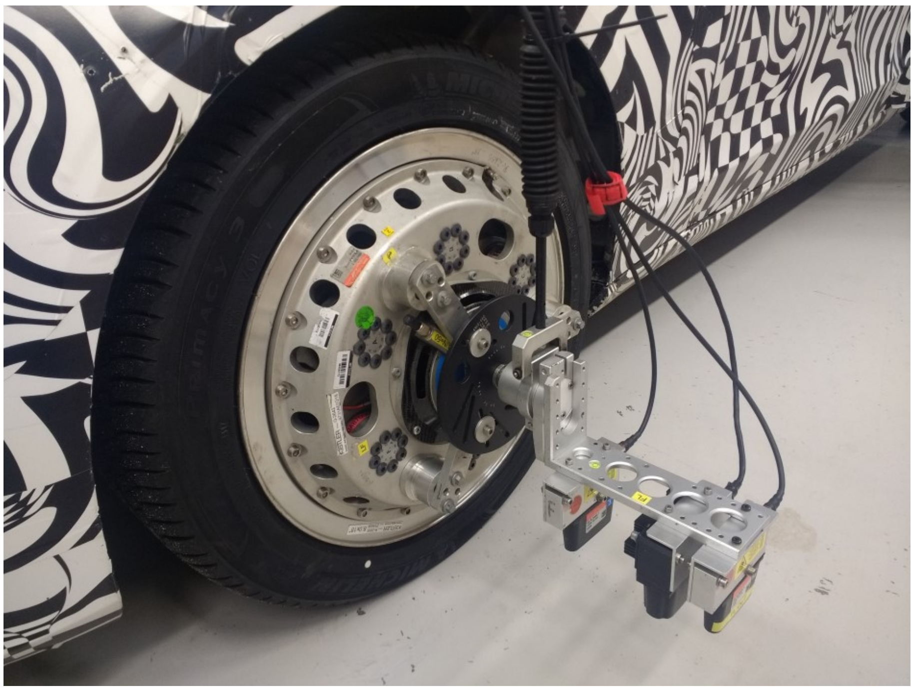
# TyreSens

## Tyre Sensing for Tyre Model Parametrization

**Public report**



Project within FFI Complex control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# Content

# 1. Summary

The accelerating development of active safety system and autonomous vehicles put higher requirements on virtual verification of these systems. The tyres are relevant in this context due to the considerable influence of the tyres on the vehicle motion and the performance boundaries set by the tyres. All forces that the driver use to control the vehicle are generated in the contact patch between the tyre and the road on a normal passenger car. Hence, the performance limits imposed by the tyres should ideally be considered in the active safety systems and in self-driving vehicles. Due to tyres influence on the vehicle motions, they are some of the key components that must be accurately modelled to correlate complete vehicle simulations models with physical testing.

Due to the complex nature of the interaction between the tyre rubber compound and tread pattern and the road surface are most used models driven by measurements. Tyre models used in this context, modelling the interaction, are often only not derived based on physical insight but also empirical experience. This makes the parameterization process of finding model parameters crucial to the accuracy of the resulting models.

The state-of-the-art practice in parameterizing tyre models is through data acquired through measurements of forces, moments and motions in dedicated testing machines. Today's testing machines comprise of a belt attached to two wheels representing the ground and its motion. The tested tyre is moved relative to the rotating belt and forces and moments are measured. The belt is covered by a sand paper like material representing the road surface. Despite attempt in the testing industry to find sand paper surfaces that can represent real road surfaces, there will be a discrepancy between real road pavement and test machine. This discrepancy, that eventually will propagate down to the simulation accuracy of the involved simulation models, was the main drive of the presented project.

The main idea of the project was to investigate the possibility to use instrumented standard production vehicles to acquire test data for parameterizing tyre models. This would enable a procedure that is faster and potentially more flexible for a stakeholder, such as vehicle manufacturer, compared to the state-of-the-art procedure of involving sending test tyres to a test house with a test machine. In addition, it would enable a procedure that can be performed on any road surface of interest.

The project was set up to investigate the possibility to firstly rescale tyre model parameters to a new road surfaces and secondly interpedently parametrize a tyre model based on vehicle measurements. Two major measurement campaigns in test tracks were planned to gather enough data to investigate the feasibility of the approach. To further support the investigation, measurements from a mobile tyre test rig and from two different stationary facilities were acquired. This enabled a comparison to study the effect of the experimental setup as well as the effect of the environmental conditions, the number one being the road surface.

