### DELIVERABLE SUMMARY SHEET

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#### Short Description:

The goal of APOLLO project was to create an intelligent tyre for improving road traffic safety. The objectives were: 1) to provide vehicle and tyre manufactures with new products to increase traffic safety 2) to enable improvements for chassis control systems and ADAS 3) to enable the implementation of new services concerning tyre and road conditions for users both inside and outside the vehicle.

The project started with state of the art analysis, sensor feasibility studies followed by definition of requirements, specifications and a system architecture. All this was highlighted by defining a reference application for the development work. The discussion of potential applications and the ranking of relevant information narrowed down the reference application for the APOLLO project to a few key parameters. The functional requirements are to provide a set of data on (i) vertical wheel force or dynamic wheel load and (ii) relative friction available for the application system. Utilising this information the performance of many applications, e.g. roll over avoidance, ABS, ESP, ACC, can be improved and additional functions can be achieved for driver information and services for external users. After the definition of the reference application, the actual R&D work was split into four blocks of activities: (i) Understanding tyre-vehicle system behaviour (ii) Sub-system development comprising of sensors, power supply and a communication interface (iii) System integration i.e. creating a mechatronic tyre and integrating it into the test vehicle and (iv) Validation to verify sub-systems and the whole Intelligent tyre concept including the final demonstration.

When assessing how the objectives of the project were met, it was stressed that this is the first attempt of this kind ever made. Tyre sensor and other development work on monitoring road surface properties have been carried out but never before a whole mechatronic tyre system with all components included has been designed and prototyped. Moreover, compared to other developments in the area with much narrower scope, the project proceeded in the sensor system development in three years time further than comparable 'advanced' tyre sensors in a considerably longer period of time. The project met most of the objectives set in the Technical Annex. However, the most ambitious and difficult parameter to obtain, available friction could not be determined by using the approaches developed.
Partners owning: The APOLLO consortium

Partners contributed: VTT, DC AG, HUT, RWTH Aachen, MM, NR, PIRELLI

Made available to: European Commission, Information Society and Media Directorate-General
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Project overview

1.1 Objectives and rationale

The overall objectives of APOLLO-project were 1) to increase road traffic safety by means of an intelligent tyre system 2) to enable improvements for vehicle control systems, Advanced Driver Assistance systems and chassis control systems, 3) to enable the introduction of innovative services concerning tyre and road conditions for different user groups both inside and outside the vehicle. This was realised by developing and demonstrating a prototype of an intelligent tyre.

Today, potential applications and systems that could benefit from more precise information on road slipperiness and tyre-road contact are control systems for driving dynamics and driving safety are numerous such as Slip Control Systems, Emergency Braking System (EBS), Electronic Stability Programme (ESP), Adaptive Cruise Control (ACC) to name a few. Vehicle safety systems on the market using information on road conditions - even indirectly, are still few. These are Slip Control Systems (e.g. ABS) and Electronic Stability Programme (ESP). Current Advanced Driver Assistance Systems contain/provide no information on a safe driving speed. If the speed is too high, the vehicle cannot be controlled even with the help of advanced systems such as ESP, since information on the friction available could not have been utilised.

Furthermore, Tyre Pressure Monitoring Systems (TPMS) standard was passed in 2002 in USA. It requires an installation of a TPMS to warn the driver if the tyre is significantly under-inflated. This legislation is a also strong driver for the overall development of advanced tyre technologies.

1.2 Approach

The project started with state of the art analysis, sensor feasibility studies followed by definition of requirements, specifications and a system architecture. All this was highlighted by defining a reference application for the development work. The discussion of potential applications and the ranking of relevant information narrowed down the reference application for the APOLLO project to a few key parameters. The overall functional requirements are to provide a data of data on:

- vertical wheel force or dynamic wheel load and
- relative friction available (given in percentage of maximum friction available)

for the application system. Utilising this information the performance of many applications, e.g. roll over avoidance, ABS, ESP, ACC, can be improved and additional functions can be achieved for driver information and services for external users.

After the definition of the reference application, the actual R&D work was split into four blocks of activities:

1. Understanding tyre-vehicle system behaviour,
2. Sub-system development,
3. System integration i.e. creating a mechatronic tyre and integrating it into the test vehicle and
4. Validation to verify sub-systems and the whole Intelligent tyre concept including the final demonstration.
1.2.1 Understanding the tyre-vehicle system behaviour

Tyre-vehicle system behaviour investigations concentrated on three different activities aimed at the creation of potential evaluation strategies to obtain information from a rolling tyre, finding the right sensor position inside the tyre and understanding signals the system provides. These investigations focussed on:

1. Tyre mechanics,
2. Tyre simulations and

Tyre mechanics-part of the work dealt with three categories to obtain information from a rolling tyre: (i) evaluation of global tyre mechanisms, (ii) local deformation analysis and (iii) possibilities, which are not directly related to either of the above mentioned categories such the evaluation of secondary information such as tyre noise.

The objectives of simulations were to draw up guidelines for finding the right sensor type and position inside the tyre. Moreover, an important goal was to improve the comprehension of acceleration correlation with the dynamic mechanical behaviour of a tyre under different operating conditions such as speed, vertical load, camber angle and slip angle.

To increase understanding of global tyre deformations, signal interpretation activities were intensified by constructing a new mechatronic tyre with three sensor integrated into the tyre: an acceleration sensor, a piezo-electric sensor and an optical sensor. This so called 3to1-tyre was to provide more information about tyre behaviour than an acceleration sensor approach only. However, by the original plan, work was continued by using ‘an acceleration sensor only tyre’.

The project focussed only on sensors in the tyre. No sensors were mounted on the chassis or other similar sources. The consortium was of the opinion that acquiring data from the chassis would have provided additional information, but considering the main component of the project - tyre - this was not done. The project wanted especially to explore the limits of the tyre-based data.

1.2.2 Sub-system development

The sub-system development comprised of investigations and design of a:

1. Batteryless power supply,
2. Communication interface and

As result of a pre-study on power supply technologies, the research was focused on two technologies (i) Inductive power transfer and (ii) Piezoelectric energy harvesting/generation. The batteryless technologies were compared and recommendations were made for further development. One patent has been applied for the energy harvesting solution and another one for the inductive power generation concept.

In the development of a communication interface, the need of flexibility concerned both communication and power supply aspects that are closely intertwined. Consequently, the splitting of communication interface and power supply development was the only way to guarantee demonstrator’s usefulness and availability as a flexible platform able to help in the definition of the final solution. Communication electronics was powered by a rechargeable battery in order to avoid obstacles and delays caused by power supply development. Substrates, wires, connections and packaging were designed in order to guarantee functionality and sufficient robustness. In the course of
the project, three versions of the communication system were developed in order to manage different
sensor system configurations.

Sensor development was split into two parts after two first years: the work was continued with an
acceleration sensor due its high robustness and potential for harsh tyre conditions. The second
approach - as explained earlier - consisted of a creation of 3to1 tyre with three different sensors in
order to better understand tyre global deformations. Accordingly, the sensor development had a more
product development oriented part and a scientific part.

1.2.3 System integration

Two mechatronic tyre prototypes were created: one for the acceleration sensor and the other one for
the three sensors. Since the relatively large amount of electronics and the sensor(s) made the
mounting of electronics difficult, custom-made dividable rims were acquired for the project to speed
up the integration process. All sensors were attached on the inner liner in order to guarantee the
integrity of the tyre and also, to provide meaningful signals.

The system functionality of mechatronic tyre was verified by appropriate tests in order to ensure the
sensor durability, signal transmission and an optimal position of the antennas.

The mechatronic tyre prototype with all the sub-systems was integrated into the test vehicle,
Mercedes Benz 500 S.

1.2.4 Validation

The project validation comprised of sub-systems verifications, verification of the mechatronic tyre.
All these verification tests were carried out in the laboratory and out-door conditions. Moreover,
validation includes also the final demonstration to be held at the Nokian Tyres plc's test track in the
town of Nokia.

The purpose of the validation is to show how the development has succeeded and the achievements of
the project.

The data obtained from the mechatronic tyre tests were post-processed by means of a dedicated signal
interpretation strategy. Each sensor of the mechatronic tyre (acceleration sensor, optical sensor and
strain sensor) was analysed to assess its performance in providing signals from the running tyre. The
potential to identify wheel load, lateral force and longitudinal force was analysed separately for each
sensor. Algorithms to calculate the desired measure would be derived in case the sensor did provide
useful signals. The potential of the three sensors turned out to be different when considered to be
used alone in the tyre.

The analysis of the 3to1 tyre did result in a clear ranking of the potential to identify wheel forces.
While the optical sensor was able to identify all wheel forces at the considered boundary conditions,
the accelerometer did show the lowest potential, but still showed the roughness of the road surface
and was able to differentiate between bare asphalt and a snow-covered surface indicating that
tangential deflection signal was different on high and low friction surfaces. Therefore, it might be
used later with supporting information for the evaluation of the friction coefficient.

Concerning the project objectives, it can be summarised that most of the objectives were met.
Priorisation in the project was given to forces, friction potential and slip angle. The sensor system is
capable of measuring forces exerted on tyre, slip and road surface qualities. Friction potential can not
be derived by the method developed in the project.
1.3 Users and scenarios

The main scenarios of intelligent tyre technologies include applications and systems that could further benefit from more precise information on road slipperiness and tyre-road contact, are control systems for driving dynamics and driving safety such as Slip Control Systems, Antilock Braking System (ABS), Emergency Braking System (EBS) and Electronic Stability Program (ESP).

In addition to vehicle control systems, another important scenario include providing information for co-operative driving and driver information more broadly. The APOLLO project took part in the project called "Mobile road conditions monitoring - state of the art and future" by Finnish Road Administration (Finnra). Since the current road conditions monitoring system is based on fixed road side weather monitoring stations, it was seen necessary to complement the system by information collected along the main road network based on a kind of Floating Car Data (FCD). One of the main conclusions of that activity was that here is a strong interest on the infrastructure owner side, especially in Nordic countries to use technologies that provide information on adverse road conditions rather along the whole network than on cross-sectional fixed sites only.

