

Fahrzeugbasierte Schätzung des Reifen- Fahrbahn-Kontaktes im FRICTI@N-Project

On-Board Estimation of Tyre-Road Interaction in FRICTI@N Project

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Summary

The overall approach to friction estimation in the *FRICTI@N* project is described. Road friction is an important parameter in vehicle control, limiting the applied steering, braking and acceleration of a vehicle. On-line and in-vehicle friction estimation is also a difficult task to be carried out in all driving situations and weather conditions. The paper describes the key friction terms, and previous work. Then the friction estimation architecture is explained, including data fusion algorithms for vehicle, environmental, and tyre based measurements, plus decision fusion. Also the inputs and outputs of the friction estimation system are listed, and demonstrator vehicles described. Finally the potential applications benefiting from more accurate friction information are discussed, and considerations for future research are presented.

1 Introduction

Except for aerodynamic forces and gravity, all other significant forces acting on a typical vehicle are put into action via the friction forces between tyre and road. But since continuous in-vehicle friction measurement has been very difficult, the estimation of friction has been the responsibility of the driver. Unfortunately drivers do not adapt their behaviour sufficiently to prevailing or changing conditions: A look at available restricted accidents statistics suggest that almost 50% of all accidents occur as a result of the driver misjudging the vehicle ahead, the driving dynamics, the weather and road conditions on the road lane. According to EU-project SAFESTAR some 40 % of accidents occur under bad road conditions [2].

Electronic control systems like ABS, ESP, etc. actively participate to the vehicle control, when the maximum friction has been exceeded. However, there is a need for more accurate and incessant friction estimation system, which can provide higher quality information for existing (ABS, ESP, etc) and future (like Emergency Braking System, Collision Avoidance System, Co-Operative Driving) systems.

The overall objective of the FRICTI@N project [1] was to “create an on-board system for measuring and estimating friction and road slipperiness to enhance the performance of integrated and cooperative safety systems”. More detailed objectives were

- Create an innovative model for an on-board estimation and prediction of tyre-road friction and road slipperiness.
- Build a prototype system of an intelligent low cost sensor clustering with a minimum number of generic sensors.
- Verify the system benefits by means of selected vehicle applications using friction and road slipperiness information.
- Enhance the functionality of preventive and cooperative safety systems applications in parallel running and upcoming EU Integrated Projects.

The key goal was to utilise existing vehicle sensors in the project as much as possible. Therefore data fusion has been the algorithmic approach used; it is described more detailed in chapter 2, and in the papers [3] and [13] found in this Proceedings. Also this project does not develop new applications – instead it tries to provide more accurate friction information for other applications. This is presented in Fig. 1.

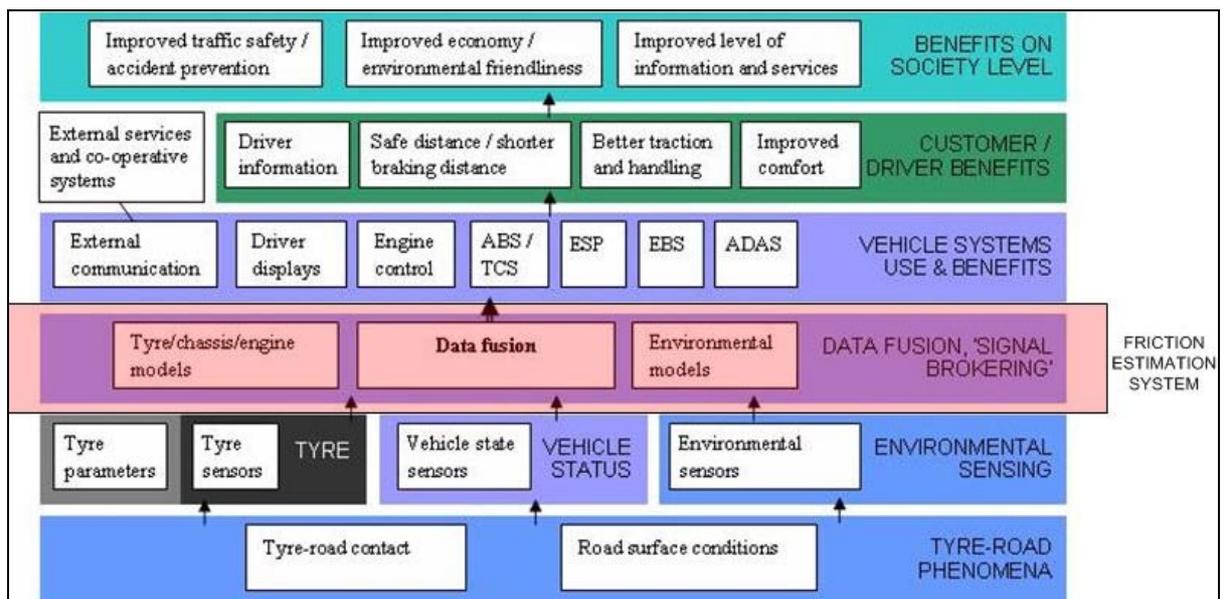


Fig. 1: The context and focus of FRICTI@N project

2 Tyre friction phenomenon, its measurement and previous work

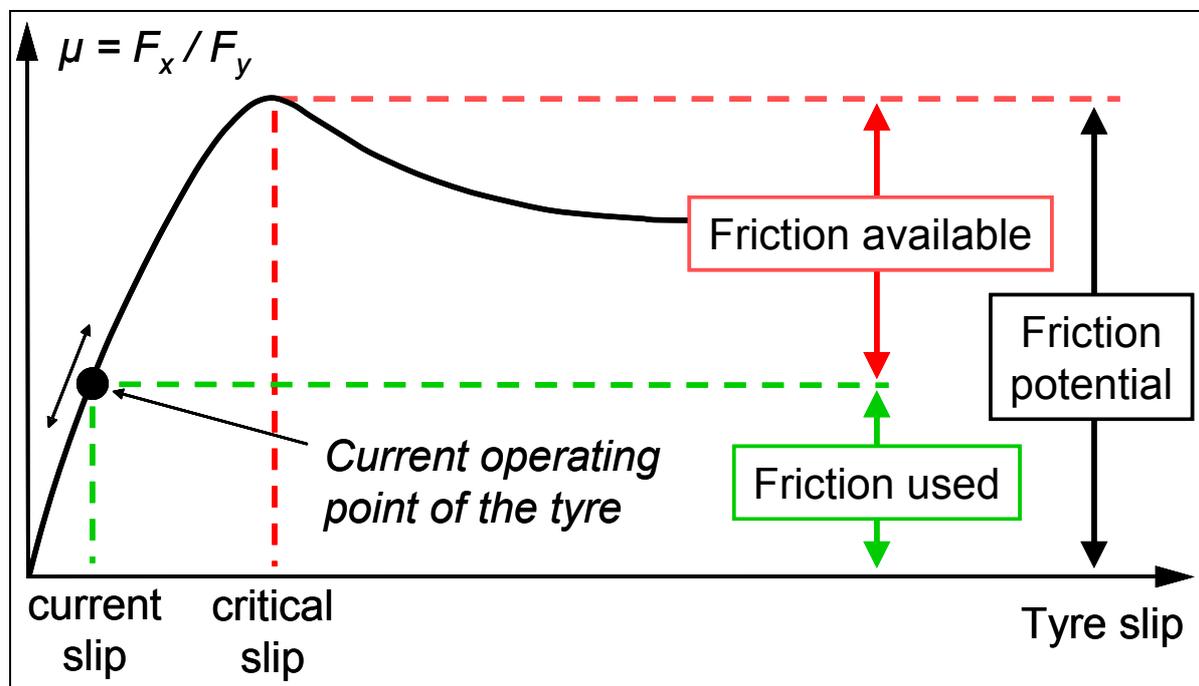


Fig. 2: The definition of Friction potential, Friction used and Friction available used in this project

2.1 Tyre friction phenomenon

The force transfer between road and tyre takes place by friction processes between the road surface and the tyre tread rubber.