After the analysis of the first measurement campaign it was evident that more factors, beside the road surface, needs to be considered to improve the accuracy of the simulation models. Two identified factors were studied further; contact patch vibrations and tyre

surface temperature. Both factors are well known in the tyre related literature. However, due to the project setup with multiple sources of the data, it was possible to quantify the effect these factors have in the context of data acquisition for tyre model. The focus of second measure campaign was shifted from full tyre model parametrisation to further investigate the effect of surface temperature of the tyre.

Tyre vibrations is a well-known phenomenon, that have been studied extensively in the literature. Different modes of vibrations have different implications. In the first measurement campaign it was identified that a mode of some 50 Hz has an impact on the corresponding steady state force. The vibration, amplified by the change of characteristics when the patch is sliding, can lower the average force that can be extracted around and after the force peak of the patch. This will change the overall characteristics of the vehicle in extreme driving situations and needs to be considered to have an accurate simulation model. Different application rates of the force as well as the mounting characteristics of the wheel will influence the build-up of these vibrations. Hence, this needs to be considered when performing tests and measurements with the purpose of parameterizing tyre models.

The effect of tyre contact temperature to the force characteristic is complex but known phenomenon in the literature as well. Typical simple tyre model used for handling simulations does not include temperature due to its complex nature. Improving the accuracy of such models, without introducing an explicit temperature model a great challenge. The second measurement campaign studied the effect of manoeuvre rate when acquiring the data and its consequences for the tyre parametrization and finally the simulation. A fast application of forces implies a significantly lower temperature build up in tyre surface compared to a slower one. Consequently, a tyre model based on a fast application will have a noticeably different characteristic than a one based on data with a slower application. This provides a mean to classify models in their applications and how they were constructed; a simulation model for fast vehicle manoeuvres should be based on data that was acquired with fast force application.

The project presents a promising procedure to acquire data for tyre model parametrization of simple handling tyre models using vehicle-based measurements. It is also shown have a relatively simple sensor set can be used to accomplished this. Different considerations for tyre vibrations and surface temperature have been investigated and means to mitigate effects of these have been presented. The procedure could very well be implemented in a stakeholder's development procedures to obtain simple handling tyre models (Pacejka 2002 tyre model) for new road surfaces using the presented rescaling technique.

# 2. Sammanfattning

Den ökande takten på utvecklingen av aktivt säkerhetssystem och autonoma fordon ställer höga krav på virtuell verifiering av dessa system. Däcken är relevanta i detta sammanhang på grund av dess betydande inflytande på fordonsrörelsen och prestandagränserna som sätts av däcken. Alla krafter, undantaget aerodynamiska, som föraren använder för att styra fordonet genereras i kontaktfläcken mellan däck och väg. Följaktligen bör de prestandabegränsningar som däcken sätter ideellt tas i beaktande i de aktiva säkerhetssystemen och så även för självkörande fordon. På grund av däckets påverkan på fordonsrörelsen är de några av de viktigaste komponenterna som måste modelleras korrekt för att korrelera komplettfordonssimuleringar med fysisk provning.

På grund av den komplicerade karaktären av interaktionen mellan däckgummiblandningen och slitbanemönstret och vägytan är de mest använda modellerna drivna av mätningar. Däckmodeller som används i detta sammanhang är ofta inte bara härledda utifrån ett fysikaliskt perspektiv utan använder också empirisk erfarenhet från mätningar. Detta gör parametriseringsprocessen för att hitta modellparametrar avgörande för exaktheten hos de resulterande modellerna.

Den rådande de facto standardproceduren för att hitta däckmodels-parametrar är genom data som erhållits genom mätningar av krafter, moment och rörelser i dedikerade testmaskiner. Dagens testmaskiner består av ett band fäst vid två hjul som representerar marken och dess rörelse. Det testade däcket rörs i förhållande till det roterande bandet och krafter och moment uppmäts. Bandet är täckt av ett sandpapperslikande material som representerar vägytan. Trots försök i testindustrin att hitta sandpappersytor som kan representera riktiga vägytor kommer det att finnas en skillnad mellan äkta vägbeläggning och testmaskin. Denna skillnad, som i slutändan kommer att propagera till simuleringsnoggrannheten hos de involverade simuleringsmodellerna, var huvudsakliga drivkraften bakom detta projektet.