User needs were charted by means of two Internet surveys. The results showed that the respondents regarded tyre pressure and tyre damage monitoring as having the greatest safety potential. Also aquaplaning threshold, friction, friction potential and tyre wear monitoring were considered fairly important. Information on tyre wear was regarded as having relatively low importance. Overall, intelligent tyre systems were found important and having a clear safety potential.
2 Project objectives

2.1 Vision

The vision of partners is accident-free traffic, where information on tyres and tyre-road contact has a recognised contributory role to vehicle control systems, Advanced Driver Assistance Systems (ADAS) and traffic services.

2.2 Objectives

The overall objectives of the APOLLO-project are 1) to increase road traffic safety by means of an intelligent tyre system 2) to enable improvements for vehicle control systems, ADAS and chassis control systems, 3) to enable the introduction of innovative services concerning tyre and road conditions for different user groups both inside and outside the vehicle (see Technical Annex).

"Intelligence" implies here that the future tyre will not be a passive rubber compound on a vehicle but an active and essential part of vehicle's control systems that contribute to both driving comfort and safety. The intelligent tyre provides additional data for control systems inside the vehicle or external systems. Therefore, APOLLO-project aims at making these data available at a communication interface on the vehicle. Using these data for the development of new control and monitoring systems will be a task of further activities, which are not a part of this project.

The three main research and technology objectives for the project are as follows:

1. Introducing innovative sensors for monitoring tyre condition, road condition and tyre-road interaction.

2. Developing novel solutions for a wireless communication interface and a batteryless power supply enabling intelligent tyre systems.

3. Creating an 'intelligent' tyre: integrating all electronic components into the tyre by means of mechatronic design, taking into account processes of manufacturing, handling and maintenance.

The potential user benefits are (i) improved performance of vehicle control systems, Advanced Driver Assistance Systems and Chassis control systems, (ii) driver information on tyres and driving conditions and (iii) information provided for various user groups such as infrastructure maintenance operators, tyre suppliers, vehicle fleet operators and other service providers.

The overall- and R&D-objectives of APOLLO as a safety-oriented project are achieved by means of the following activities:

- Investigating the needs and expectations of various user groups concerning an intelligent tyre.
- Showing the added value the intelligent tyre can provide for driving safety and comfort as well as providing with other services for different user groups also outside the vehicle.
- Defining a reference application for the intelligent tyre prototype in APOLLO-project.
- Developing a novel sensor system mechanically integrated into the tyre such as capacitive sensors for sensing the following signals or parameters: forces exerted on the tyre, slip, friction potential, tread wear and prediction of tyre damage, road surface qualities.
- Developing a new type of a wireless communication interface between tyre and vehicle.
- Developing a novel power supply technique without a battery.
- Developing an intelligent tyre/wheel prototype with integration of sensor system, communication interface and a power supply.
- Integrating the intelligent tyre/wheel prototype into a vehicle and verifying in real driving conditions that the signals from the tyre are available for vehicle systems as specified.
- Disseminating the results of the work throughout the project life-span and linking the project to other ADAS-projects including a RESPONSE-project addressing the legal issues of ADAS-products (using the results).
- Preparing the way and drawing up a road map for the exploitation of intelligent tyre systems.

The outcome of the project is a novel and innovative prototype of an intelligent tyre. The mechatronic tyre/wheel system consists of a tyre, an integrated sensor system, a wireless communication interface and a batteryless power supply.

The measurable goal of the project is to verify and show that an intelligent tyre system integrated in a vehicle is functional in real driving conditions so that the data produced by the intelligent tyre system are available for various purposes described above. For the assessment and evaluation of the prototype system the sensor data will be sent to a test system for data monitoring inside the vehicle.

As a result of project’s activity, by the end of the project, all major vehicle, electronic and tyre manufacturers in Europe are aware of both the business and safety potential intelligent tyre systems provide. Moreover, drivers as well as infrastructure owners and other users of tyre-based information know the possibilities the intelligent tyre system have in the areas of traffic safety, logistics and other traffic related services.

In this way, the APOLLO-project aims at supporting the general EU Objective to decrease road fatalities by 40% within 2010 expressed in the White Paper by introducing an innovating approach focussing on preventive safety rather than active and passive safety solutions.

### 3 Approach

#### 3.1 Project rationale

##### 3.1.1 Safety

Today, the wish and determination for considerably fewer accidents have been pronounced by a number of European stakeholders. European Union launched the eSafety Programme in 2002. eSafety is a joint initiative of the European Commission (DG Enterprise and DG Information Society and Media), industry and other stakeholders. This safety initiative aims at accelerating the development, deployment and use of Intelligent Integrated Safety Systems, that exploit information and communication technologies in intelligent solutions, in order to increase road safety. Moreover, EU has launched a programme Halving the number of road accident victims in the European Union by 2010 : A shared responsibility.

This communication was announced in the White Paper on European transport policy approved by the Commission on 12 September 2001. Essentially, this programme sets out, with the requisite level of detail, specific measures in accordance with what the Commission has already endorsed, and reaffirms the overall of halving the number of road accident victims by 2010.
In parallel, there are currently running national and industry-based R&D programmes for better road safety. A brief introduction of selected programmes gives a good overall idea of the commitment that has arisen in the recent years to promote safety.

The high potential of accident prevention by using an intelligent tyre/wheel system can be clearly seen through this accident analysis. It has been shown, that adverse road conditions, tyre defects or their combination play an important role in road accidents.

Very often, adverse conditions have been a contributing factor to the birth of an accident. For this reason, systems informing drivers of risk factors such as aquaplaning, road sections with invisible "black" ice or reduced friction, can be seen as having great safety potential. Also systems for longitudinal and stability control may have a greater impact when receiving either real time or early information on so called hot spots that drivers would not otherwise respond to early enough.

Today, no representative European wide statistical data is available on road traffic accidents showing the proportion of accidents having adverse road conditions as a main cause or a contributory factor. The following sporadic statistical figures and calculation examples, however, show convincingly how great the impact of road conditions - not adapted to - in accidents is today. A look at available restricted accidents statistics suggest, where friction/slipperiness information supporting ADAS would be most successful: 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 (www.vtt.fi/rte/projects/yki6/safestar/safestar.htm) some 40 % of accidents occur under bad road conditions (Figure 1).

![Figure 1. Causative factors in severe road accidents.](image)

Road condition is the most significant single parameter causing a loss of driving control. For example, in Germany 55 % of accidents with personal injury are caused by slippery roads. Providing information on adverse road conditions with the vehicle applications, drivers and other road users have a high potential in mitigating the consequences of accidents and preventing them from happening. With this information, drivers have the opportunity to adapt their speed and driving behaviour to the prevailing conditions. Furthermore, existing active safety systems such as ABS and ESP are able to work much more effectively, if current road conditions can be used as a parameter in control algorithms. This information is missing today, and deriving the information from tyre-road contact patch is one of the objectives in the APOLLO project.

Tyre-related risk factors were recorded in 16 % of all fatal accidents in Finland during the period of 1991 - 2001. In two out of three tyre-related accidents either worn-out tyres or tyres unfit for road conditions were a major contributory factor. Under-inflated tyres were a risk factor in 12 % of tyre related accidents. Defective tyres have a significant role in fatal accidents especially in adverse road conditions. According to the federal statistical office in Germany, defective tyres cause about 30 % of all accidents, which are due to technical faults. These figures show, that monitoring tyre condition and
detecting tyre defects are important objectives with respect to accident prevention. There is a clear need for monitoring not only tyre pressure, but also tyre wear and damage.

### 3.1.2 User needs

User needs were investigated by means of two web-based surveys (see Deliverable D6: Needs of various user groups, the interview method and -results). The respondents believe that tyre pressure and tyre damage monitoring have the greatest influence on traffic safety. Also aquaplaning threshold, friction, friction potential and tyre wear monitoring were considered fairly important. Tyre wearing importance was found relatively low. Systems such as tyre telematics, tyre and safety related Internet services for consumer and tyre mileage monitoring were seen less beneficial for the traffic safety.

Experts were sceptical about providing third parties with tyre-based information. Vehicle maintenance seemed to be the most potential third party. Road maintenance, traffic management, other vehicles on the same road section and tyre/car manufacturers and dealers were regarded as equally insignificant.

On average, experts had slightly negative opinions on the confidentiality of tyre-based information and recording that data. However, respondents were willing to use tyre-based data for accident reconstruction purposes. The respondents were in favour of standardization of both sensor and vehicle output. It was regarded as clearly unacceptable that only selected tyre brands could be used together with intelligent tyre system. Making intelligent tyre systems mandatory for some vehicle types (e.g. in dangerous goods transportation vehicles) was accepted. It was considered that intelligent tyre systems would have a great influence on traffic safety especially when installed into Heavy Goods Vehicles (HGV) and busses.

The possibility of negative side-effects such as drivers ignoring the warnings, information overload could not been clearly seen from the answers.

Tyre damage monitoring seems to have very solid support from the respondents. Estimation of usability of tyre-based information for entertainment was ranked very low.

The main obstacle seems to be the costs of the system. Drivers’ attitudes towards the use of intelligent tyre technologies were found to be the least significant obstacle.

Tyre and vehicle industry were regarded as the best promoters for the system. Fleet operators as well as legislative bodies were not found good promoters. Overall, intelligent tyre systems were regarded as important and having a clear safety potential.

### 3.1.3 Scenarios of use

During the past 20 years we have seen substantial development both in active and passive safety systems of vehicles. Furthermore, a number of innovations and technological solutions are just round the corner still invisible to a man in the street.