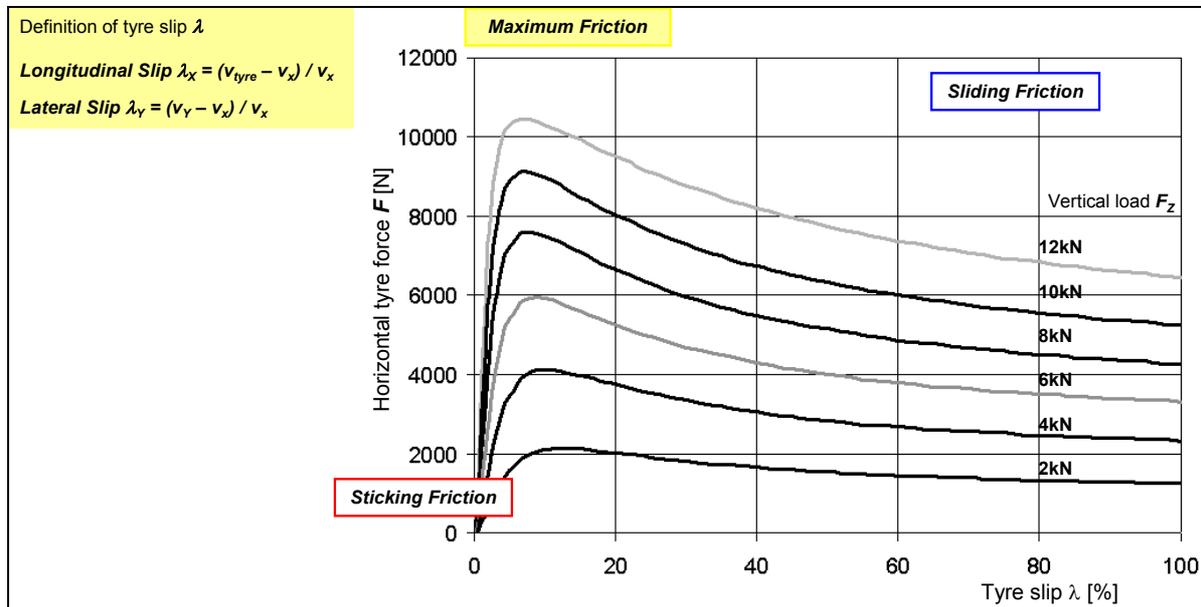


Fig. 3: Friction characteristics of the overall tyre [5]

Responsible for the force by friction are the two main phenomena hysteresis friction and adhesion friction. Adhesion describes the friction by molecular attraction while hysteresis describes friction by the interlocking of the rubber with the ground. When characterizing force transfer properties of a vehicle tyre, the two types of rubber-road friction are not separated from each other. Adhesion friction is mainly responsible for tyre grip on dry roads while hysteresis friction assures tyre grip on wet roads. The force transfer between tyre and road is directly connected to a certain slip condition of the rolling tyre (Fig. 3). This slip state describes the point of operation. Low slip quantities mean that there is mainly adhesive friction force transfer between tyre and road. At very high slip values, mainly sliding friction is responsible for generating tyre forces.

Besides the effects described there are other parameters that influence the force transfer behavior and therefore the friction coefficient. They can be classified into four main categories Tyre related parameters, the current driving state, road surface related parameters and the current road condition. To estimate the friction available, all these parameters have to be taken into account by a friction determination system [5].

2.2 Strategies and concepts to determine tyre-road friction

Up to now there have been several approaches to determine the tyre–road-friction. Depending on the kind of friction (“used”, “potential”, “available” or “friction ahead”), different approaches can be chosen to determine friction. “Friction used” will mainly be determined by using standard vehicle based driving dynamics sensors like those already available for ABS or ESP systems. Using these online measurements of the vehicle motion to support a real-time capable vehicle dynamics calculation model, the current “friction used” can be estimated very precisely.

Friction used	Friction potential	Friction used ahead	Friction potential ahead	Friction available (ahead): $\mu_{available} = \mu_{potential} - \mu_{used}$
<ul style="list-style-type: none"> • Vehicle state observer (based on vehicle sensors: wheel speeds, yaw rate, lateral acceleration...) with friction used estimation • Wheel force dynamometers • Apollo optical tyre sensor (global tyre forces) • Other tyre force sensors (global tyre forces) • Other approaches that describe vehicle motion (e.g. GPS) accurately 	<ul style="list-style-type: none"> • Tread lug deformation tyre sensor (TU Darmstadt) • Tread block friction measurement device • Mobile tyre test rigs (application of very high slip quantities resp. critical slip) • Active tie rod in combination with tyre force sensors (application of very high slip quantities resp. critical slip) • Road friction tester • Estimation based on sensor cluster (environmental and others) 	<ul style="list-style-type: none"> • GPS, road and traffic conditions and digital road map combined with vehicle state observer • Model that can predict driver behaviour • Vehicle to vehicle communication 	<ul style="list-style-type: none"> • Vehicle to vehicle communication • External services (weather forecast, GPS, digital (friction) road map, traffic situation, construction areas,...) • Environmental sensors that can determine road, traffic and weather condition • Estimation based on sensor cluster (environmental and others) 	

Fig. 4: Methods for friction estimation [5]

The “friction potential” is a value that can not be measured directly because it is a theoretical value that is not available if it is not turned into “friction used”. But being aware of the parameters that influence the friction value an estimation can be performed by measuring these parameters. As it is known the road surface condition has a huge influence on the friction value it is one approach to detect water, ice or snow coverage by sensors. Also the knowledge of surface itself gives a hint if there is a high grip or a low grip level to be considered. To get information about the friction value ahead, systems have to be considered that are based on infrastructural information or other communication devices because in vehicle measurement is not capable for this task. Fig. 4 gives an overview of different possible friction measuring methods that have been investigated since now.

On-board sensors monitoring the state of vehicle motion provide information about the current driving state of the vehicle such as e.g. locked wheels or the vehicle's position on the intended trajectory. These sensors measure only changes caused by impaired friction and not directly road conditions. They are not capable of predicting friction ahead.

The measurements must be processed and they could be inaccurate or their response time is too slow for time critical safety applications. However, vehicle state sensors provide useful driving state information, which, when combined with e.g. environmental sensors, is worthwhile for friction estimation. The following section presents some examples of friction estimation systems that were realised in the past.

A Swedish company, NIRA Dynamics AB, commercialised the Road Friction Indicator “RFI” that alerts for slippery road conditions by monitoring the available tyre-road friction. RFI primarily provides information to the driver, but it can also be configured to deliver friction information to other vehicle applications in order to enhance their performance. RFI is a purely software-based system that uses only existing ABS sensors and advanced signal processing algorithms to monitor the tyre-road friction. The RFI system has not turned out to be successful in varying road conditions.

The University of Karlsruhe has introduced a new system for estimating “friction potential” during driving. The system is based on the detection of environmental data to determine one of six “friction potential” classes and its working principle can be classified as an “indirect” friction measurement method. The system does not depend on specific car / truck properties (type of tyre, tyre pressure, wheel load) and it allows an estimation of the friction level of the track ahead. The method is motivated by the fact, that the weather and the road conditions have the most distinctive influence on the friction coefficient. The described method detects this environmental conditions by several indirect sensors:

- Sensing road surface temperature
- Acoustic sensor
- Acceleration sensor at the axle
- Rain sensor
- WSE-Sensor (prototype that detects: Water, Snow, Ice)

The weather conditions are identified by using three information. First of all the measured road temperature leads to three possible situations. At temperatures of 0°C or more a rain sensor supports by detecting dry or wet road conditions. If the temperature does not reach more than 0°C a new developed sensor called “WSE”-sensor (water, snow, ice) provides further information about the friction coefficient. Furthermore the type of the road is detected by the use of acoustic sensors involving the measurement of the accelerations of the vehicle axles. Every type of road possesses an appropriate transmitted frequency band which allows the differentiation of cobblestone, asphalt or dirt road. Feeding this information to an algorithm an estimation of the friction level is provided [6].

The “IVDC” (Integrated Vehicle Dynamics Control) is a concept that combines different, previously separated, control algorithms. The system was introduced by the Ford Forschungszentrum in Aachen.

The concept is able to provide information that cannot directly be measured like the friction coefficient or the lateral vehicle velocity. Based on a vehicle model which uses a Kalman filter to correct calculated and measured values the IVDC provides the friction coefficient [7].

The “Darmstädter Tyre Sensor” has been developed by the fzd of the University of Darmstadt since 1988 within the frame of the Sonderforschungsbereich (special research field) IMES 241 (Integrated mechanical electronic systems for mechanical engineering). The sensor uses a Hall generator to detect tread lug movements within the tyre tread. Based on the knowledge of these deflections at different friction levels within the tyre contact patch, the “friction used” can be detected [8].