Huvudidén för projektet var att undersöka möjligheten att använda instrumenterade standardproduktionsfordon för att samla testdata för att parametrisera däckmodeller. Detta skulle möjliggöra ett förfarande som är snabbare och potentiellt mer flexibelt för en intressent, såsom fordonstillverkare, jämfört med det rådande tillvägagångssättet att sända testdäck till extern part med en däckstestmaskin. Dessutom skulle det möjliggöra ett förfarande som kan utföras på vilket underlag och väg som helst av intresse.

Projektet inrättades för att undersöka möjligheten att först skala om däckmodellparametrar till nya vägytor och för det andra fullt ut parametrisera en däckmodell baserad på fordonsmätningar. Två större mätkampanjer på provbanor planerades för att samla in tillräckligt med data för att undersöka möjligheten av tillvägagångssättet. För att ytterligare stödja undersökningen insamlades mätningar från en mobil däckprovningsmaskin och från två olika stationära anläggningar. Detta möjliggjorde en jämförelse för att studera effekten av utrustning samt effekterna av miljöförhållandena, varav den primära är underlaget.

Efter analysen av den första mätkampanjen var det tydligt att fler faktorer, utöver underlaget, måste betraktas för att förbättra simuleringsmodellernas noggrannhet. Två identifierade faktorer studerades ytterligare; vibrationer i kontaktytan samt däckytans temperatur. Båda faktorerna är välkända i däckrelaterad litteratur. På grund av projektuppsättningen med flera datakällor var det emellertid möjligt att kvantifiera effekten av dessa faktorer samt dess inverkan på de resulterande däckmodellerna. Inriktningen för den andra mätkampanjen skiftades då från den fullständiga däckmodellsparametriseringen till att istället ytterligare undersöka effekten av däckets yttemperatur och vibration.

Däckvibrationer är ett välkänt fenomen som har studerats i stor utsträckning i litteraturen. Olika vibrationer har olika konsekvenser. I den första mätkampanjen identifierades mode på cirka 50 Hz har en inverkan på motsvarande medelkraften. Vibrationen, förstärkt av egenskapskiftet när kontaktytan glider, kan sänka den genomsnittliga kraften som kan extraheras runt och efter däckets kraftstopp. Detta kommer att ändra fordonets övergripande egenskaper vid extrema körsituationer och måste därför beaktas i simuleringsmodeller. Olika applikationshastigheter för kraften samt hjulets upphängning kommer att påverka uppbyggnaden av dessa vibrationer. Därför måste även detta beaktas vid provning och mätning med syfte att parametrisera däckmodeller.

Effekten av däckkontakt temperaturen till kraftegenskapen är komplex men känt fenomen i litteraturen också. Typisk enkel däckmodell som används för simuleringar av fordonsbanor inkluderar inte temperatur på grund av sin komplexa natur. Förbättra exaktheten hos sådana modeller, utan att införa en explicit temperaturmodell är en stor utmaning. Den andra mätkampanjen studerade effekten av manövreringshastigheten vid inskaffande av data och dess konsekvenser för däckparametrisering och slutändan också simuleringen. En snabb applicering av krafter innebär en betydligt lägre temperaturuppbyggnad i däckytan jämfört med en långsammare. Följaktligen kommer en däckmodell baserad på en snabb applikation att ha en märkbart annan egenskap än en baserad på data med en långsammare applikation. Detta ger ett medel att klassificera modeller i sina tillämpningar och hur de konstruerades; en simuleringsmodell för snabba fordonsmanövrar bör baseras på data som erhållits med snabb kraftapplikation.

Projektet presenterar ett lovande förfarande för att erhålla data för däckmodellparametriering av enkla däckmodeller med hjälp av fordonsbaserade mätningar. Det visas också att relativt enkla sensorer kan användas för att uppnå detta. Olika överväganden för däckvibrationer och yttemperatur har undersökts och medel för att mildra effekterna av dessa har presenterats. Förfarandet kan mycket väl genomföras i en intressents utvecklingsprocedurer för att erhålla däckmodeller fordonsdynamiksimulering (Pacejka 2002-däckmodell) för nya vägytor med hjälp av den presenterade omskalningsmetoden.