Driver support systems such as Advanced Driver Assistance Systems (ADAS) will continue to evolve to support cooperative driving in the end. Consequently, ADAS should be more than to serve as information or comfort systems only. Furthermore, these systems need to be complemented by assistive functions aiming at correcting driver behaviour in case the driver is not willing or capable of using safety relevant information. Most of ADAS applications under development have been targeted to adaptive functions. Knowing drivers’ tendency to behave not by optimising safety but rather guided by other non-safety relevant motives, there is still a great potential for driver support systems. One of
the first accident studies on the impacts of active safety systems, that is to say Electronic Stability Programme (ESP) was published by DC AG, and the results support this assumption (Figure 2). After that, several other studies of the beneficial safety effects of ESP have been published by other car manufacturers and independent research institutes. The figures vary depending on the study, method and parameters used from 30% accident risk reduction up to 67% (Bosch, 2005).

In principle, drivers have available various sources of information on adverse driving conditions with low available friction included. Furthermore, a great mystery is why the driver does not use effectively his/her senses while driving. Numerous accidents on slippery roads testify the need of system sensing road surface properties. During an emergency breaking, a rough estimation of friction is made by means of ABS and ESP, but when travelling at higher speeds, this information is too late when considering the optimal intervention of active safety systems.

The main bottle neck of all ADAS- other driver support systems has been the lack of the friction information under the vehicle and rather, the estimation of friction ahead of the vehicle. When this information is delivered to the vehicle control systems, the possibilities and performance of ADAS systems will accelerate. The tyre with road surface measuring capabilities has the key role in breaking though this bottle neck.

Potential applications and systems that can considerably further benefit from more precise information on road slipperiness and tyre-road contact are control systems for driving dynamics and driving safety listed below:

- Slip Control Systems,
  - Antilock Braking System (ABS)
  - Traction Control System (TCS or Anti-Slip Control)
- Emergency Braking System (EBS),
- Electronic Stability Programme (ESP),
- Adaptive Cruise Control (ACC),
- Roll over avoidance and

Figure 2. Percentage of loss of control accidents with and without ESP.
Vehicle to vehicle communication / Driver Information Systems, DIS (not actually on the market yet).

Actions and initiatives to improve safety will be targeted to all areas of human life. Today, there can be seen a number of players sharing the same target of improving safety. They have different responsibilities and apply different means and have - in most cases - very different opinions of the cost effects.

"Co-operative safety" is defined as: “Road operators, infrastructure owners, vehicles and their drivers and other road users will cooperate to achieve the most efficient, safe, secure and comfortable journey”. This target and need for co-operation are obvious, but the means and methods are more complicated.

The APOLLO project took part in the project called "Mobile road conditions monitoring - state of the art and future" by Finnish Road Administration (Finra). Since the current road conditions monitoring system is based on fixed road side weather stations, it was seen necessary to complement the system by information collected along the main road network based on a kind of Floating Car Data (FCD). Looking at accidentology in Western countries, it is easy to see that accidents are today rather spread across the whole network - weighted by traffic volumes - than concentrated on so called black spots. The problem in traffic safety today relates not so much to black spots but rather 'black behaviour' that can lead to an accident anywhere, and road conditions combined with drivers inability to adjust their behaviour accordingly often play an important contributory role in accidents.

The project developed different scenarios to realise information collection by using mobile systems (see Deliverable D13: Scenario description: safe traffic, safe vehicle and safe tyre). Intelligent tyre technologies was seen a potential method when the applications are on the market. This could be realised either by means of commercial vehicles travelling along the same route repeatedly or by using private passenger car fleet. Overall, it was concluded in the project that here is a strong interests on the infrastructure owner side, especially in Nordic countries to use technologies that provide information on adverse road conditions rather along the whole network than on cross-sectional fixed points.

Figure 3. Envisaged uses for signals provided by intelligent tyre systems.
3.1.4 State of the art

Over the years, a number of projects addressing also road slipperiness and adverse road conditions have been carried out. Previous work has, however, included road surface monitoring as a secondary research topic only. In addition to the complexity of the friction phenomenon, a lack of dedicated efforts to determine friction / road slipperiness has consequently been an important cause for not yet having a precise friction parameter written in vehicle control algorithms.

Since 1984, when European Parliament launched its Resolution on Road Safety proposing "appropriate research" on the potential of information and communication technologies for road and vehicle safety, Framework Programmes from the very beginning recognized the need to capture and manage road and driving conditions as follows:

- The first steps were taken in the DRIVE I (2nd Framework Programme) during 1989-92 to be continued as a follow-up in the 3rd FP. Feasibility studies on the automatic detection of incidents by video image processing, a test database for digital maps and methods for monitoring road and weather conditions were carried out. The best-known vehicle application during this era is Anti-lock Braking System (ABS) using different rotation speeds of wheels as a reaction to differences in road surface properties.

- 4th and 5th FP's throughout the 1990's focused mainly on the lateral and longitudinal control of a vehicle. In this connection, the concept of Advanced Driver Assistance Systems (ADAS) was created. Electronic Stability Programme (ESP) and Adaptive Cruise Control (ACC) entered the market as the most prominent outcomes of this work to be later followed by more advanced deceleration/braking systems. Systems and prototypes developed were stand-alone. The functioning of these and systems under development is not optimal due to the lack of precise information on road surface slipperiness.

- The current 6th FP in intelligent vehicle field focuses on the integration of the most promising ADAS applications and cooperative driving. The underlying reasoning behind this is the integration of existing ADAS and related technologies enabling driver assistance on a broader time scale ranging from imminent crash up to several seconds informing drivers on hazardous conditions.

In parallel with the development of more mature technologies for immediate lateral and longitudinal control of a vehicle, the current trend is clearly moving towards vehicle to vehicle communication (v2v) and communication between the vehicle and road infrastructure and/or background systems. The rationale for this is to lend the driver more time to respond to changes in the driving environment and keep him/her firmly in the control loop. Both trends assume the availability of relevant information on driving conditions either for vehicle control systems and/or the driver. This is clearly manifest in the large Integrated Project PReVENT and furthermore, in the currently open eSafety 4th call for cooperative systems.

While wireless communication technologies needed in cooperative driving are rapidly maturing, there is a concern for providing the vehicle/driver with continuous on-line information on road surface conditions. Today, cross-section measuring of road surface qualities at fixed road side weather stations is possible. However, looking at accidentology in Western countries, it is easy to see that accidents are today rather spread across the whole network - weighted by traffic volumes - than concentrated on so called black spots. The problem in traffic safety today relates not so much to black spots but rather 'black behaviour' that can lead to an accident anywhere, and road conditions combined with drivers inability to adjust their behaviour accordingly often play an important contributory role in accidents.

Tyre Pressure Monitoring Systems (TPMS) are the first series products in the field of intelligent tyre/wheel systems which are already introduced in the automotive market (see Deliverable D7: Intelligent tyre systems – State of the art and potential technologies). The development activities on
TPMS are still high. This applies to nearly all aspects of components and technologies used for a TPMS such as indirect measurement principle or direct measurement principle, sensor, power supply, data transmission and data handling. Further improvements for TPMS for direct measurements are expected in an increased robustness of the electronics, an easy way of vehicle integration including vehicle assembly process and a simple handling for service and maintenance purposes. Therefore, many pre-development activities are focused on wireless data transmission and batteryless power supply. These technologies are important for the way of integrating a TPMS into the vehicle and the tyre/wheel system.

The legislation in the US by the NHTSA is a strong driver for new developments, a fast market introduction and standardisation of TPMS. These activities are supporting the development of more advanced intelligent tyre/wheel systems the APOLLO project is aiming at. The functionality of TPMS can not be replaced by a more sophisticated tyre/wheel system. The tyre inflation pressure and temperature are important data to derive information on forces or friction parameters from more advanced sensors. Therefore, future development might result in a solution for an intelligent tyre/wheel system with an incorporated functionality of TPMS. During the past few years, tyre sensors have figured a topic for R&D to estimate tyre-road contact. First prototypes will be demonstrated soon. Mathematical tyre models are being developed and used together with sensors to estimate friction coefficient (µ) when the required acceleration signals are provided. Today, only early laboratory prototypes of advanced tyre sensors with limited performance exist. These include a magnetic side wall torsion sensor by Continental, a Darmstadt position sensor based on a magnet and Hall sensor, and a SAW (Surface Acoustic Wave) sensor by Siemens. Basic sensor technologies that are used in future development of intelligent tyre/wheel systems are acoustic, optical, vibrating, radio technology and deformation sensors.

Vehicle safety systems on the market using information on road conditions - even indirectly, are still few. These are Slip Control Systems (e.g. ABS) and Electronic Stability Programmes (ESP). There are a number of sensors providing information on vehicle dynamics such as yaw rate, longitudinal and lateral acceleration, differences in wheel rotation speeds and engine torque. However, they have not yet been used to provide accurate information on friction or even road surface slipperiness (Figure 4).

![Figure 4. State of the art in the use of tyre-related information for vehicle control and driver information (RWTH Aachen, 2005).](image-url)
3.2 System description

3.2.1 Applications and requirements

Overview on applications

The intelligent tyre/wheel system should provide on-line data on the individual tyre-road contact to improve chassis/vehicle control systems as well as to establish advanced features for driver information and services for external users (see Figure 5). The most important applications in the different areas introduced in Figure 5 are listed in Figure 6. For further details see Deliverable D8: Potential applications, requirements and reference application.

Figure 5. Supporting automotive applications by an intelligent tyre system for improved road safety.