The APOLLO project (EU IST-2001-34372, 2002-2005) studied the possibilities of intelligent tyre systems. Tyre deformation sensors were found the most promising technology, and an intelligent tyre system was realised with wireless data transfer and tyre integration. Acceleration and strain sensors as well as an optical sensor were used for tyre belt deformation measurements. The tests showed that the optical as well as the acceleration sensors were able to quite accurately determine the contact length of the tyre from radial velocity and tangential position signal. On snowy surface the tangential deflection signal was different on the high and low friction surfaces. On asphalt, bitumen and concrete friction potential could not be estimated because of high signal variation. Tentative results of the project also suggested that the detection of nascent aquaplaning would be possible [11,12].

BMW developed a procedure to determine the friction coefficient between the vehicle tyre and the road surface when approaching a lateral dynamics critical motion state. This procedure is described in the patent DE 3912014 (EP 0392164) published in 1998. In a first step of the determination of the friction coefficient between the vehicle tyre and the road, the rotational speed (ω_L , ω_R) of the non-driven wheels, the steering angle (δ_S) and the lateral acceleration (y'') were measured in a well-known way. With the rotational speed of the non-driven wheels and the dynamic wheel radius (r_{dyn}) the longitudinal velocity of the vehicle is calculated according to the formula

$$v = \frac{(\omega_L + \omega_R) \cdot r_{dyn}}{2}$$

Furthermore the yaw rate of the vehicle is calculated based on the rotational speed of the non-driven wheels (ω_L , ω_R), the dynamic wheel radius (r_{dyn}) and the track width of the non-driven axle (s_V) by using the formula

$$\dot{\psi} = \frac{(\omega_L + \omega_R) \cdot r_{dyn}}{s_V}$$

In a second step a desired value for the yaw rate is calculated on the basis of a vehicle model. The calculated longitudinal velocity (v) of the vehicle and the measured steering angle (ΔS) are the input values.

The yaw rate difference between the desired yaw rate of the vehicle and the current yaw rate is obtained in a further step.

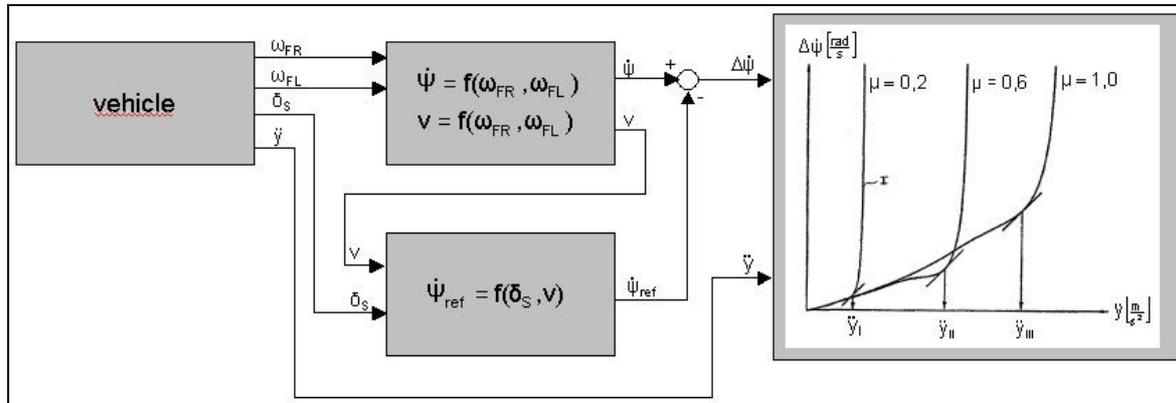


Fig. 5: BMW principle of friction value estimation [9]

The transverse acceleration, at which the yaw rate difference increases strongly, is determined as a measure for the friction value. Thresholds for the yaw rate difference gradient are defined to determine the lateral acceleration, which is related to the friction coefficient [9].

"The estimation of tyre-road friction by tyre rotational vibration model" requires only ABS wheel speed sensors. The measurement was based on the fact that the resonance characteristics of wheel angular velocity vary by tyre-road friction. The presented method was able to detect changes in friction during normal driving. The weakness of this system is that the resonance characteristics change when braking, accelerating or cornering occurs. The method can not be used in these cases. This method can detect friction changes and derive some road condition categories, but not to estimate the actual friction value. The method was patented by Toyota in 2004 [10].

3 FRICTI@N system

3.1 System architecture

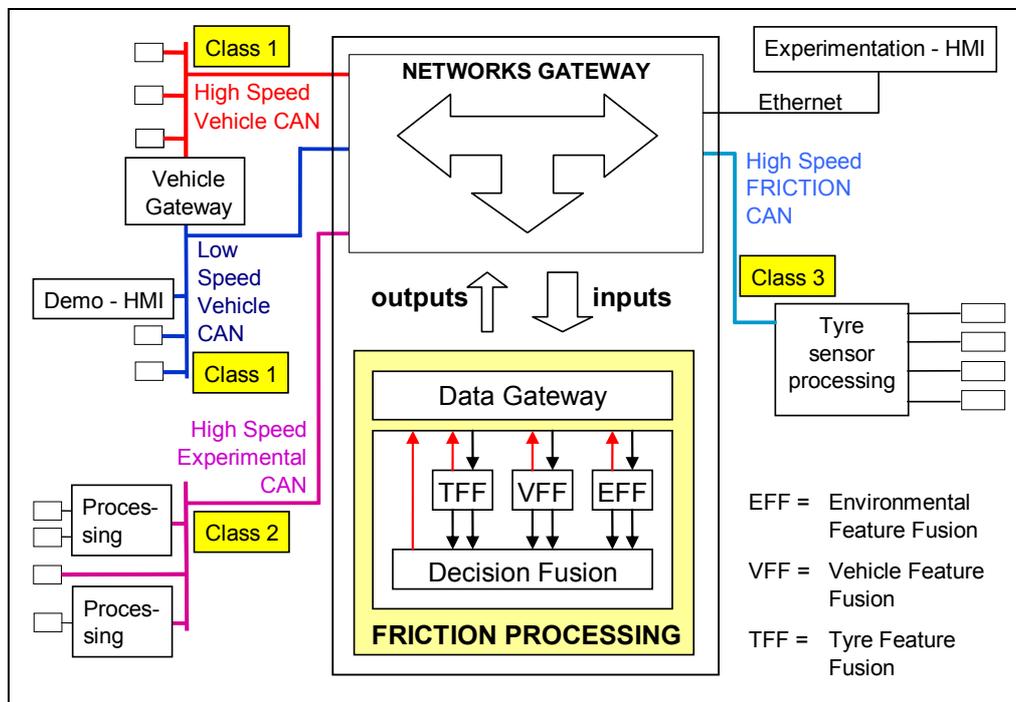


Fig. 6: Overall FRICTI@N system architecture. The inputs and outputs of the friction processing block are listed in Tab. 2 and

The FRICTI@N PROCESSING block details (especially EFF, VFF, TFF and Decision Fusion) are explained more detailed in the papers of Haas [3] and Tuononen [13] found later in this Proceedings.

Currently the FRICTI@N PROCESSING is implemented with a Rapid Prototyping Unit, RPU (made by dSPACE), which collects information from each sensor, and estimates friction. In production vehicles basically any ECU can be used, which has enough processing capacity, and all the required communication interfaces. Network classes are explained in Table 1.

Network class	Description	Specifications
Class 1	Vehicle normal production buses (high & low speed CAN)	Only normal production signals utilised in FRICTI@N System are specified
Class 2	New buses for experimental activities other than FRICTI@N	Only experimental signals utilised in FRICTI@N System are specified
Class 3	A dedicated FRICTI@N bus (high speed)	All signals are specified

Tab. 1: Network classes of Fig. 6

The system is based on sensor data of various sources: environmental sensors, vehicle sensors and dedicated tyre sensors.

All sensor signals are passed to a data gateway, which provides them to three independent friction feature fusion modules (EFF, VFF & TFF). The output of friction estimation modules is one or several of the following information:

- actual friction used and its validity
- friction available and its validity
- the predicted friction ahead of the vehicle and its validity

The output is dependent on the capability of each module, and the availability of appropriate sensors. Also the type of error distribution should be available for fusion.

The outputs of feature fusion modules are processed by the Decision Fusion module, which – depending on how well the sensors available support the estimation - combines them into the following estimations:

- the final actual friction used and its validity (see Fig. 2)
- the final friction available and its validity (see Fig. 2)
- the maximum upcoming friction and its validity
- road and tyre condition information (like dry, icy, ... see Table 4)

These values are provided to an output interface gateway (Data Gateway), which makes them accessible to the applications.