# 3. Background

The development process of active safety systems involves extensive full vehicle testing on designated test tracks. Both the development cost and time could be reduced if the amount of physical testing could be limited. The active safety systems could also be improved if the development proves were made more efficient and repeatable and based on objective metrics. The main enabler for reducing full vehicle tests is complete vehicle simulation tools. To make the transition from physical tests to virtual tests, the simulations models must achieve sufficient accuracy. A passenger car is a very complex system with many components. This makes it challenging to achieve required accuracy and correlation to physical testing.

All driver or system demanded steering, propulsion and braking forces are transmitted through the contact patch of the tyre on a normal passenger car. Tyres are therefore one of the key components that should be modelled accurately when simulating the motion of the vehicle. Accurately modelling the tyres is one large challenge in the transition from physical to virtual testing for verification and homologation of active safety system, such as Electronic Stability Control (ESC). For ESC, a new legislation proposal from the UNECE allows for homologation of the system in different vehicle variants in simulations provided that the simulation model is representative of the real vehicle [1]. The need for accurate Force and Moment (F&M) models of the tyres has led to new testing procedures.

The force and moment characteristics of tyres are dependent on both the current operating conditions and road surface. The variation in tyre-road characteristics between different tyres on the same surface can be large, see e.g. [5]. The vehicle motion will consequently be affected by these variations. The characteristics of the contact makes the forces to saturate in a strongly nonlinear manner close to the performance limits of the vehicle. Due to the complex nature of the interaction between the tyre rubber compound and tread pattern and the road surface are most used models driven by measurements. Tyre models used in this context, modelling the interaction, are often only not derived based on physical insight but also empirical experience. This makes the parameterization process of finding model parameters crucial to the accuracy of the resulting models.

Previously, rotating drums were commonly used for tyre testing. As research showed that the curvature of the drum affected the measurement results, low speed flat-track machines replaced the rotating drums as the current state-of-the art [6]. When several studies highlighted the sensitivity of the tyre characteristics to varying velocity, e.g. [6,7], high speed flat-track machines became the new state-of-the-art, e.g. [2]. The surface of these rotating belts is normally covered with an abrasive surface coating to better, compared to steel, represent a real road surface [2]. Naturally, the accuracy of a tyre model parameterization based on indoor testing on a surface different from the road surface on the test track and the current tyre characterises will vary depending on the properties of the road surface and with environmental conditions.

Several companies have therefore developed tyre testing trailers and trucks that can operate directly on the road surface of interest, e.g. [8, 9]. These types of equipment enable testing the tyres on the same road surface and environment as the vehicle. However, they are not part of the standard testing equipment found for example at most car manufacturers and their suppliers and are costly both to obtain and maintain.

An alternative is to equip a passenger car with sensors to measure all the inputs and outputs of the Standard Tire Interface (STI) [10] and use the vehicle as a tyre testing rig [3,4]. These types of measurements make it possible to test the tyres for similar operating conditions as the vehicle should be evaluated in without a mobile test truck or trailer. However, using the same tyre model for different vehicles can give inaccurate results if the data does not cover enough operating conditions. An alternative to full tyre model parameterization is to use a tyre model parameterized based on flat-trac measurements and use the vehicle-based tyre test data to scale this model to the new road surface.

# 4. Purpose

The purpose of the present project was to present a procedure to obtain tyre models that are accurate enough to support a fast, cheap and precise development of vehicles. Such a procedure could also be used in general to obtain simulation models with high reproducibility which would support work conduced by research institutes and universities.

# 5. Objective

The initial objective of the project was to investigate a procedure to obtain tyre models that are accurate w.r.t to road surface using vehicle-based tyre testing. Two measure campaign were planned, where the first one had the focus of obtaining data to scale an existing parametrization to a new road surface while the second one was to obtain data for a full parameterization. Beside the instrumented test vehicle, a mobile tyre test rig was included in the campaign. In addition, measurements from two types of indoor test facilities was also acquired in the project.

Based on the data, it was early in the project decided to move from the ambition of making a full parameterization of a tyre model and instead study the influence temperature (and in turn manoeuvre rate) and vibrations. The new objective of the project was then to study the feasibility of a procedure to rescale an existing tyre model to new road surface that is accurate for certain types of manoeuvres and suspensions.

# 6. Results

As illustrated in [C], the force and moment characteristics between the two different asphalt surfaces can vary. Even if some road surface has good correlation to flat-trac measurements being able to verify the correlation is advantageous. To evaluate the validity of the complete vehicle model, the tyre model used must provide sufficient precision. This is true both in tuning and development of for instance ESC systems but also for homologation simulations. As shown in [C], the tyre surface temperature at the peak lateral tyre force varies for the different manoeuvres depending on the time history of the slip angle and force.