Figure 6. Applications that can benefit from intelligent tyre technology.
These applications and the potential benefits using an intelligent tyre/wheel system are discussed in the APOLLO project. An example is given for an advanced Adaptive Cruise Control. The overall functional requirement of this ADAS is to maintain a safe distance to a vehicle ahead. Therefore, it is necessary to control the braking distance and the braking itself depending on friction at the tyre-road contact, see Figure 7. An improvement of the control system could be achieved by providing friction information by an intelligent tyre/wheel system.

\[
\text{Braking distance: } s_s = \frac{v^2}{2 \cdot \mu \cdot g}
\]

Influence of max. friction available: \( \frac{1}{\mu} \)

Max. velocity (range of radar system: 160 m)

\[\begin{array}{c|c}
\text{Velocity [km/h]} & \\
\hline
0 & 0 \mu \\
0.1 & 0.3 \mu \\
0.2 & 0.5 \mu \\
0.3 & 0.7 \mu \\
0.4 & 0.9 \mu \\
0.5 & 1 \mu \\
\end{array}\]

Figure 7. Calculation example for Adaptive Cruise Control (ACC).

The potential information of the tyre-road contact and the tyre/wheel system such as signals, parameters and status data are clustered in the following (Table 1).

Table 1. Information on tyre-road contact and tyre/wheel system.

<table>
<thead>
<tr>
<th>Information Cluster</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving dynamics</td>
<td>Wheel forces (longitudinal-, lateral-, vertical-)</td>
</tr>
<tr>
<td></td>
<td>Wheel torques</td>
</tr>
<tr>
<td></td>
<td>Friction used</td>
</tr>
<tr>
<td></td>
<td>Maximum friction available</td>
</tr>
<tr>
<td></td>
<td>Slip / vehicle velocity</td>
</tr>
<tr>
<td></td>
<td>Slip angle</td>
</tr>
<tr>
<td>Tyre data</td>
<td>Identification (type, characteristics)</td>
</tr>
<tr>
<td></td>
<td>Logistic data (tyre history, ...)</td>
</tr>
<tr>
<td></td>
<td>Inflation pressure</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
</tr>
<tr>
<td></td>
<td>Tread depth / Height of tread lug</td>
</tr>
<tr>
<td></td>
<td>Damage, stress</td>
</tr>
<tr>
<td></td>
<td>Age of tyre/mileage</td>
</tr>
<tr>
<td>Road data</td>
<td>Road paving (concrete, asphalt, ...)</td>
</tr>
<tr>
<td></td>
<td>Texture of road surface</td>
</tr>
<tr>
<td></td>
<td>Road damage</td>
</tr>
<tr>
<td></td>
<td>Road condition: dry/wet/cy/snowy</td>
</tr>
</tbody>
</table>
This clustering is used to select a reference application for the APOLLO project and to specify the functional requirements on the intelligent tyre/wheel system. Therefore the most important information are allocated to the applications and prioritised (Table 2).

**Table 2. Evaluation of applications and information.**

(The information are of high (H), medium (M) or low (L) importance for the specific application.)

<table>
<thead>
<tr>
<th>Application</th>
<th>Information</th>
<th>Friction information</th>
<th>Slip angle</th>
<th>Wheel forces</th>
<th>Tyre data</th>
<th>Road data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chassis/veh. control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABS</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>L - M</td>
<td>L - M</td>
<td></td>
</tr>
<tr>
<td>TCS</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>L - M</td>
<td>L - M</td>
<td></td>
</tr>
<tr>
<td>ESP</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>L - M</td>
<td>L - M</td>
<td></td>
</tr>
<tr>
<td>Driving condition observer</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>L - M</td>
<td>L - M</td>
<td></td>
</tr>
<tr>
<td>Rollover protection</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>L - M</td>
<td></td>
</tr>
<tr>
<td>Load distribution observer</td>
<td>M</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>ADAS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACC</td>
<td>H</td>
<td>L</td>
<td>M</td>
<td>L - M</td>
<td>L - M</td>
<td></td>
</tr>
<tr>
<td>Autom. emergency braking</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>L - M</td>
<td>L - M</td>
<td></td>
</tr>
<tr>
<td>Collision avoidance</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>L - M</td>
<td>L - M</td>
<td></td>
</tr>
<tr>
<td>Other (stop a. go assist. etc.)</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Driver information</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Information level</td>
<td>H</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Warning level</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Services f. external users</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle to/from vehicle</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>Veh. to/from infrastructure</td>
<td>M</td>
<td>L</td>
<td>L</td>
<td>L - M</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>(maintenanc., road auth. etc.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (logistics, service etc.)</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td></td>
</tr>
</tbody>
</table>

**Selection of reference application for APOLLO Project**

The discussion of potential applications and the ranking of relevant information lead to the selection of the reference application for the APOLLO project. The overall functional requirements are to provide a set of data of data on:

- vertical wheel force or dynamic wheel load and
- relative friction available (given in percentage of maximum friction available)

for the application system. Utilising this information the performance of many applications, e.g. roll-over protection, ABS, ESP, ACC, can be improved and additional functions can be achieved for driver information and services for external users (Figure 6).

### 3.2.2 Specifications

**Functional requirements of application systems**

The functional requirements on the output data of an intelligent tyre/wheel system are derived from the operation and performance requirements of the application systems. In Table 3, the requirements are listed for a passenger cars.

The relevant signal range for passenger cars is given as follows:

- Vehicle weight: 800kg – 2 800kg
- Wheel load: 0 – 15 000N
Max. friction avail.: 0.1 – 1.2
Friction levels:
- Low friction (LF): $\mu < 0.4$
- Medium friction (MF): $0.4 < \mu < 0.7$
- High friction (HF): $\mu > 0.7$

Table 3. Functional requirements of application systems.

<table>
<thead>
<tr>
<th>Application</th>
<th>Information</th>
<th>Friction information</th>
<th>Wheel load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate/s</td>
<td>Accuracy</td>
<td>Rate/s</td>
</tr>
<tr>
<td>Chassis/vehicle control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABS</td>
<td>0.01 - 0.1</td>
<td>+/- 0.2</td>
<td>0.01 - 0.2</td>
</tr>
<tr>
<td>ESP</td>
<td>0.1 - 0.2</td>
<td>+/- 0.2</td>
<td>0.1 - 0.2</td>
</tr>
<tr>
<td>Roll-over protection</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Load distribution observer</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Veh. load</td>
<td>-</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>$x$, $y$ Pos. cent. of gravity</td>
<td>-</td>
<td>-</td>
<td>30 - 60</td>
</tr>
<tr>
<td>$z$ Pos. cent. of gravity</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>ADAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACC</td>
<td>0.1</td>
<td>3 lev: HF, MF, LF</td>
<td>-</td>
</tr>
<tr>
<td>Other (stop a. go assist. etc.)</td>
<td>0.5</td>
<td>3 lev: HF, MF, LF</td>
<td>-</td>
</tr>
<tr>
<td>Driver information</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Information level</td>
<td>0.1 - 0.5</td>
<td>3 lev: HF, MF, LF</td>
<td>30 - 60</td>
</tr>
<tr>
<td>Warning level</td>
<td>0.1 - 0.5</td>
<td>Level LF</td>
<td>30 - 60</td>
</tr>
<tr>
<td>Services f. external users</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Veh/veh., information level</td>
<td>0.1 - 0.5</td>
<td>3 lev: HF, MF, LF</td>
<td>-</td>
</tr>
<tr>
<td>Veh/veh., warning level</td>
<td>0.1 - 0.5</td>
<td>Level LF</td>
<td>-</td>
</tr>
<tr>
<td>Veh/infrastruct., inform.-lev</td>
<td>&gt; 1</td>
<td>3 lev: HF, MF, LF</td>
<td>-</td>
</tr>
<tr>
<td>Veh/infrastruct., warning-lev</td>
<td>0.5</td>
<td>Level LF</td>
<td>&gt; 60</td>
</tr>
</tbody>
</table>

Measurement task and sensor concept

To provide the envisaged data on wheel load and friction available for application systems a measurement task and a sensor system is specified. It is specified to measure the length of the contact patch dynamically and to detect the local effect that is called “transition from adhesion to sliding”. This effect occurs when a part of the tyre contact patch turns from adhesion to sliding, especially at the end of the contact patch area. It is assumed that this effect could be detected by a sensor. An overview on the previous specification of the sensor system is given as follows:

- **Sensor concept for measurement of length of contact patch**
  - Sensor technology: Capacitive sensor
  - Sensor signal: Acceleration (or deformation) Longitudinal and/or radial signal
  - Sensor location: Inner liner
  - Sensor configuration: 1 acceleration sensor is minimum configuration.

- **Sensor concept for measurement of local effect “transition from adhesion to sliding”**
  - Sensor technology: Capacitive sensor
  - Sensor signal: Acceleration (or deformation) Longitudinal and lateral signal
- Sensor location: Level between belt and tread lug or inner liner
- Sensor configuration: Sensor at inner liner combined with sensor(s) at level between belt and tread lug.

Moreover, the final sensor system should contain a tyre inflation pressure sensor to combine all sensors on a wheel into one single electronics. It is expected that information from dynamic tyre/wheel models are necessary too to derive the system output data to be provided for applications.

The tests performed with a triaxial acceleration sensor between the belt and the tread lug show that the measured signals can not be analysed properly. Reasons for that are the unknown rotation of the sensor relative to the tyre in the contact patch area during wheel rotation and the influence of the road surface (e.g. roughness, stones). Therefore, the demonstrator is equipped with a triaxial acceleration sensor at the inner liner of the tyre.

**Technical requirements for intelligent tyre/wheel system**

An overview on technical requirements is given for the subsystems sensor, wireless data transmission, batteryless power transmission and the electronics inside the mechatronic tyre (Table 4).