Fig. 7 below gives a schematic overview about the interfaces with the friction system.

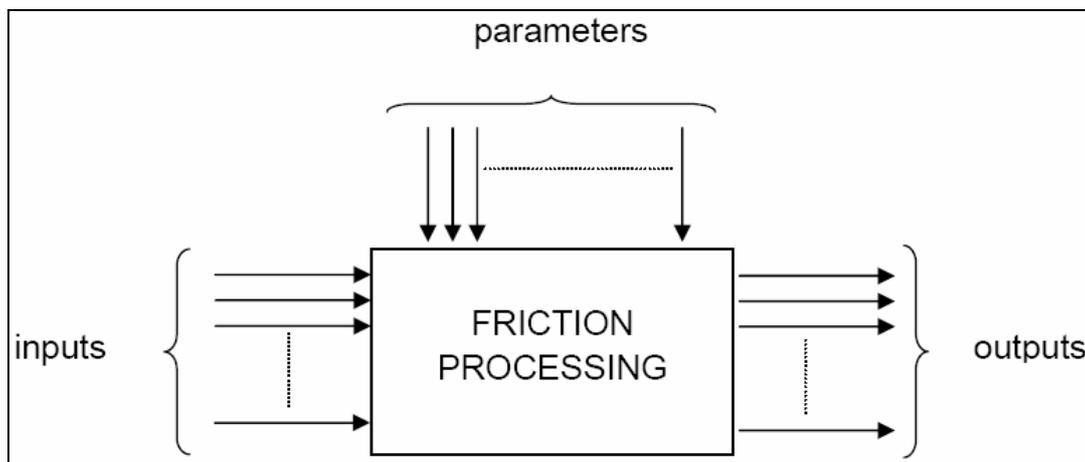


Fig. 7: *FRICTI@N system interfaces*

3.1.1 Inputs

The system inputs are raw sensor data, except data coming from the tire sensors, that needs to be pre-processed by a dedicated ECU, currently an other RPU.

Most input signals will be CAN messages, read from the CAN buses (class 1, 2, 3).

Currently the friction processing RPU provides dedicated input connections for signals that are not available on the FRICTION CAN bus.

The provisional sensor inputs are listed in the following table:

Input sensor signals	Corresponding signal name	Unit	Used by			Remarks
			VFF	EFF	TFF	
steering wheel angle	delta	rad	x	x		
longitudinal acceleration	ax	m.s ⁻²	x		x	
lateral acceleration	ay	m.s ⁻²	x		x	
vertical acceleration	az	m.s ⁻²	x			
pitch rate	pitchRate	rad.s ⁻¹	x			
roll rate	rollRate	rad.s ⁻¹	x			
yaw rate	yawRate	rad.s ⁻¹	x		x	
wheel velocity	vWheelij	m.s ⁻¹	x		x	one for each wheel
brake pressure	pBrakeij	Pa	x		x	one for each wheel
brake signal	brakeSignal	Boolean	x			1 bit
engine torque	MEngine	N.m	x		x	
steering torque	MSteering	N.m	x			
Vertical force	Fz_ij	N			x	ij – see below table
Lateral force	Fy_ij	N			x	ij – see below table
Rotational velocity	vel_tyre_sensor_ij	1/s			x	ij – see below table
Possibility of aquaplaning	aquaplaning_ij	%			x	0% none; 100% full
Tyre estim. Frict. potential	myy_tyre_sensor_ij	-			x	ij – see below table
Air temperature	airTemperature	°C		x		
Road temperature	roadTemperature	°C		x		
Precipitation_density_ALA_SCA	precDensityAl	-		x		
Ground Truth vehicle Velocity_x	vehicleVelocityGroundTruthX	m/s		x		
Ground Truth vehicle Velocity_y	vehicleVelocityGroundTruthY	m/s		x		
Ground Truth vehicle Velocity_x, confidence	vehicleVelocityGroundTruthYConf	%		x		
Ground Truth vehicle Velocity_y, confidence	vehicleVelocityGroundTruthYConf	%		x		
Roadeye sensor	Wavelength1_Intensity	-		x		Data to be processed in EFF
	Wavelength2_Intensity	-		x		
Camera system based on light polarization plane differences	icePolarization	%		x		0: Dry; 1: Icy; 4: Wet; 7: N/A
	icfePolarization_conf			x		Accuracy level * 0: 100 - 80% 1: 80 - 60% 2: 60 - 40% 3: 40 - 20% 4: 20 - 0% 5: not updated ** 6: not valid
Camera system based on light intensity in 1200-1600 nm wavelengths, result and confidence	roadCondNIR	-		x		Optional. 0: Dry; 1: Icy; 2: Snowy; 3: Slushy; 4: Wet; 7: N/A
	roadCondNIR_conf	%		x		confidence
GPS	NMEA standard	-		x		Optional.
vehicle velocity	vVehicle	m.s ⁻¹		x		
Tyre pressure	pTyre	Pa	x		x	

ij ∈ {00=FL, 01=FR, 10=RL, 11=RR} If more complex indexing is needed, use ISO 11992-2 chapter 5.4.2.10.

* Definition tbd.

** The friction value could not be reliably estimated. The output will be the last valid friction value.

Tab. 2: Inputs to friction system

3.1.2 Parameters

The system also needs as input some parameters. These are typically values describing the car geometry, mechanics, wheels etc., and tuneable values for the algorithmic (thresholds, factors...). The following Table 3 shows an example of required parameters for the VFF subsystem.

Some system parameters	Unit
sampling time	s
static wheel radius of front axle	m
static wheel radius of rear axle	m
moment of inertia of the wheels of the front axle	kg.m ⁻²
moment of inertia of the wheels of the rear axle	kg.m ⁻²
distance centre of gravity - front axle	m
distance centre of gravity - rear axle	m
wheel track of the front axle	m
wheel track of the rear axle	m
total mass of the vehicle	kg
height of the centre of gravity in chassis system	m
moment of inertia of the car around its z-axis	kg.m ⁻²
...	

Tab. 3: Some required system parameters

3.1.3 Outputs

The system must deliver the friction values (see Fig. 2) estimated by the algorithm and additional information concerning weather, road and tyre condition. The system outputs are listed in Table 4.

Output type	Signal	Unit	Range		Remarks
			min	max	
estimated friction used	Friction_used	-	0	1.6	
estimated friction available	Friction_avail	-	0	1.6	
predicted upcoming max. friction available	Friction_pred	-	0	1.6	
estimated friction used validity	Friction_used_valid	-	0	6	Accuracy level * 0: 100 - 80% 1: 80 - 60% 2: 60 - 40% 3: 40 - 20% 4: 20 - 0% 5: not updated ** 6: not valid
estimated friction available validity	Friction_avail_valid	-	0	6	Accuracy level * 0: 100 - 80% 1: 80 - 60% 2: 60 - 40% 3: 40 - 20% 4: 20 - 0% 5: not updated ** 6: not valid
estimated friction predicted validity	Friction_pred_valid	-	0	6	Accuracy level * 0: 100 - 80% 1: 80 - 60% 2: 60 - 40% 3: 40 - 20% 4: 20 - 0% 5: not updated ** 6: not valid
time to reach friction predicted	Friction_pred_offset	ms	0	60000	
estimated friction available position	Friction_avail_pos	-	0	3	0: left side; 1: right side 3: overall vehicle
vehicle slip angle	Vehicle_slip	rad	-0.5	0.5	
weather condition	Weather_cond	-	0	7	0: Rain; 1: Snow 2: Fog; 7: N/A
road condition	Road_cond	-	0	7	0: Dry; 1: Icy 2: Snowy; 3: Slushy 4: Wet; 7: N/A
tyre force - vertical	Tyreforce_vert_ij *	N	0	8000	ij – see below table
tyre force - lateral	Tyreforce_lat_ij *	N	-8000	8000	ij – see below table
possibility of aquaplaning	Aquaplaning	-	0	7	Devel. stage of aqpl. * 0: 100 - 80% 1: 80 - 60% 2: 60 - 40% 3: 40 - 20% 4: 20 - 0% 7: N/A
possibility of aquaplaning position	Aquaplaning_pos	-	0	3	0: left side; 1: right side 3: overall vehicle

ij ∈ {00=FL, 01=FR, 10=RL, 11=RR} If more complex indexing is needed, use ISO 11992-2 chapter 5.4.2.10.