Depending on how large slip angles that are reached during a sine-with-dwell manoeuvre and how long they are maintained, different tyre surface temperatures and thus also maximum lateral forces are expected on the real vehicle. The Pacejka 2002 model does not take these temperature effects into account. Hence, the testing procedure must produce a similar tyre surface temperature at the same slip angle as the manoeuvre that should be simulated. In practice, this is hard to achieve. Using tyre models that can account for the change in tyre-road friction coefficient with tyre surface temperature is therefore recommended for the sine-with-dwell manoeuvres. As also seen in [C], not even the fast steering angle sweep rate produce the low enough tyre surface temperatures.

As seen in [A], the lateral tyre force vibrations at large slip angles can affect the average lateral force generated by the tyres. Further investigations are needed to quantify how much these vibrations affect the average lateral force. Depending on these findings, recommendation regarding the suspension of the tyre testing equipment can be made. As also shown in [A], both the suspension and slip angle sweep rate will affect the amplitude of these vibrations and therefore also the average lateral tyre force.

Vehicle based tyre testing offers a straightforward approach to reparametrize tyre models to new road surfaces. It can thus improve the correlation between full vehicle experiments and simulations. The main drawback with the methods used in within the scope of this thesis is the long preparation time of the test vehicle and the relatively expensive sensor set required, [B]. Similar accuracy can be obtained by estimating the slip angle, forces, and the camber angle from K&C data and IMU signals, [F], with only minor trade-off in accuracy. This shortens the whole procedure significantly. The sensors and manoeuvres required to obtain required data could easily be included in standard tests performed on a regular basis, enabling an easy way to improve simulation results with very limited extra cost.

The project used a multiple of sources to compare the data obtained from the test vehicle, namely from a mobile test rig (the BV12 from VTI) as well as from two different indoor test facilities (a Flat trac machine and from the unique Camber Ridge facility). This enabled a data driven analysis to compare the influence of manoeuvre sweep rate, road surface and other conditions. For example, it was discovered that the mobile test rig had an error compared to the other sources that scaled with the applied tyre force. A devoted stationary test of the compliance between the sensor and the tyre confirmed the predicted compliance with very high accuracy. This substantially improved the quality of the measurements of that rig and will be used in the future. The different sources also enabled a quantification of the effects of manoeuvre rate and vibrations of the tyre measurements.

The project did not investigate the case of full tyre model parametrization as it was initially intended. Instead, the influence of vibrations and temperature was investigated. Full tyre model parameterisation would likely involve a more detailed scheme of manoeuvres, sensors and data processing than the approach studied in this project with rescaling as the objective. Full parameterisation would eliminate the need of using indoor tyre testing facilities to parameterize tyre models, which would be cost reducing and potentially more efficient. On the other hand, a full parameterization would not be cost efficient since the model would have to be rescaled for all other road surfaces and operating conditions. In addition, the investigations regarding surface temperature and vibrations are necessary to have a sound and accurate procedure that generate tyre models of good quality.

## 6.1 Future Work and Recommendations

The vibrations found in the vehicle-based tyre testing should be further investigated using more advanced suspension model and an improved Ftire model that is validated against tests specifically designed to capture these vibrations, e.g. external disturbances at large slip angles. The influence of tyre surface temperature on tyre-road friction is documented both in this thesis and in previous research. Further experiments are required to find a manoeuvre that is suitable for identifying the parameters of the magic formula for simulation of the vehicle motion in sine-with-dwell manoeuvre. However, it should be remembered that the tyre force characteristics may change due to differences in operating conditions in different sine with dwell manoeuvres. It is thus recommended to use a tyre model that can model the thermal states of the tyre and that takes the effect of tyre surface temperature on the maximum lateral force into account. This could perhaps be a slightly modified version of the magic formula as presented in [13] or a more complex model as CD-tire [14] but this must be further evaluated.

# 7. Dissemination and publications

The project was mainly a PhD student project and much of the activities evolved around the procedures and routines in this process. This involved writing papers and submitting these to scientific journals as well as attending and presenting papers at scientific conferences in the relevant fields. The dissemination activities and the publications are further described below.

