., Pettersson, P., Jonasson, M. & Jacobson, B. (2015). Estimation of the inertial parameters of vehicles with electric propulsion, Accepted for publication in *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*

Publication C
Albinsson, A., Bruzelius, F., Gustafsson T., Jonasson, M. & Jacobson, B (2015). Identification of tyre characteristics using active force excitation. In *The 24th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD'15), Graz, Austria*.

Publication D
M. Jonasson, T. Gustafsson, A. Albinsson, and F. Bruzelius, "Tyre to road friction estimation arrangement by exiting wheel torques," Patent Application nr. EPO 15172369.9 Patent, 2015.

Publication E
Albinsson, A. (2015) *Online State Estimation in Electrified Vehicles Linked to Vehicle Dynamics*. Göteborg : Chalmers University of Technology (Technical report - Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden, nr: 2015:18).

Publication F
Albinsson, A., Bruzelius, F., Jacobson, B. (2016). Friction Utilization for Tyre-Road Friction Estimation on Snow: An Experimental Study, In *The 13th International Symposium on Advanced Vehicle Control,(AVEC'16), Munich, Germany*.

Publication G
Albinsson, A. Bruzelius F., Jacobson B. Fredriksson, J. (2016), Design of Tyre Force Excitation for Tyre-Road Friction Estimation, In preparation for journal publication.

7 Conclusions and future work

Some benefits of using the electric motor as an additional sensing element have been shown in this project report. These benefits are mainly based on the accurate torque estimation from the electric propulsion. Other signals from the electric motor have not been considered in the project, e.g. electric motor speed etc.

The main benefit of the accurate torque estimation from the electric motor is the improved knowledge about the current longitudinal tyre forces. This information can be utilized to improve parameter and state estimates. Estimates which are directly related to the applied longitudinal tyre forces will benefit from this information. However, as shown in [20] other estimates can also use this information for decision making or switching between different estimation strategies. This project report provides a few examples of how the estimated electric motor torque can be used for the online estimation of vehicle and tyre parameters and states.

Although some comparisons have been made between the torque estimation accuracy based on an electric motor and an internal combustion engine, it is difficult to make any general comparisons. Depending on the method used to estimate the torque from an internal combustion engine, the estimation accuracy can vary. However, the details of these torque estimation algorithms have not been studied in this project. In Paper C, it is shown that the torque estimation from internal combustion engines can be accurate enough for online estimators. The internal combustion engines are complicated systems with many moving parts, especially modern engines that are supercharged to a larger extent. In contrast, the electric motor has few moving parts and the torque is straightforward to estimate. It is therefore viable to regard the electric motor torque estimate as a signal that can be a source of information for other estimators.

The accuracy of the estimates presented in the project report is dependent on accurate wheel torque estimation. Thus, with improved wheel torque estimation these estimates can be improved as well. Since the potential to increase the performance of active safety systems are linked to the accuracy of the estimates, the accuracy of the wheel torque estimation determines how much the performance of these systems can be improved. If the wheel torque estimation from electric motors is generally more accurate than the torque estimate in vehicles with combustion engines, a potential to improve active safety systems for electric vehicles through better vehicle state and parameter estimation exists, and consequently is a possibility for improving the competiveness of electric vehicles. However, further studies are required to quantify the differences in torque estimation accuracy.

Furthermore, the required friction utilization and estimation error for different tyre models on snow has been investigated. It was shown that the magic formula and the Dugoff model requires relatively low utilization on snow. Different excitation strategies were also evaluated in order to find the strategy which minimizes the friction estimation error. It was shown that a simple force ramp is quite good in most cases, especially with measurement noise. For the Dugoff model on the other hand a faster force ramp which saturates at the maximum allowed tyre force was more efficient.

7.1 Assumptions

The flexibility of the powertrain is neglected in Paper B and C. The elastic deformation, in combination with the inertia of the individual powertrain components, filters the torque from the engine or motor to the wheels. In fast transient events the wheel torque might therefore differ from the steady-state wheel torque that would be achieved with the same motor/engine torque. In Paper C, the active tyre force excitation is performed slowly in order to minimize the influence of the tyre or powertrain dynamics. In Paper B, the estimation is based on the driver inputs. Hence, manoeuvres where the powertrain elasticity influences the estimation performance can occur since the conditions for activating the estimators do not consider the derivative of the applied wheel torque. For most practical cases though, the influence of the powertrain elasticity should be small, since drivers normally aim to have an acceptable comfort level while driving.