* Definition tbd.

**The friction value could not be reliably estimated. The output will be the last valid friction value.

Tab. 4: Current outputs of the FRICTION PROCESSING block

The system has to provide the outputs in a time duration $t < 100\text{ms}$ after an event. This requirement is related to the usage of the friction information at ADAS systems. The FRICTION PROCESSING RPU makes friction information available to the HMI and/or ADAS, on their respective CAN bus (class 1, 2 or 3).

3.1.4 Data Gateway

The data gateway is the common interface for all the input and output signals managed by the FRICTION system.

3.1.4.1 Tasks for Input

- Gathering all sensor signals and providing a common interface to all subsystems which is independent of the platform the system is running on (different demonstrator vehicles)
- Time stamping incoming data
- Pre-processing of input data (plausibilization, offset compensation, filtering) according to the requirements of the friction algorithms VFF, EFF, TFF and Decision Fusion.

3.1.4.2 Tasks for Output

- Converting estimated friction values (common signal definition) according to interface specification of applications on the different demonstrator platforms (platform dependent signal definition)

The data gateway shall also make the system output defined in chapter 2.1.3 available for other applications – both in-vehicle, or cooperative ones.

3.2 Data transmission via buses

The architecture of the demonstrators and experimental vehicles used in the FRICTION Project is conceived in order to allow easy connection of sensors according to flexibility and modularity concepts. Three different classes of network are considered:

1. Vehicle normal production buses (high and low speed CAN)
2. New buses for experimental activities other than FRICTION
3. A dedicated FRICTION bus (high speed)

The overall FRICTION architecture is quite complex for the following reasons

- It is a multi-bus architecture, so there are several buses to specify, model, test, and verify
- Class 1 & 2 information are needed, which may rise confidentiality issues due to the use of normal production vehicle messages
- Class 3 information are needed on at least one Vehicle/Experimental Bus, where the estimated friction value has to be visualized on instrument cluster or other vehicle display. Also the friction information has to be delivered to selected ADAS applications

In order to achieve a more manageable system the RPU is given the additional function of Network Gateway, see Fig. 6. Since the RPU is physically connected to every bus of the vehicle, it is made to acquire messages from Class 1 and Class 2 networks and to replicate selected ones on the FRICTION Bus. In this way the FRICTION Bus will gather the following contents:

- Messages generated by the new devices
- Messages containing Friction information
- Messages containing enable signals for devices connected to the FRICTION Bus
- Messages mirrored from the vehicle CAN Buses

The dedicated Network Gateway allows information exchange among the whole system buses. This solution provides the following advantages:

- A multi-bus complex architecture is converted into a single-bus simple architecture easing specification, modelling and simulation
- Such a solution guarantees no impact on existing demonstrator vehicles configuration
- It allows the non disclosure of proprietary vehicle message maps since vehicles' owners provide a data processing in the network gateway

4 Demonstrator vehicles

The project will demonstrate the performance and applicability of the FRICTI@N system with three different vehicles, each focusing on slightly different aspects. The passenger vehicle demonstrator focuses on minimum FRICTI@N system configuration. Development vehicle will also be utilised in the passenger car demonstrator, to show the additional features of the full FRICTI@N configuration. Commercial vehicle demonstrator has a larger FRICTI@N configuration, and main focus is on co-operative applications in collaboration with EU projects SAFESPOT and CVIS.

4.1 Development vehicle - ika Audi

This vehicle, owned by Institut für Kraftfahrwesen Aachen, has been an important research tool, and also a development environment, where new sensors and workable algorithms are accumulated during the project. The extra instrumentation – see Fig. 8 – is integrated out of sight under the furnishings. The vehicle features are summarised below:

- Audi A6 4.2l, 220kW, passive 4WD
- Air springs at the rear axle to reduce driving behaviour changes caused by load variations
- ABS / ESP brake system
- Hydraulic power steering with variable hydraulic steering torque support (open interface)
- Active steering with variable steering ratio (not utilised by this project)
- Dedicated CAN-bus interface (not vehicle-CAN) available on dSpace Autobox
- Sensors for individual brake pressure at each wheel
- Prepared for easy installation of new sensors

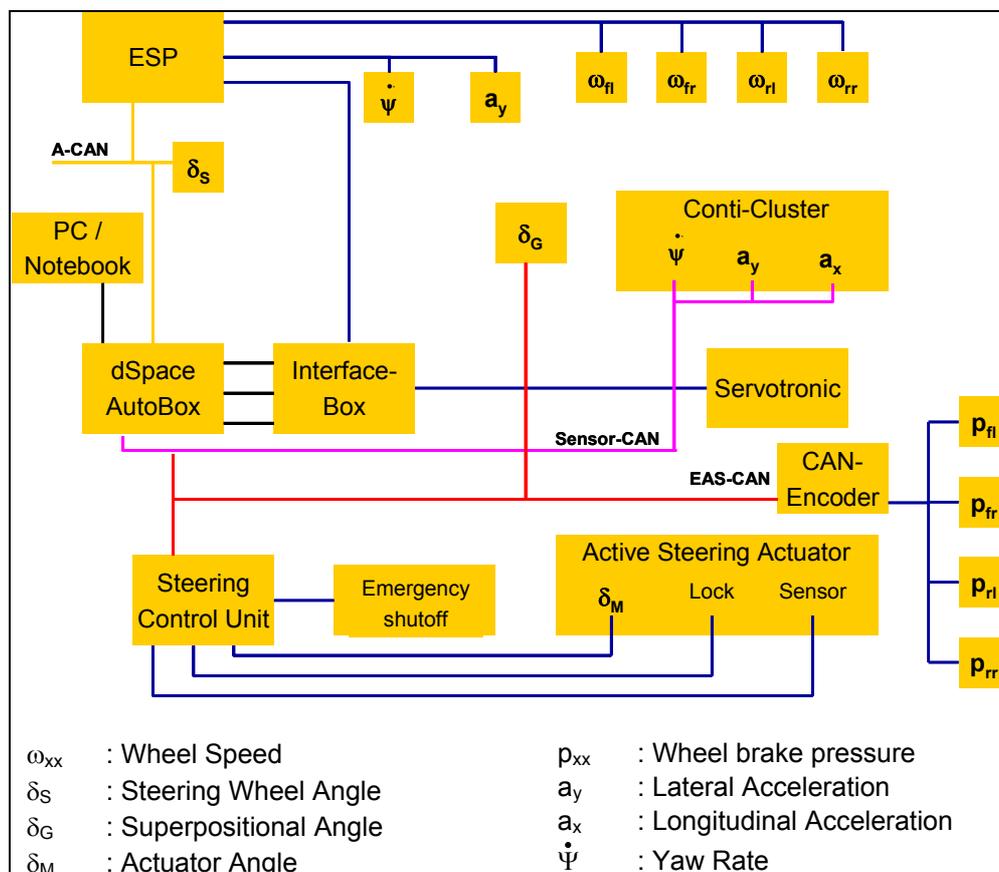


Fig. 8: Instrumentation of the ika Audi. The vehicle is on display at ika proving ground

The car is not allowed to be driven on public roads. Consequently the use for development purposes has to take place on closed proving grounds. To use the car as development platform a validated vehicle simulation model is available in MATLAB / Simulink. By this tool driving manoeuvres can be simulated before real tests are done.



Fig. 9: The ika Audi equipped with extra sensors running a test program in Ivalo, Lapland, Finland

4.2 Passenger vehicle demonstrator - Fiat Stilo

A Fiat Stilo is owned by Centro Ricerche FIAT S.C.p.A, one of the project partners. It will be used as a passenger vehicle demonstrator. The vehicle is equipped with a collision warning and mitigation system developed in the subproject APALACI of a larger PReVENT project. The system prevents low speed accidents involving pedestrians, by monitoring the frontal area close to the vehicle and, more generally, mitigates the severity of unavoidable collisions, by significantly reducing the kinetic impact energy and improving the control of restraint systems to enhance the protection of car passengers.

The success of collision mitigation depends heavily on tyre-road friction coefficient. This way FRICTI@N system can add accuracy and quality to collision mitigation systems, especially under changing conditions.