## 7.1 Dissemination

The project was mainly a PhD project with one active student. The student successfully defended his PhD thesis during the project and his work was to 50% based on the current project. The project has hence led to an increase of knowledge for the PhD student specifically and for the research field in general through the publications.

The project results could be used a procedure to improve accuracy of simulation models, by using standard measurements of vehicle on the test track to rescale tyre models to new surfaces. The simplicity of the procedure, together with benefits of using speaks for this implementation in the future by all the involved parties. The number of papers published in the project suggests that there is a great potential that the ideas and results of the project will be used elsewhere and on in a global manner.

## 7.2 Publications

The following publications have been produced within the presented project:

[A] Albinsson, A., Bruzelius, F., Els, P.S., Jacobson, B., Bakker, E. (2017), *Lateral Tire vibration considerations in vehicle based tyre testing*. Presented at the 36th annual meeting of The Tire Society, Akron, Ohio, USA, Accepted for journal publication in Tire Science and Technology.

[B] Albinsson, A., Bruzelius, F., Jacobson, B., Bakker, E. (2018), *Evaluation of vehicle based tyre testing methods*. To appear in Proceedings of the Institution of Mechanical Engineers Part D -Journal of automobile engineering, special issue on "Tyre modelling and technology"

[C] Albinsson, A., Bruzelius, F., Jacobson, B., Bakker, E. (2018), *Validation of vehicle based tyre testing methods*. Accepted for publication in Proceedings of the Institution of Mechanical Engineers Part D -Journal of automobile engineering, special issue on "Tyre modelling and technology"

[D] Shenhai Ran (2018) "*Tyre Measurements and Modelling for Parking Manoeuvres* ". In The 25th International Symposium on Dynamics of Vehicles on Roads and Tracks IAVSD'27), Rockhampton, Australia.

[E] Albinsson, A., Bruzelius, F., Ran, S (2018). *Scaling tire models to different road surfaces using an external IMU and K&C measurements*. The 14th International Symposium on Advanced Vehicle Control, (AVEC'18), Beijing, China.

[F] Anton Albinsson, (2018) *Online and Offline Identification of Tyre Model Parameters*. Doktorsavhandlingar vid Chalmers tekniska högskola. Ny serie: 4401. ISBN 978-91-7597-720-1.

The papers [A] to [E] will be briefly described below, while paper [F] will also give a similar but more comprehensive description as well as the actual papers attached.

### 1.1.1. Paper A

This paper investigated the influence of lateral force vibrations at large slip angles observed during the vehicle-based tyre testing campaigns. The objectives were to investigate if these vibrations could be captured by flexible ring model (Ftire). The model was also used to investigate the influence of the wheel suspension on the vibrations and to study the vibrations influence on the lateral force.

A parameterized Ftire and measurements from the parameter identification procedure, all from a third party, was used. Some parameters in the Ftire model were tuned to fit the outof-plane cleat tests better. It was found that the suspension has an impact on the amplitude of these vibrations, especially the damping of the lateral rim movement. The simulated vibrations were similar to the observed vibrations, both had most energy at around 50Hz but with harmonics at higher frequencies. Furthermore, it was found that the slip angles and propulsion torque affected the amplitude of these vibrations. The rim mass had however a small impact. The results showed that these vibrations lower the average lateral force generated by the tyres. Further investigations are required to quantitively describe both the influence of the suspension and operating conditions on these vibrations but also how much the average lateral force is lowered.

### 1.1.2. Paper B

This paper evaluates the feasibility of vehicle-based tyre testing in terms of sensor accuracy and uncertainties. The method used for measuring the inputs and outputs of the Pacejka 2002 model is described. Measurement results from three different measurement sources are compared and observed differences are discussed from a tyre perspective. The measurement of the camber angle and lateral force are validated. It was shown that the lateral forces are reasonable compared to the lateral acceleration of the vehicle. The measurements of the longitudinal force with respect to bump spin compensation is also discussed as well as the noise levels from different measurement sources for longitudinal velocity of the tyre.

Furthermore, lateral tyre force vibrations are shown to be present for both the vehicle-based tyre testing and the mobile tyre testing rig measurements. These vibrations were the main reason for the investigation in [A].

### 1.1.3. Paper C

This paper investigates how the choice of manoeuvre affects the correlation between a scaled tyre model and the measurements. The main difference between the manoeuvres is the steering wheel angle rate. The steering wheel angle rate will affect the tyre surface temperature for a given slip angle. The difference in tyre behaviour and in tyre surface temperature are thus evaluated for realistic cooling conditions on a test vehicle for different manoeuvres. The influence of combined slip is also investigated by performing manoeuvres both at constant speed and at zero propulsion torque.