The sensor set that was available to the estimators was limited to a reasonable sensor set for a production vehicle in 2020. This means that the vehicle has limited sensor information that can be used in the estimator. With more sensors the amount of information that is available to the estimators is increased, which has the potential to improve the estimation accuracy. However, the main focus of the project was to investigate the potential benefits of using the electric motor torque as an input to the estimators. Regardless, there are a number of potential sensors that could be fitted to the vehicle to improve the performance of the estimators.

Wheel angle sensors can be used to enable individual lateral tyre force estimation on the front axle [39]. Accelerometers and suspension deflection sensors can be added to improve the estimation of the longitudinal centre of gravity position and the yaw inertia [50, 51]. These sensors are some of the more reasonable additional sensors that could be added to the vehicle. An external GPS can be added to the vehicle to improve the estimation of the longitudinal velocity and hence the slip ratio estimation, see Paper C.

Furthermore, the environmental sensors that are used for the autonomous emergency braking and the autonomous cruise control systems can be used for estimating the velocities of the vehicle. This would provide additional information which can be used for longitudinal and lateral velocity estimation. The vehicle state information from these sensors should therefore be included in the future development of other state or parameter estimators.

The parameters used in the proposed estimators were limited to parameters that can reasonably be known in production vehicles. By providing the estimators with additional information regarding other vehicle and tyre parameters, further improvements in estimation accuracy can be achieved. On the other hand, introducing new uncertain parameters can decrease the estimation accuracy if the model differs too much from the real measurements. As shown in Paper B, the parameters required for longitudinal tyre force estimation can be estimated online in the vehicle. However, the longitudinal centre of gravity position and the yaw inertia are still challenging to estimate online with a production vehicle sensor set. Additional sensors might therefore be required in order to enable the estimation of these parameters. The longitudinal centre of gravity position determines the vertical force distribution between the front and rear tyres and will thus directly affect the friction estimation accuracy for the proposed method in Paper C. The effect of an erroneous vertical force distribution and its impact on the accuracy of the friction estimate should therefore be further investigated. As discussed in Section 2.4 a target system is required to specify the minimum estimation accuracy. The current knowledge on the vertical force distribution might hence be sufficient for some systems but not for others.

An estimation or measurement of the longitudinal velocity is required for the active tyre excitation intervention in Paper C. Because of the actuator limitations, all tyres have large slip ratios during the intervention. No wheel can therefore be used as a reference to estimate the vehicle velocity. This is the motivation behind the advanced algorithm in Paper C where the vehicle velocity is estimated simultaneously with the tyre parameters. The assumptions made in order to estimate the longitudinal velocity make the estimator more sensitive to noise and disturbances on the wheel speed signals. Furthermore, the accuracy of the velocity estimation is dependent on the accuracy of the tyre parameter estimation. An external estimation or measurement of the longitudinal velocity that is independent of the tyre parameter estimation would thus be preferable. However, the peak in the tyre force as a function of the slip ratio can occur for as low slip ratios as five percent or lower, depending on the tyre and road surface, see Figure 3.5. An external estimation or measurement of the longitudinal velocity must therefore have a high accuracy and low variance. More importantly, the change in longitudinal velocity during the manoeuvre must be accurately measured. A small constant error during the manoeuvre can be handled better by the friction estimator than an error that varies during the manoeuvre. The longitudinal velocity is normally not measured directly in production vehicles due to the expensive sensors required.

7.2 Applications and Implications

One of the main applications from the results in this the project is the ability to estimate the friction coefficient during normal driving. This enables the possibility to estimate the friction freely in time and space. By sharing this information with other road users, a map of the current road surface conditions for different roads can be obtained. This information is valuable for other drivers, on-board active safety systems and the road authorities. Other drivers can use the information to adapt their driving when approaching a low friction area. The active safety systems can adapt the controllers or the decision making to the current road conditions. Road authorities can use the information to distribute their resources in order to keep the roads clear from snow and ice. Without communication between vehicles, the friction coefficient on the road ahead of the vehicle will be unknown for cause-based estimation approaches. For future autonomous vehicles, adaptation of the vehicle velocity before entering a corner is crucial to ensure vehicle stability. On low friction surfaces the maximum possible cornering speed can be greatly reduced in comparison to high friction surfaces. Reliable friction information is thus a crucial issue that needs to be resolved in order to have fully autonomous vehicles on the roads.

The inertial parameters estimation and the tyre force estimation enable the tyre parameter estimation. The inertial parameters are also useful for adapting the reference models in active safety and vehicle dynamics control functions. The tyre force estimator quantifies the tyre forces on the wheels which together with a friction estimator indicate the remaining force potential of each tyre. The estimators in the three papers are hence interconnected.

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