The Fiat Stilo is equipped with the following conventional sensors:

- Wheel speed (x4)
- Lateral acceleration
- Yaw rate
- Longitudinal acceleration
- Steering wheel angle
- Steering wheel torque (EPS)
- Steering column torque (EPS)

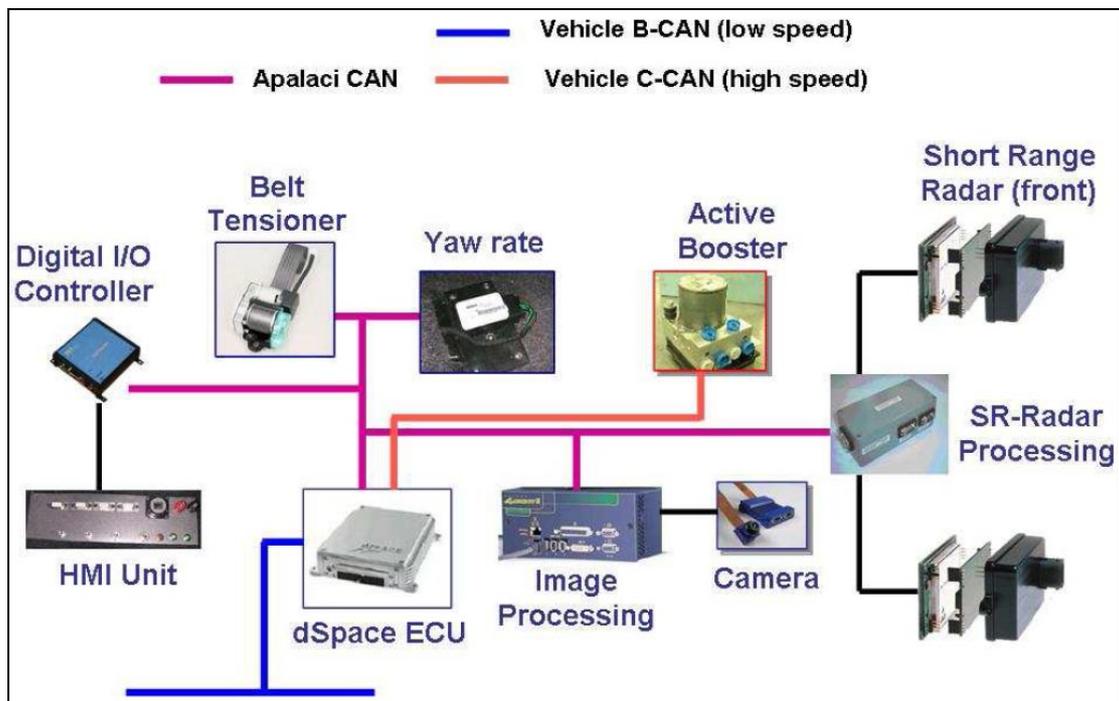


Fig. 10: The instrumentation of the CRF Fiat Stilo

4.3 Commercial vehicle demonstrator - Volvo FH12 truck

A Volvo FH12 is owned by Volvo Technology Corporation, one of the project partners. It will be used as a truck demonstrator. In addition to the conventional sensors, a number of environmental sensors are mounted on the truck:

- 1 long range forward looking radar
- 2 short ranged forward looking radars
- 1 FIR camera
- 1 camera for the blind spot in front of the truck

- 1 camera for the blind spot to the right of the truck
- 1 lane tracker camera
- 1 laser scanner (225 deg FOV)
- 1 RoadEye sensor prototype for road surface classification

From production the truck is equipped with ABS, ESP and ACC systems. It also supports a number of applications developed in different ongoing PREVENT subprojects. These applications are:

- Active Lane Keeping Support
- Collision Mitigation by Braking
- Start Inhibit
- Curve Speed Warning
- Lane Change Assistance
- All Around Warning

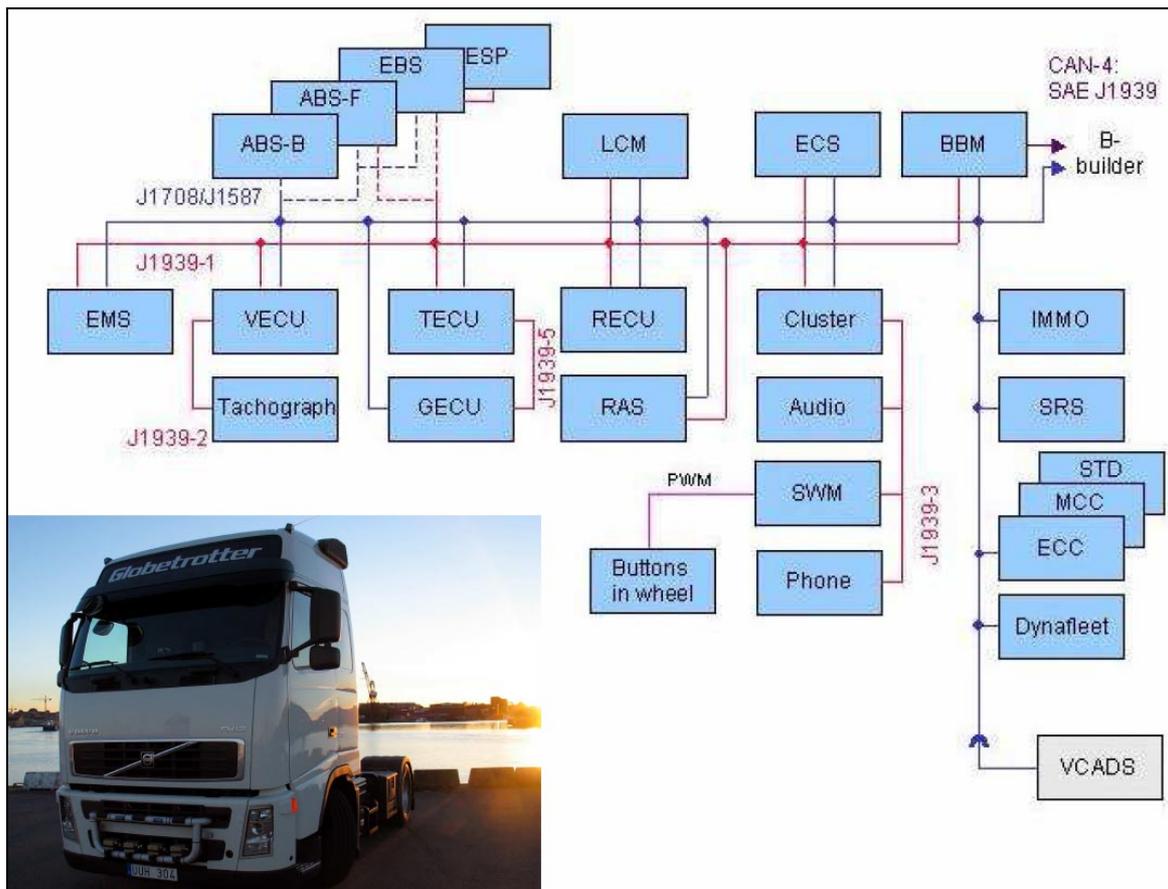


Fig. 11: The control system architecture of the Volvo FH12, and the vehicle itself

Since this vehicle is also used as a demonstrator vehicle in SAFESPOT and CVIS projects, which are developing and demonstrating wireless transmission of driving critical information between vehicles or between vehicle and infrastructure. One studied driving critical information is suddenly decreased road friction.

5 Potential applications benefiting from more accurate friction information

Driver assistance systems use several variables in their calculations of safe margins for driving manoeuvres and when to warn the driver. Some of these variables, especially the behaviour and movement of other road users, the driver's capabilities and alertness, and future tyre-road friction are generally difficult for a computer to measure. This results in systems sometimes calculating safety margins even larger than a human would use or alternatively the safety system would be taking risks.

Drivers are generally good at interpreting actions of other road users, like a pedestrian wanting to cross the road, their own driving performance and also road weather conditions. Computers and sensor systems on the other hand excel at measuring distances, speeds and vehicle state. In some cases the vehicle can correct errors made by the driver. To further improve the benefits and accuracy of ADAS, the unknown variables regarding classification and detection of objects, driver performance and environmental conditions need to be studied and estimated.

There are several projects concentrating on measuring driver alertness, adapting systems to driving history and car-to-car communication for exchanging information of current and future actions. Environmental sensing has received a lot of attention during the last years and results were recently demonstrated in PReVENT project. On-board sensing for friction has also received more interest as the systems are being tested in adverse weather conditions and suitable parameters are being searched.

When considering the performance improvements from a friction estimation system, we have to first estimate the measuring ranges, sample frequencies and driving situations; how and when the measurement works. As no single sensor, ultimate sensor cluster or a "fifth wheel" has been found suitable for continuous and accurate friction measurement, the friction measurement systems will be a trade-off between price, operation ranges and benefits.