**Table 4. Technical requirements for intelligent tyre/wheel system.**

<table>
<thead>
<tr>
<th>Part of tyre system</th>
<th>Information</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration sensor</td>
<td>Sampling rate @ 1 sample per 2mm</td>
<td>35kHz</td>
</tr>
<tr>
<td></td>
<td>Dynamic range (m/s²)</td>
<td>0 – 22 500</td>
</tr>
<tr>
<td></td>
<td>Dynamic range in bits</td>
<td>2m/s²</td>
</tr>
<tr>
<td>Data transmission</td>
<td>Technology</td>
<td>RF @ 434MHz</td>
</tr>
<tr>
<td></td>
<td>Data rate / channel</td>
<td>6kbps</td>
</tr>
<tr>
<td></td>
<td>Other ?</td>
<td></td>
</tr>
<tr>
<td>Power supply</td>
<td>Frequency</td>
<td>6.8MHz</td>
</tr>
<tr>
<td>Inductive supply</td>
<td>Available power</td>
<td>&gt; 100mW</td>
</tr>
<tr>
<td>Generator</td>
<td>Distance tyre – feed coil</td>
<td>&gt; 50mm</td>
</tr>
<tr>
<td></td>
<td>Technology</td>
<td>Piezoelectric film</td>
</tr>
<tr>
<td></td>
<td>Available power</td>
<td>0.1 – 10mW</td>
</tr>
<tr>
<td></td>
<td>Dimension</td>
<td>&lt; 100 x 100 mm²</td>
</tr>
<tr>
<td>Electronics</td>
<td>Power consumption</td>
<td>&lt; 100mW</td>
</tr>
<tr>
<td>Tyre contraints</td>
<td>Dimension (x, y, z)</td>
<td>&lt; 20 x 20 x 15 mm³</td>
</tr>
<tr>
<td></td>
<td>Weight</td>
<td>&lt; 15gr</td>
</tr>
<tr>
<td></td>
<td>Location</td>
<td>Inner liner</td>
</tr>
<tr>
<td></td>
<td>Temperature range in operation (°C)</td>
<td>-40…+80 (+100)</td>
</tr>
<tr>
<td></td>
<td>Max. temp. in tyre production (°C)</td>
<td>180 (20min)</td>
</tr>
</tbody>
</table>

The tyre sensor should have the spatial resolution of about 1 millimetre along the periphery of the tyre in the optimal case, which seems to be very demanding. Therefore, the spatial resolution of 2 millimetres was selected for the specifications. In general, the system has to be designed for the speed range 0 – 250 km/h. It seems to be acceptable to reduce the upper speed level for normal system operation and to reduce requirements on accuracy depending on the speed. The technical requirements on the tyre/wheel system are summarised in Table 4. The data are calculated for a tyre with a diameter of 600mm. The requirements for the wireless data transmission in Table 4 are equal to the design data of the demonstrator system. Some reasons for that can be explained. The goal is to achieve a sampling rate as high as possible for investigation purpose. In the APOLLO project it is necessary to use a radio transmitter that is available in the market. The requirements on a data
transmission can be defined after the sensor and the algorithms for signal analysis are finally designed.

**General requirements for automotive applications**

For the future phase of product development other general requirements has to be taken into account. The relevant categories are outlined in the following list. For more details, see D8: Potential applications, requirements and reference application.

- Operational requirements (operation of intelligent tyre/wheel system, …)
- Handling requirements (final assembly, maintenance, service, …)
- Vehicle integration requirements (vehicle design constraints, …)
- Tyre/wheel requirements (tyre constraints, tyre manufacturing, …)
- Environmental requirements (temperature, humidity, …)
- Other requirements (additional cost, lifespan of electronics, homologation, recycling, …).

### 3.2.3 Architecture

The general architecture of the intelligent tyre/wheel system is shown in Figure 8. The block diagram gives an overview of the subsystem inside the tyre and the subsystem at the vehicle chassis, which should be located near the wheel houses.

*Figure 8. Architecture of electronics of an intelligent tyre/wheel system.*
In the APOLLO project, the subsystems were developed and tested stepwise. The electronics of the data transmission is set up on PCB’s, because integrated electronics are not yet available on the market. Therefore, the electronics were installed on the rim and a battery was used as a power supply. The subsystems for a batteryless power supply are installed and tested separately. Figure 9 shows an overview on the demonstrator system. A triaxial acceleration sensor and a three-channel data transmission is used for the demonstrator. In parallel a second test system is realized which contains an optical sensor and a piezoelectric sensor in addition to the triaxial acceleration sensor. The purpose of this test system is to acquire additional data for detailed investigations of the tyre/wheel dynamic behaviour. The test system is equipped with an 8 channel data transmission system. The effective sampling rate per channel of the 8 channel data transmission system is 3.10kHz. In the demonstrator, the µprocessor of the subsystem in the tyre/wheel is used for the data encoding and a message control. All measured data are transmitted online to the subsystem in the chassis. For a final system design, a pre-processing of sampled data in the tyre subsystem is suggested. But before this step can be discussed in detail, algorithms for the analysis of measured data have to be developed and verified.

![Figure 9. Block diagram of APOLLO demonstrator system.](image)

### 3.3 Tyre-vehicle system behaviour

#### 3.3.1 Tyre mechanics

Three categories are defined as a source of obtaining information from a rolling tyre. Here, the term *information* is used to describe any data that can help to improve active safety systems (e.g. forces) or information, which will support the driver such as friction. The three categories in the analysis of tyre mechanics are: (i) the evaluation of global tyre mechanisms, (ii) local deformation analysis (see Deliverable D9: Dynamic tyre behaviour with respect to sensor technologies and Deliverable D16: Overall tyre-vehicle-system behaviour and test results) and (iii) other sources of data (Table 5).

Global tyre deformations describe the relation between forces and deformation of the entire tyre. Thus, longitudinal forces result in a deformation of the tyre in the same direction, in which the force is applied.
Local deformations are mainly concerned with an evaluation of tread lug deformation. On one hand, this approach is promising, since the relatively soft tread block reacts sensitively to changes in the contact patch. On the other hand, disturbances from the road tyre contact will influence all measurements performed in this context. The third category describes possibilities, which are not directly related to one of the others. A summary of potential evaluation strategies is given in Table 5. A detailed description of tyre mechanics can be found in Deliverable 9 “Dynamic Tyre Behaviour with Respect to Sensor Technologies”. The headline of the table divides all approaches into three categories, while the first column summarises required tyre information.

**Table 5. Overview of potential evaluation strategies to obtain information from a rolling tyre.**

<table>
<thead>
<tr>
<th>Local Deformation</th>
<th>Global Effects</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheel load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integration of ground pressure distribution</td>
<td>Identification of contact patch length based on Tread lug deformation</td>
<td>Distance rim and belt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Determination of contact patch length based on belt deformation</td>
</tr>
<tr>
<td>Long Force</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integration of longitudinal tread deformation</td>
<td>Determination of deformation gradient (long. Slip) and break point based on model post processing</td>
<td>Determination of longitudinal belt deformation and rotation relative to rim</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evaluation of drive train and brake system information</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Application of strain gauges</td>
</tr>
<tr>
<td>Lateral Force</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integration of lateral tread deformation</td>
<td>Determination of deformation gradient (lateral Slip) and break point based on model post processing</td>
<td>Determination of lateral belt deformation and rotation relative to rim</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evaluation of lateral vehicle acceleration and yaw rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Application of strain gauges</td>
</tr>
<tr>
<td>Friction Straight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Determination of transition point from adhesion to sliding</td>
<td>Post processing of side force and aligning torque</td>
<td>Evaluation of secondary information (e.g. noise)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slip angle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Determination of gradient between lateral deformation along contact patch</td>
<td>Evaluation of side force and aligning torque</td>
<td>Evaluation of lateral vehicle acceleration and yaw rate</td>
</tr>
</tbody>
</table>

Wheel load can be calculated from the integral of the ground pressure distribution along the contact patch area. When the pressure in all tread lugs is known, it is possible to calculate the wheel load from the integral. The pressure distribution may be available from a displacement measurement of each tread block. In the determination of wheel load by global effects, the deformation of the tyre structure
is of interest. The deformation of the belt relative to the rim (the higher the wheel load, the shorter the distance between the rim and the belt) can be used as a measure to obtain wheel load.

Concerning other target information, a similar approach can be used. The measurement of lateral force can be obtained from the characteristics of the tread pattern deformation, but also from the relative displacement between the rim and belt (global deformation). The friction coefficient as one of the most interesting but also most difficult parameter to derive, is available from the tread pattern deformation when cornering at low friction coefficients under straight rolling. In cornering, the different characteristics of the tread pattern deformation results in different global deformation of the tyre.

### 3.3.2 Tyre Simulations

A predictive model for a steady-state rolling was developed using a finite element method (ABAQUS/Standard code). The model has been used to predict accelerations that could be measured with micromechanical sensors.

Goals of the simulations were the identification of guidelines for a sensor type and position and to improve the comprehension of accelerations correlation with the dynamic mechanical behaviour of tyre under different operating conditions (i.e. speed, vertical load, camber angle, slip angle....).

Several sensor positions along the inner liner and through the tread depth (see Figure 10) were investigated in order to find out the most optimal one in various operating conditions, and hence, the most useful on the final application to get the tyre real dynamic condition from obtained accelerometer signals.

![Figure 10. Investigated sensor positions shown on a tyre cross-section.](image)

The simulated accelerations along three axes on a reference frame fixed on the inner liner are shown in Figure 11 for a tyre 195/65R15 rolling at speed of 30 kph on a drum.

The outermost lateral positions analyzed (points 1 and 5) show less marked features on the radial and longitudinal directions, and such features decrease further in other cambered and cornering conditions simulated; hence, the sensor axial position should be carefully selected in order to guarantee that it is located in the contact patch region for all the operating conditions to be monitored.
Figure 11. Predicted accelerations along three axes fixed to inner liner during a complete tyre revolution (tyre contact patch is around 0° on the wheel turn axis). Different positions are shown.

The simulations allowed to predict that a sensor placed in a lateral position (points 1, 2, 4 and 5) would show in lateral direction an offset value (see Figure 11) that is a function of its axial position and is related to the liner profile and tyre deflection during rolling.

Simulated accelerations (peaks and offset values) are proportional to squared speed, and for speeds up to 150 kph sensor ranges should be up to 1000 g on radial direction and up to 300 g on lateral and tangential direction.