It also shows how the choice of manoeuvre for tyre testing affects the simulated complete vehicle behaviour, both in steady-state and in a sine with dwell manoeuvre. It is shown that the difference between the tyre models from different testing methods are outside the tolerances specified in ISO19364 [11] for validation of simulation models in steady state cornering. It is also shown that the lateral force is underestimated in a sine with dwell manoeuvre even when compared to the fastest steering wheel angle rate. This is also explained by the difference in tyre surface temperature.

### 1.1.4. Paper D

This paper studies the tyre performance at low speed for parking manoeuvre. A comprehensive set of measurements was conducted at Camber Ridge, where the tests could be performed on asphalt surface. It turns out that the force and moment generated by the tyre yaw motion i.e. turn slip, are the most important ingredient for parking manoeuvre.

Next, an innovative approach is proposed to characterize the corresponding force and moment in the numerical simulation environment. The new tyre model for parking is based on the extension of the Magic Formula that is widely used in the automotive industry. The validations between the measurements and simulations suggest that proposed method is promising for the steering system development.

### 1.1.5. Paper E

While the results of [B] and [C] rely on tyre force transducers, optical slip angle and camber angles, this paper investigate the feasibility of using a minimal set of cheap standards sensors to obtain data for tyre model parameterisation using a test vehicle on a test track.

The influence of replacing the directly measuring slip and force sensors with indirect estimates based on inertial measurement units (IMUs) and Kinematics & Compliance (K&C) measurements is investigated with respect to quality in the obtained tyre models. A direct consequence of using only IMU sensors and K&C data is that only the axle forces can be estimated, see [12]. The effect of this consequence is also studied.

It is shown that the vehicle speed is one of the most sensitive signals in this context, implying that this is the best sensor to invest in if accuracy is a concern. On the other side, the tyre model accuracy is least sensitive to the camber angle sensor, implying that this sensor does not need to be of high quality. The paper also indicates that effect of only axle force information is very limited. Hence, the paper show that vehicle-based tyre testing can be performed with good result with a very limited sensor set of an IMU and the availability of K&C measurements.

# 8. Conclusions

The current project investigated a procedure to obtain data for tyre model parametrization using an instrumented standard production vehicle and a test track. The procedure enables a cheap and fast method to obtain accurate tyre model adaptions to new road surfaces. It is shown that this can be achieved even with a simple set of standard sensors. Hence, the sensors and manoeuvres required for this procedure can be included in day to day test track activities and enable a very convenient procedure to improve simulation results during the development of vehicles and tyres.

Furthermore, it is shown that the rate of which the tests are performed have noticeable impact on the tyre parameters and consequently the simulations based on these tyre models. The surface temperature of the tyre along the build-up of tyre vibrations will require more complex models than the ones typically seen in todays application of handling simulations in both academia and industry. A remedy to mitigate the effects of temperature and vibrations in this context is to acquire data from the test vehicle using a rate of change that is similar to the one intended for tyre model and the simulation.

# 9. Participating parties

The project involved many people from all the three parties, including Max Boerboom and Shenhai Ran from Volvo Cars and Mattias Hjort and Harry Sörensson from VTI. The key contact persons for the project is listed below with the general roles of the organisations within the project.

| Organisation | Role of organisation | Contact person |
|---|---|---|
| **VTI** | Project lead, supervision, research, reference measurements | Fredrik Bruzelius, fredrik.bruzelius@vti.se |
| **Chalmers** | PhD student, main conductor of research | Prof. Bengt Jacobson, bengt.jacobson@chalmers.se |
| **Volvo Cars** | Measurements, expert consultations, research | Egbert Bakker, |

# 10. References


[1] Proposal for a new Regulation on Electronic Stability Control (ESC), United Nations Economic Commission for Europe, 2016.

[2] K. D. Bird and J. F. Martin, "The Calspan Tire Research Facility: Design, Development, and Initial Test Results," presented at the National Automobile Engineering Meeting, Detroit, USA, 1973.

[3] H. Olsson, E. Hugon, and C. Rouelle, "Efficient acquisition of tire data and its application in vehicle handling simulation," Tire Science and Technology, vol. 40, pp. 234-245, 2012.

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