As an easy generalization, friction potential (maximum) can be measured with a reasonable accuracy when there is relatively large (around 0.3 G) acceleration or a tyre is slipping [14]. Environmental sensing can give an estimate most of the time, but the confidence intervals can be large. When driving on snow for example, the patches of asphalt and snow are very close to each other. Tyre deformations and sensing has the potential of providing a friction measurement even in straight driving with almost no forces used, but the development status is still early considering products. Aquaplaning and improved measurement of tyre forces, thus the used friction, are the first results from tyre sensors.

The friction used is relatively easy to continuously measure with reasonable error, but most of the time the vehicle doesn't use all friction available, so the friction used is considerably lower than the friction potential. Using environmental sensing and measurements to check if the conditions have changed, some historic information of measured friction can also be used. When friction used reaches maximum, i.e. there is high slip, this information can be used in many ways: broadcasted to other vehicles, used in calibration of tyre parameters and of course as a reliable friction measurement for ADAS.

Friction measurement sample rate and delay of processing information are still to be tested, but some applications like ABS will for surely test the limits. ABS measures the friction frequently by locking the tyre and basically only environmental sensors pointing forward or tyre sensors could improve the performance while braking. For now it seems a bit unlikely that friction measurement systems could considerably improve ABS performance in other way than giving a more accurate initial estimate of friction. On ice this would considerably improve the performance in the beginning of braking as ABS loses time by braking too hard at first.

The potential applications are here divided into slip control, collision mitigation and avoidance, safety margin estimation, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications.

5.1 Slip Control Systems

ABS, TCS and ESC already contain friction estimation algorithms and generally cannot be improved. As explained above, on slippery roads ABS would benefit from a more accurate initial guess for friction value, but only an optimal friction measurement system could considerably improve the performance when braking. There have been calculations for an optimal friction measurement system that show improvements, but generally at this point the initial value is the main application.

TCS similarly could use an initial guess to limit excessive acceleration, especially when switching gears.

For ESC algorithms the weight and friction distribution between tyres could be something to improve by a friction estimation system, giving information e.g. of different friction on left and right side of the car. However these tests are not yet actual when the accuracy of friction measurement system is still being improved. Rather the friction estimation can help preventing dangerous manoeuvres than later correcting them.

5.2 Collision Mitigation and Avoidance

While full collision avoidance awaits considerable improvements in environmental sensing, collision mitigation is technically closer to the market. In PReVENT / PReVAL and eIMPACT projects, considerable safety impacts were estimated (even 10-20 % less fatalities), could this system be introduced. Theoretically collision avoidance avoids all collisions of course, but even mitigation, a decrease of 20 km/h, 0.5 seconds of full braking, greatly reduces collision energy. Collision mitigation is about the reliability of environmental sensing, but friction also plays a big part. In winter conditions, if friction is thought to be 1.0 but is actually 0.2, the vehicle would not be able to slow down much before collision. Braking should start earlier. Due to unreliable environmental sensing, also in the case of future friction measurement, the braking cannot start very early. However, friction measurement would help these systems to reach their full potential also in adverse weather conditions.

5.3 Safety Margin Estimation

Applications such as curve speed warning, safe distance to a vehicle in front and intersection safety where the movements of several vehicles are estimated, are examples where friction estimation would improve the accuracy of calculations.

Curve speed warning requires camera systems and accurate maps so that the steepness of the curve can be estimated. This is difficult, as is road weather sensing to a distance of tens of meters. The vehicle trajectory can change a lot in this time and vehicle may move from asphalt to snow. However it's likely that considerable speeding can be detected and at least the driver warned. Friction measurement in the calculations would rather be a historical value than a true measurement 50 meters forward. Cooperative applications could naturally bring more range.

Safe distance to a vehicle in front is a more clear case for utilising friction. V2V applications may support the calculation by broadcasting the friction measured by other vehicles and environmental sensing can better reach the distances required. The information would be guideline for the driver so occasional errors in friction estimation wouldn't matter.

In intersection safety and generally in traffic, the movement of other vehicles and the capabilities of ego vehicle to accelerate or brake, require friction estimation. With high friction, the acceleration can be large and the location of objects can change quickly. The location of other road users is something that will be calculated quite conservatively, ensuring that collisions won't happen. The bigger benefit from friction estimation is being able to estimate, whether ego vehicle can perform manoeuvres such as crossing an intersection safely or joining traffic when there's a small gap. Basically a warning would be active if the vehicle cannot calculate a collision-free path. This is a matter of further study, mainly carried out by Intersafe and Intersafe2 EU projects. Partly intersection applications, like many safety margin applications optionally belong to V2V applications category.

5.4 V2V

Vehicle-to-vehicle applications are often improved versions of normal applications, where e.g. safety margin calculation is improved with information from other vehicles. Friction estimation here serves as extra information that can be broadcasted. The main problem is being able to transmit information in a form that can be used, as tyre-road friction is different for each tyre and trajectory. Generally only road weather information, rough classification into some 5 levels and warnings of dangerous spots can be broadcasted. But improving this information is being studied: environmental information can be mapped to tyre-road friction history under similar conditions.

The main applications could be classified into:

5.4.1 Safety Margin

Using a cooperative systems approach it will be possible to calculate and suggest a safety margin to the driver. The dynamic capabilities of the vehicle, road conditions, driver status and a dynamic map including other road users will be used in the calculation. The safety margin calculation can be used in enhanced ACC, emergency braking systems, intersection safety and curve speed warning.

5.4.2 Local Danger Warning

Local warnings are sent to other vehicles in case of a danger, e.g. accident, breakdown, stop in a dangerous place, fire or bad road weather conditions. Warning of a slippery road segment should include environmental measurements, measured friction, coordinates, road segment ID and time. The information could be shown on a navigator screen for example.

5.4.3 Visibility Enhancer and Information Quality

To improve the range, quality and reliability of road weather information in other vehicles and their applications.

5.5 V2I

Vehicle-to-infrastructure applications are a clear example of using friction measurement systems as part of probe vehicle concepts. The main purpose is to collect information of dangerous locations and statistical friction information to be processed further. The main applications could be divided into:

5.5.1 Real time weather information

Vehicle systems will collect and transmit real time weather information to all road users and to road operators' and public authorities' traffic information servers. The information can be used by vehicle safety applications in the receiving vehicle.

5.5.2 Long distance road weather information

Potential methods to present statistical road information to driver

5.5.3 Warnings and road departure prevention in a black spot

Coordinates and classification of a black spot that caused problems

5.5.4 Curve speed warning based on statistical friction information

The curve speed warning application aids the driver in choosing appropriate speed using information from roadside units located ahead. On-board information is used to determine if the driver needs to be alerted.

6 Considerations for future work

VFF can easily be seen as a continuation for friction sensing approach dating back to ABS, ESC etc. When ABS and ESC could really detect the friction after some sliding took place, VFF can estimate friction already when the vehicle is under medium level acceleration. (hefty lateral acceleration component is preferred, since currently it seems to provide more accurate results) We believe that future VFF development should focus on more accurate friction estimation when acceleration is in the range of 0.1g utilising sensors in chassis, power transmission, suspension or steering. Theoretically it would be nice to be able to estimate friction when driving straight at constant speed, but this may be too challenging in the foreseeable future.

EFF will gain more importance, since the number of various environment perception sensors will increase; ACC, EBS, lane departure warnings, etc. These sensors can detect road surface conditions in various ways, thus providing input for EFF. Important benefit is also that information is provided BEFORE the vehicle is on the measured location, so the chassis control system and driver have somewhat more time to react to the hazards. Also the vehicle may be driving straight with constant

velocity. The drawback is that these sensors can only classify what the surface is – the real friction value depends on several other things, many of which are difficult to measure. For instance an icy surface may have a friction coefficient between about 0.2...0.4 depending on surface temperature (measurable), whether the surface is well polished (more difficult to measure), and some other things even more difficult to measure. We believe that future research should focus on more accurate friction estimation utilising a combination of sensors (when available), and more versatile surface classification including also wet leaves, loose gravel, etc.