Simulations under different tyre operating conditions allowed to find good correlation of the measurable accelerations by the load (see Figure 12), inflation pressure and a cornering angle.
As far as position through thread depth is concerned, the levels 1, 2, and 3 are almost equal concerning deflection induced acceleration on a non-treaded tyre; on the level 4, acceleration diagrams show interesting features, but the model used should be further improved for the better comprehension of the thread influence.

### 3.3.3 Signal interpretation

In the course of the project, a decision was made to construct a mechatronic tyre equipped with three sensors in one tyre (a so called 3to1 tyre). The three sensors were (i) an optical displacement sensor, (ii) a three axial acceleration sensor and (iii) a strain sensor. These sensors were mounted on the tyre in order to measure global deformations of the tyre structure. The three sensors also enabled tests with a number of configurations. Especially, a comparison of different sensor concepts under the same, comparable conditions were now possible.

The optical sensor was designed to measure the displacement between one point on the inner liner and the rim in the coordinate frame of the wheel. This position is measured in three axes. Sensor signals are post-processed within the angular range, where the point concerned is running through the contact patch. External forces result in global deformations of the tyre structure. These deformations are measured and, a correlation between the force and displacement signal was obtained. As an illustration, the raw data of one wheel revolution with a wheel load as parameter is shown in Figure 13.
Furthermore, the acceleration sensor is analysed to assess its potential regarding wheel forces. A strategy to identify different wheel loads, lateral forces and longitudinal forces will be described in the following. For each of the three forces a different post-processing concept is considered:

1. The greater the applied wheel load, the greater the radial deflections of the tyre in the contact patch. In parallel the contact patch will increase mainly in longitudinal direction (length of contact patch). The acceleration sensor, which is mounted on the inner liner, can identify the contact patch length (ptp-time multiplied by the velocity) by a sudden change of the radial acceleration (zero in a contact patch, a centrifugal force outside).

2. A lateral force results in a lateral displacement of the contact patch relative to the rim. A double integration of the lateral acceleration can be used to obtain this deformation when the entire rim is accelerated in lateral direction. Finally, a correlation between the lateral force and the lateral displacement is used to obtain the required force.

3. A measure for the longitudinal force is the torsional deflection of the belt relative to the rim. A delay angle is defined as a difference between the angle, when the accelerometer is expected to enter the contact patch of the free rolling tyre and the actual angle (with an applied braking force). This angle can be measured and finally calculated by using a trigger signal or an incremental angular transducer. The most promising approach would be the angular transducer, which can detect an angular delay between the accelerometer peak at free rolling and braking.

As an illustration, the raw data of one wheel revolution of the radial acceleration sensor is shown in Figure 14 below.
Figure 14. Measured radial acceleration during one wheel revolution on a flat track tyre test bench.

The third sensor used, was a piezo strain sensor. The identification of wheel load and longitudinal force followed the same strategy as already described concerning the acceleration sensor. In contrast to the change in radial acceleration, the change in strain is analysed to identify the contact patch length or the delay angle (wheel load identification and longitudinal force identification). Lateral forces are obtained by means of a second strain transducer measuring compression in lateral direction of the belt. This approach cannot identify the direction of the lateral force (force from left and right results in compression).

### 3.4 Sub-system development

#### 3.4.1 Sensors

When a sensor is to be mounted on the inner liner or embedded in the rubber compound of a tyre, it must fulfil a number of requirements. The power available from the sensor is low, the sensors must have wide frequency response, wide dynamic range, reasonable resolution and nonlinearity. In addition, the sensor should be robust, small, light, and capable of withstanding harsh conditions: high accelerations, shocks, as well as low and high temperatures. In the project, various sensor candidates were reviewed but only one of them was found to meet the requirements: a micromechanical acceleration sensor. A strain sensor based on piezoelectric film was also considered to have potential and worth investigations, although the robustness of present piezoelectric films was known not to be sufficient yet.

**Piezoelectric Deformation Sensor**

When stretching a piezoelectric film, a voltage $U$ is generated across the film according to equation $U = k \Delta L/L$, where $k$ is strain constant, $L$ is initial length, and $\Delta L$ is change in the length of the film length. In Apollo, a PVDF film was used whose strain constant is $k = 12$ kV. The output voltage is independent of the film area and the output impedance is inversely proportional to the film area.

Figure 15. Piezoelectric film as a deformation sensor.
Figure 16 shows measurements of the inner liner strain with 1 kN and 6 kN wheel loads at a speed of 5 kph. The strain waveforms clearly show higher amplitude and longer pulse length for a higher load. The piezoelectric film is highly temperature dependent and absolute strain detection requires temperature compensation. The tyre contact patch length can be estimated by measuring the time difference between the up- and down-going edges of the strain pulse. The deformations in the signal shape may also yield information on road conditions and aquaplaning. Contrary to acceleration, strain changes in the tyre are essentially independent of the speed.

![Figure 16. Strain vs. rotation angle at two wheel load values at speed of 5 kph.](image)

**Micromechanical Acceleration Sensor**

The silicon technology called microelectromechanical systems (MEMS) has experienced a revolution in recent years. In principle, MEMS sensors can be designed for measuring nearly all quantities (temperature, pressure, acceleration, electric voltage, current, etc.). Also components for many different purposes can be realised.

Silicon capacitive sensor is made of single crystal silicon and glass. This design ensures good linearity, accuracy, and stability over time and temperature. Hermetically sealed structures reduce packaging requirements. No particles or chemicals can enter the element, a fact that increases reliability. Automotive industry has already a long experience of accelerometers in airbag systems. There is a large effort in the semiconductor industry to integrate MEMS with the mainstream manufacturing technology of integrated circuits, CMOS (Complementary Metal Oxide Semiconductor). The integration of sensors with their readout electronics and signal processing circuits will enable mass production with reduced sensor prices. The dual capacitor structure (Figure 17) thanks to its symmetry, has improved zero stability, linearity and cross-axis sensitivity of the accelerometer. Temperature dependence typically achieved is less than 5 per cent of the full scale range/°C and a cross-axis sensitivity typically less than 3%.

![Figure 17. MEMS acceleration sensor.](image)
Acceleration sensor as a tyre sensor has also some disadvantages. The sensor detects all the accelerations including rotational, vibrational, and gravitational accelerations. Therefore, a sophisticated signal processing is needed to extract the wanted information from the signal flow. The acceleration signals in tyre are proportional to the wheel rotational velocity squared, which results in a requirement of a high dynamic range for the sensor. With a proper design of the sensor (progressive sensor) or by integration the signal in time this problem can, however, be solved.

The Apollo prototype sensor is based on the micromechanical acceleration sensor (ZRI-06V600g) fabricated by VTI Technologies by bulk micromachining (Figure 19). The read-out of the sensor developed by VTT is done with Microsensors MS3110 universal capacitive-readout integrated circuit (IC). The simplified schematic diagram of the sensor readout electronics is shown in Figure 18.

![Figure 18. Schematic diagram of the sensor block containing the acceleration sensor, the readout electronics IC (MS3110) and the external capacitors needed.](image1)

Two variations of sensors packaged with readout electronics were fabricated by VTT. The sensor for inner liner of tyre has aluminium housing. The size of the packaged sensor is 15x15x8 mm³ and the weight is about 4 gr. The sensor embedded in the tread of the tyre was made as slim and light as possible. The size of the packaged sensor is 10x12x3.5 mm³ and the weight of about 2 gr.

![Figure 19. Mechanical structure of the acceleration sensor block.](image2)
**Optical Positioning Sensor**

An optical positioning sensor was developed to measure the displacement of a contact patch relative to the rim. The Sensor consists of a PSD (Position Sensitive Diode), a lens and a light source on the inner liner of the tire. As light source a diode with a power consumption of 90 mW was glued to the inner liner. The PSD-chip and the lens are located in a housing on the rim. The distance between lens, PSD and diode defines the focal distance of the lens. A schematic setup with main dimensions is given in Figure 20.

![Figure 20. 3-axial optical sensor on the inner liner.](image)

From the sketch in Figure 20, the measuring range of the optical sensor can be calculated using the theorem of intersecting lines. Since the measuring range depends on the distance between the lens and the IR-diode, the measurable displacement varies between 35 and 47.5 mm according to the distance between the lens and the inner liner. This distance in turn is a function of wheel load. A similar sketch can be derived in the x-z-plane and yields the same measuring range for x displacement.
As can be seen in Figure 21, the light beam, which is emitted from the IR-diode, is focused on the PSD-chip. The centre of the light spot on the PSD-lens is responsible for the current at the corners of the PSD-chip. While higher intensity of the light beam results in an increasing current at all corners of the chip, a movement of the light beam influences the current at the corners behind and towards the spot that moves.

Applying the theorem of intersecting lines, the distance of the IR-Diode on the inner liner can be measured. The type of the two dimensional PSD-chip is called “Pin Cushion”. This is an improved tetra-lateral type with an improved sensitive surface and electrodes. In addition to small dark current, a fast response and easy bias application, which are advantages of the tetra-lateral type, distortion in the circumference has been greatly reduced.

3.4.2 Communication interface

Although a sensor system was defined for the demonstrator, a good level of flexibility was required in order to comply with possible running changes during the development of the project. The aim of the mechatronic demonstrator was not to show an optimised solution but to allow experimentation and verification of simulation results. The need of flexibility concerned both communication and power supply aspects, which are closely associated.

For that reason, the splitting of communication interface and power supply development has been considered the only way to guarantee demonstrator’s usefulness and availability as a flexible platform assisting in the definition of the final solution. For this reason, the communication electronics is powered by a rechargeable battery in order to avoid obstacles and delays caused by the power supply development. Technological and industrialization aspects are not an issue at this step. Substrates, wires, connections and packaging are designed in order to guarantee functionality and sufficient robustness to allow static and dynamic tests but are not necessarily requested to comply with durability requirements. Concerning electronics in particular, both size and power consumption are not optimised due to the unavailability of custom integrated circuits. For other aspects, like antennas the demonstrator has been used to evaluate different mechatronic solutions, allowing the development of electromechanical solutions, which would hardly be analysed without the aid of a physical prototype.
The basic concepts concerning demonstrator’s communication interface are a high data rate, a license free frequency band, wheel mounting (electronic board and antenna), PC card data acquisition and a PC data analysis, a CAN controller for future vehicle tests, low power consumption, a battery operation.