TFF is theoretically fed with the best possible information, since we believe the best location for tyre-road friction measurement is in the tyre, especially near - or in - the tread block. However, it is technically a very challenging environment: At speeds over 200km/h the acceleration of the tyre inner liner may exceed 2000g when it touches the road. Also the wireless sensor signal transmission from the tyre to the chassis has to be widely standardised and accepted in order to enable any tyre to be placed under any vehicle. And most of all, friction available and friction potential cannot be measured directly, and we do not know yet what is the physical quantity that proves out to be the best information source for this estimation. The sensor construction used in this project is a research instrument and not suitable for serial production. It measures the relative motion between one point in the inner liner and rim [13]. We believe that long term future research should focus on better understanding of tyre-road interaction, and measurable physical quantities in the tyre that provide best information for friction estimation. This research should go hand in hand with improved tyre simulation models.

7 Conclusion

This paper has described the current results of the ongoing *FRICTI@N* project. Road friction is an important parameter in vehicle control affecting how much steering, braking and acceleration can be done with the vehicle. However, on-line friction estimation is also a difficult task to be successfully done in all driving situations and weather conditions. Nevertheless, if this information would be available continuously for all vehicle applications, vehicle safety would be clearly improved in many ways, see Fig. 12 below.

Of vehicle on-board applications the main benefiting application group is probably Active Safety, because ESP etc. algorithms are more accurate when friction available is better known. Application group called ADAS will benefit also from more accurate friction information, especially of road conditions ahead of the vehicle (EFF). Also Advanced Protective Safety –application group will benefit thanks to e.g. more accurate time-to-crash estimation.

Co-operative IVIS and ADAS applications will also benefit from the project results, since the better individual vehicles ‘probe’ the road friction, the easier it is to make

important friction information available for other vehicles. One clear benefit of the project is, that friction potential is estimated even if the vehicle is driving straight without sliding, thus providing more information of this important road parameter to co-operative systems.

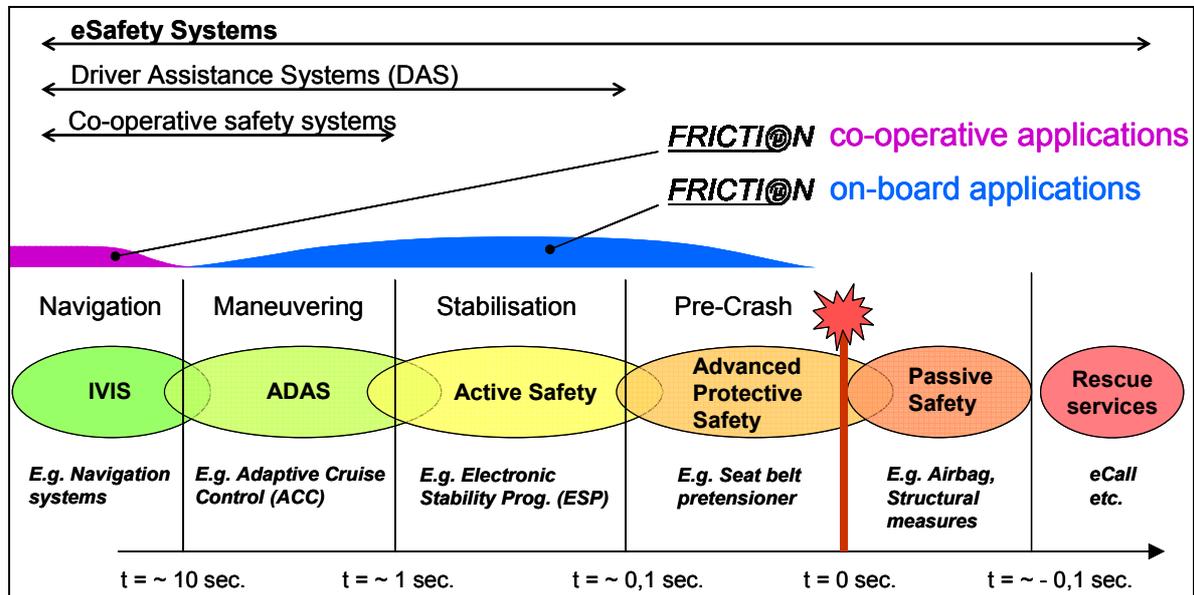


Fig. 12: Application areas, which benefit from friction information

8 Acknowledgement

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9 Definitions, Acronyms, Abbreviations

ABS	Antilock Braking System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
CAN	Controller Area Network
CAS	Collision Avoidance System
DAS	Driver Assistance System
EBS	Emergency Braking System

ECU	Electronic Control Unit
EFF	Environmental Feature Fusion, part of the FRICTION algorithm
EPS	Electric Power Steering
ESC	Electronic Stability Control (almost a synonym to ESP)
ESP	Electronic Stability Program (almost a synonym to ESC)
FOV	Field Of View
HMI	Human Machine Interface
IVDC	Integrated Vehicle Dynamics Control
IVIS	In-Vehicle Information Systems
MATLAB	A commercial general purpose mathematical software package
PREVENT	Integrated Project for preventive safety applications
RPU	Rapid Prototyping Unit
SAFESPOT	Integrated Project for co-operative driving applications
Simulink	An optional simulation tool package for MATLAB
TCS	Traction Control System
TFF	Tyre Feature Fusion, part of the FRICTION PROCESSING algorithm
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VDC	Vehicle Driving Control
VFF	Vehicle Feature Fusion, part of the FRICTION PROCESSING algorithm

10 References

- [1] <http://friction.vtt.fi/index.html>
- [2] MÄKINEN, T & et al.
APOLLO Final Report including Technical Implementation Plan
Deliverable 22/23 for the European Commission
Tampere, Finland, 2005

- [3] HAAS, T., KÖHLER, M., KOSKINEN, S., JOKELA, M., KUTILA, M., PESCE, M., HARTWEG, C., CASSELGREN, J., BIAN, N., GAMULESCU, C.
Fusion fahrzeugbasierter Fahrdynamik- und Umgebungssensorik
17. Aachener Kolloquium Fahrzeug- und Motorentechnik 2008
- [4] TUONONEN, A. J.
Optical position detection to measure tyre carcass deflections
Vehicle System Dynamics, 46:6, 471 — 481,
Taylor & Francis 2008
- [5] Information Society Technologies (IST) Programme
FICTION, Deliverable D4
User needs, application scenarios and system requirements
Brussels, 2006
- [6] GNADLER, W.; MARWITZ, H.
Ermittlung des Kraftschlusspotenzials im Fahrbetrieb;
ATZ, 5/2004, Jahrgang 106
- [7] MAO, Y.
Zustandsschätzung bei der Integration verschiedener Fahrzeugregelsysteme
Ford Forschungszentrum Aachen
VDI-Berichte Nr. 1931, 2006
- [8] STROTHJOHANN, T.
Reibwerterkennung mit dem Darmstädter Reifensensor
4. Darmstädter Reifenkolloquium, VDI Fortschritt-Bericht Reihe 12 Nr. 511
VDI Verlag GmbH, Düsseldorf, 2002
- [9] Verfahren zur Ermittlung des Reibwertes zwischen der Fahrbahn und den
Reifen eines Fahrzeuges
Patentschrift DE 39 12 014 C2,
Bayerische Motorenwerke AG, 1998
- [10] UMENO, T.
Estimation of Tyre-Road Friction by Tyre Rotational Vibration Model
R&D Reviews of Toyota CRDL
Vol. 37, No.3 2003.
- [11] HOLTSCULZE, J.; GOERTZ, H.; WUNDERLICH, H.; MÄCKLE, G.;
VARPULA, T.; MANCOSU, F.
Der Reifen – Informationsquelle zur Fahrerassistenz, 13. Aachener Kolloquium
Fahrzeug- und Motorentechnik 2004, Band 1, S. 559 - 580
- [12] The Apollo Consortium.
Dynamic Tyre Behaviour with Respect to Sensor Technologies, Deliverable D9.
European Commission, Information Society Directorate-General, 2003.

- [13] TUONONEN, A., HARTWEG, C., NORD, S., LIUKKULA, M., RAUTIAINEN, A., NEPOTE, A., MANCOSU, F., HÜSEMANN, T., SAINIO, P.
Reifensensorik zur Reibwertschätzung
17. Aachener Kolloquium Fahrzeug- und Motorentechnik 2008
- [14] ANDERSSON, M., BRUZELIUS, F., CASSELGREN, J., GÄFVERT, M., HJORT, M., HULTÉN, J., HÅBRING, F., KLOMP, M., OLSSON, G., SJÖDAHL, M., SVENDENIUS, J., WOXNERYD, S., WÄLIVAARA, B.
Results "Road Friction Estimation"
IVSS Project Report, 2007