In a first configuration, a tri-axial piezoresistive accelerometer wired to the electronics on the rim was employed. The sensor’s sample rate, 6.5 KHz each signal and resolution, ≥10 bits were specified in order to guarantee a correct acceleration signals reconstruction for the data analysis and algorithms development. A pressure and a temperature sensor channels were also prepared. The sample rate for these ones is extremely low (very low variation speed of physical quantities).

The carrier transmission frequency and relative power level had to comply with attenuation effects of tyre and with regulations relating to short-range devices. The choice of the frequency band has also been determined by the availability of high bit-rate transceivers on the market (433.050 – 434.790 MHz; 576 Kbps).

The communication interface between the receiver and the PC is realized by means of a high speed (1Mbps) CAN card because of specific know-how in automotive industry and predisposition for vehicle application and tests.

The transmitter provides sensors’ signal Analogue to Digital conversion, Cyclic Redundancy Check (CRC) calculation, data encoding, frame forming and data RF transmission (Figure 22).

Transmission protocol has been conceived in order to maximize payload to packet lengths ratio and therefore increase sampling frequency. Preamble and CRC have been minimized for that reason. A 4 to 6 bit encoding is performed according to a 16 elements look-up table in order to guarantee a good balance of low and high level pulses avoiding long sequences of the same bit value limited by transceiver’s specifications. A preamble containing a wake-up byte and a clock synchronization sequence completes the frame to be sent, resulting in 11 bytes (88 bits).

The maximum allowable bit rate is 576 Kbps for the selected transceiver. Since an 8 MHz microprocessor’s clock is used, a data rate of 8 MHz / 14 = 571 Kbps is affordable. This means that 154 ms are needed to transmit every packet, giving a maximum sampling frequency for each axis of 6.49 KHz.

The radio link is implemented with a 433.92 MHz band RF transceiver circuit using amplitude shift keying (ASK) modulation.

![Figure 22. Block diagramme of transmitter electronics.](image)

The receiver has been developed in order to gather raw information coming from the tyre electronics, decode/validate data and send them to a PC card by means of a CAN Interface (Figure 23). In other words, the unit acts like a Gateway. Measured values are then stored into the PC hard disk for data logging and post-processing operation.
The first block is the RF interface. It uses the same transceiver employed in the transmitter electronics. A programmable logic device, an FPGA (Field Programmable Gate Array) is used to recover data and clock from the bit stream coming from the RF module. The same component is used to acknowledge the data preamble and to allow only valid data transfer to the serial communication interface of the Microcontroller. The Software provides for data decoding (6 to 4 bits), original sensors’ data reconstruction and CRC verification.

![Figure 23. Block diagramme of receiver electronics.](image)

In the application acceleration values and CRC are sent using 8 data bytes. The length of a complete message frame (Standard Frame Format) is 111 bits and (111 bits at 1Mbps bit rate). Since the tri-axial sensor is sampled at a frequency of 6.49KHz data concerning the three axes takes 154ms: the CAN interface is therefore able to transfer in real time information leaving an interval of 43ms between packets.

During the development of the project, three versions of the communication system have been realized in order to manage different sensor system configurations. In particular, after the first version able to manage three acceleration signals, a four-channel for optical sensors and an eight-channel communication interface for mixed acceleration, optical and piezo sensors have been developed and used. For such different versions specific transmitter devices have been designed, while the Hardware receiver chain has remained the same. The software was changed in order to manage different frame configurations. Since the maximum allowable bit rate was restricted by bandwidth limitations and the availability of physical components, the resulting sample rate changed according to the following table:

**Table 6. Sample rate as a function of number of channels.**

<table>
<thead>
<tr>
<th>Channels Number</th>
<th>RF frame length</th>
<th>Sample rate</th>
<th>CAN Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>11 bytes</td>
<td>6.5 kbps</td>
<td>1 frame/sample</td>
</tr>
<tr>
<td>4</td>
<td>14 bytes</td>
<td>5.1 kbps</td>
<td>1 frame/sample</td>
</tr>
<tr>
<td>8</td>
<td>23 bytes</td>
<td>3.1 kbps</td>
<td>2 frames/sample</td>
</tr>
</tbody>
</table>

Due to the high data rate, the messages had to be buffered in the PC-card’s memory and then transferred as blocks to the Personal Computer’s hard disk. To manage such operations an application Software was developed.

Different versions of the transmitter, receiver (RF interface) and antennas have been developed in order to make installation in the mechatronic demonstrator easier and to guarantee good data transmission in drum and car tests. In particular, for the receiver a circularly polarized antenna was
designed in order to eliminate transmission failures due to particular reciprocal orientations with the transmitter’s rotating antenna.

For vehicle tests, an Ethernet connection to a second PC was set up in order to visualize in real time the acceleration signals and process the data.

### 3.4.3 Power supply

As result of a pre-study on power supply technologies, the research was focussed on two technologies:

1. Inductive power transfer and
2. Piezoelectric energy harvesting or generation.

A method and several evaluation prototypes for harvesting energy from tyre deformations were developed. A prototype consists of a piezoelectric PVDF film sensor/generator element with its control and voltage converter circuits (Figures 24 and 25).

![Figure 24. Block diagram of the piezo generator.](image-url)

![Figure 25. Piezoelectric power harvesting element on the right hand side and its control and voltage converter circuits on the left hand side.](image-url)

A piezoelectric film is attached on the tyre inner liner. When the tyre is flattened against the road surface, the film is stretched and the system generates electric energy. The magnitude of power output is proportional mainly to the tyre speed and piezo film area. Also tyre pressure and wheel load have
effect on the power output. The figure 26 shows the variation in the inner liner strain by different wheel loads.

Figure 26. Measured strain at 20kph speed with different wheel load values.

A number of drum tests for the generator were carried out. These tests showed a maximum power output of 0.9mW at 80kmh speed with 80mm x 80mm size one layer piezo element (Figure 27). The graph shows also the speed and wheel load dependence of the power output. The generated energy is sufficient for simple measurement and communication functions.

Figure 27. Generated power as a function of driving speed at two wheel loads.

The PVDF film proved not to be suitable material for the production phase generator because its lack of resistance against high temperatures and high mechanical effects. However, new piezo materials are under development, and there are some possible solutions like Macro Fibre Composites that could be suitable for these applications.

A patent has been applied for the basic energy harvesting concept.

The inductive power system for real-time operation of sensors in a rolling tyre consists of three parts. Oscillator, power amplifier, and a feed coil in the vehicle chassis generate an alternating magnetic. The magnetic field causes an alternating voltage in the tyre receiver coil system that is rectified with a voltage rectifier. In order to produce a continuous power with a high efficiency, the power amplifier, the feed coil as well as the tyre receiver coil structure and the associated voltage rectifier must be carefully designed and optimised. In Apollo, a novel receiver coil structure and voltage rectifier was
invented (Figures 28 and 29). The structure consists of four separate overlapping coils that are connected with voltage rectifiers so that the power is continuously delivered to the sensor in a rolling tyre. The alternating magnetic field of the inductive power supply conforms to ETSI regulations and its frequency is within the licence-free band of 6.765-6.795 MHz.

![Diagram of receiver coil structure in the tyre.](image)

**Figure 28. Receiver coil structure in the tyre.**

![Diagram of optimised voltage rectifiers for the receiver coils in the tyre.](image)

**Figure 29. Optimised voltage rectifiers for the receiver coils in the tyre.**

A patent has been applied for the inductive power transmission concept depicted above.
4 System integration - mechatronic tyre

4.1.1 Mechatronic tyre scheme

The following Figure 30 shows an overall scheme of the mechatronic tyre prototype having one acceleration sensor (a so called 1to1 tyre). According to the figure, the sensor is mounted on the inner liner, whereas the power supply and transmitter are attached on the rim. Also, concerning the 3to1 tyre, the other sensors (piezo, optical) were mounted on the inner liner.

![Figure 30. Mechatronic tyre prototype scheme. On the left, the components mounted on the tyre: the sensor, glued on inner liner, is linked (by wires) to electronic device and battery (on the rim). Signals from tyre are transmitted on vehicle and processed by a Personal Computer (block on the right).](image)

4.1.2 Sensors

In order to achieve the best solution for a mechatronic tyre, a variety of sensor types was investigated: pressure, acceleration, displacement; sensors based on capacitive, piezo, optical, piezo-resistive transducers. According to the knowledge accumulated in the course of the project concerning measurements, signal analysis and model analysis such as tyre mechanical model, FEM, etc., three different sensors were selected. The implementation of sensors and electronic devices were also selected in view of an easier mounting of the electronics on the rim and safe & endurable operation on a drum facility and a road. The sensors selected were mounted on two different mechatronic tyre prototypes.

As described earlier, two mechatronic tyre prototypes were built as follows:

1. The tyre having an acceleration sensor only (1to1 tyre) with all needed electronics and
2. A so called 3to1 tyre with three different sensors, accelerometer, a piezo and an optical sensor integrated in the same tyre mainly for research purposes to obtain more understanding of tyre deformations
The three-axial piezo resistive accelerometer was attached to the inner liner (Figure 31). It provides signals due to tyre deformation in rolling conditions.

![Triaxial accelerometer attached to inner liner by silicone rubber. The sensor is positioned in the centre of a footprint area.](image)

The triaxial optical sensor that consists of a LED on inner liner and a PSD (Position Sensitive Diode) with the lens mounted on the rim (Figure 21). The signal provided by the optical sensor, related to the displacement of the tyre in normal driving condition, has been used to improve the understanding of the signals provided by accelerometer sensor.

The third sensor selected is a piezo strain sensor also fixed in the inner liner to monitor strains only in longitudinal and lateral directions (Figure 32). The signals provide information related to the strain in running conditions. The strain sensor was used also to further improve the understanding of information from the previous sensors described.

![Longitudinal and lateral direction of strain sensors positions.](image)

All sensors used have been mounted on the inner liner in order to guarantee the integrity of the tyre in providing usable signals.

### 4.1.3 Sensor integration

The implementation of the 3-axial accelerometer sensor (the so called 1to1 tyre) was realised by using a Pirelli P6000 Powergy, 225/60 R16, and the 3to1 mechatronic tyre by using a Nokian Hakkapeliitta RSi 225/60 R16. The electronic devices were attached to the rim as shown in Figure 33 (the upper part of the figure showing the 1to1 configuration, and the lower part the 3to1 tyre, respectively).
Due to a relatively large amount of the electronics needed, it was difficult to use a commercial rim, and the mechatronic tyres were built by using custom made dividable rims in order to make the installation of electronics easier (Figure 34).

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*Figure 33. Electronic devices for one sensor tyre (up); an electronic device, optical sensor and battery for three sensor tyre (bottom).*

*Figure 34. Dividable rim made of three parts used for both mechatronic tyres implementation.*
4.1.4 Mechatronic tyres

The mechatronic tyres have been tested on the drum and on a road. The tests were performed at the MTS Flat Track® facility of Pirelli enabling the investigation of several variables such as wheel load, longitudinal and lateral force and speed. The results have been used also for final validation activities. Figure 35 shows the 1to1 tyre on the drum on the left hand side, and 3to1 tyre on MTS Flat Track® on the right hand side.

![Mechatronic tyre prototypes in indoor tests.](image)

**Figure 35. Mechatronic tyre prototypes in indoor tests.**

4.2 Validation of the mechatronic tyre

4.2.1 Sub-systems verification

*Power supply*

The laboratory tests of the inductive power supply (Figure 36), showed that for a distance of about 5 cm between the feed coil and tyre surface, a power of 0.26 W could be delivered to the tyre sensor system (Figure 37). This is high enough not only for powering the sensors but to carry out substantial signal processing in the tyre and for the radio communication from the tyre to the receiver in the vehicle chassis. The inductive power system lends itself also to the communication. This can be done in the same way as in 13.56 MHz inductive radio-frequency identification systems: The load impedance of the tyre coil system is modulated which cause detectable voltage changes in the feed in the vehicle chassis. Laboratory tests showed that this kind of a communication scheme is feasible.

![Laboratory test of the inductive power supply.](image)

**Figure 36. Laboratory test of the inductive power supply.**
Communication interface

The verification of a communication interface consisted of three steps:

1. Static test bench verification,
2. Shaker verification and
3. Drum verification

In the static test bench, basic transmitter and receiver functionalities were verified. Especially, protocol aspects and a data integrity were investigated by connecting transmitter’s inputs to variable resistors and gathering data on a PC by means of the CAN card.

As a second step, a tri-axial accelerometer was electrically connected to the transmitter device and glued on a shaker machine in order to stimulate inputs with variable frequency sine waves. In these tests, the sampling rate, overall timing and calibration aspects were verified.

As a last step, the tri-axial sensor was glued on the inner liner of the mechatronic tyre. Real acceleration signals were obtained at different loads and equivalent speeds. Different receiver antenna positions were investigated in order to find the best orientation and location.

Sensors

The sensor verification was a gradual process carried out in a number of tests in the course of the development process (see Deliverable D12: New types of sensors for tyres, their preliminary specifications and fabrication instructions).
4.2.2  Mechatronic tyre verification

Test on the Pirelli shaker

First indoor test were carried out on the Pirelli shaker in order to test the system in terms of RF performances.

During this test session, the sensor was glued on the shaker and connected by wire to the transceiver attached to the rim. The receiver was linked to a PC in order to store signals from the accelerometer (Figure 38 and 39).

The correct sampling frequency and TX/RX coherence were tested during this session by forcing a sine excitation (several amplitude and different frequency) to the shaker and measuring the sensor response.

![Indoor test on Pirelli shaker. Endevco accelerometer glued on shaker (on the left) and transmitter linked to rim (on the right).](image)

Figure 38. Indoor test on Pirelli shaker. Endevco accelerometer glued on shaker (on the left) and transmitter linked to rim (on the right).

![Indoor test on Pirelli shaker. Receiver (on the left) and Personal Computer (on the right) to store and analyze data from sensor.](image)

Figure 39. Indoor test on Pirelli shaker. Receiver (on the left) and Personal Computer (on the right) to store and analyze data from sensor.

As can be seen in Figure 40, no spikes in centripetal acceleration (Figure 40 shown as an example. Also longitudinal and lateral direction were tested) were stored.

The good results obtained during this test session allowed the testing of the system on a Pirelli drum facility.
Test on the Pirelli drum

A number of tests on the Pirelli facility were carried out to test system performances in terms of mechanical and electrical reliability and to find out the best receiver antenna position (Figures 41 and 42).

As reported above, the maximum running speed was restricted to 100 km/h in order to ensure the functioning of the mechatronic tyre.

The tests were conducted under the following conditions:

- wheel speed: from 10 to 100 km/h (10 km/h step);
- vertical load: 0, 2000, 3000 and 4000 N.

No other parameter (i.e. slip angle, camber, etc.) was varied.

Good results were obtained in terms of mechanical (sensor gluing and electronic device positioning) performance, and no problems occurred during the indoor test session on the drum.

Also, a number of trials were carried out to find out the best receiver antenna position. The receiver antenna position has been changed in order to find the best one in terms of RF transmission: in Figure 41, two positions are shown: the best one is on the right hand side.

The best antenna position is characterized by the receiver antenna oriented in parallel to a tyre meridian plane.

*Figure 40. Indoor test on Pirelli shaker. Shaker sine excitation, 800 m/s$^2$, 1000 Hz. Z direction (yellow line).*
Figure 41. Best antenna position seeking. One tested position (on the left) and the best one (on the right).

Figure 42. The prototype running on Pirelli drum facility. The receiver RF module is positioned near the tyre (see the white box in the photo above): antenna is oriented in parallel to the tyre meridian plane.

The best antenna position allows to achieve good RF transmission results: as can be seen in Figure 43, there are no spikes (= no failures in transmission) in measured acceleration. See also Figure 44 as an example of various test conditions.
Figure 43. Test on Pirelli facility. Tyre P6000 Powergy, 225/55 R16. Test condition: vertical load 3000 N, drum speed 80 km/h. Longitudinal (green), lateral (red) and centripetal (black) acceleration. On X-axis: number of samples, on Y-axis: acceleration (g).

Figure 44. Test on Pirelli facility. Tyre P6000 Powergy, 225/55 R16. Test condition: vertical load 3000 N, drum speed 80 km/h. Longitudinal (green), lateral (red) and vertical (black) acceleration. **Zoom on a single wheel turn.** X-axis: number of samples, Y-axis: acceleration (g).
Finally, pre-tests of the mechatronic tyre, equipped with three sensors in one tyre (3to1 tyre) were conducted to check the functioning of the sensor system. From each plot the sensor signal is available for one wheel revolution under cornering (Figure 45). Plots are organised to show one sensor in each row. The different transducer channels are depicted in different colours by their measuring direction. All sensors provided a signal per wheel revolution. This confirms that all sensor channels are working and feed signals to the data logger.

![Figure 45. Raw signals of the mechatronic tyre: the piezo sensor (uppermost row), acceleration sensor (middle row) and the optical sensor the (lowest row). Data was obtained under cornering and free rolling by means of a test rig.](image)

Overall, the verification procedures as shown and explained above describes a more or less general procedure for appropriate and systematic testing of the mechatronic tyre.

### 4.2.3 Test results

The data obtained from the mechatronic tyre was post processed by the described signal interpretation strategy. Each sensor of the mechatronic tyre (acceleration sensor, optical sensor and strain sensor) was analysed to assess its performance to provide information out of the running tyre. All post-processing algorithms are described in Deliverable 16 “Overall tyre-vehicle-system behaviour and test results” in detail. The raw data is obtained from measurements performed on a flat track test rig.

The potential to identify wheel load, lateral force and longitudinal force was analysed for each sensor. Algorithms to calculate the desired measure are derived in case the sensor did provide useful signals. This evaluation was performed under more or less ideal boundary conditions (constant wear, constant temperature, low surface roughness). Despite, the target measures ($F_z$, $F_y$, and $F_x$) a variation of inflation pressure was considered. But even in this ideal case, the potential of the three sensors came out to be very different. Results are summarised in Figure 46 below.
The analysis of the 3to1 tyre did result in a very clear ranking of the potential to identify wheel forces. While the optical sensor was able to identify all wheel forces at the considered boundary conditions, the accelerometer did show the lowest potential. However, in terms of robustness, the accelerometer is by far the best option.

4.2.4 Demonstration

The final demonstration of Apollo project was carried out on Nokian Tyres plc’s test track in Nokia, Finland (Figure 48). The demonstration car was a Mercedes-Benz S 500 car provided by DaimlerChrysler (Figure 47). The car was equipped with the 3to1 intelligent tyre prototype and the necessary receiver and graphical display technology. One front wheel of the car was replaced with the Nokian tyre including three different sensors. This 3to1 prototype had an acceleration sensor, an optical sensor and a piezo film sensor. Due to the multiple sensor approach, the data transmission rate was slower than in the first prototype.

The functioning of the prototype was demonstrated in several driving manoeuvres on different surfaces. Varying wheel load was demonstrated on high-friction surface. The car was driven in a curve with the wheel load shifting from the inner tyre to the outer tyre. The information from the intelligent tyre prototype are displayed on the screen of a laptop computer by means of custom made graphical interface. A second demonstration comprised driving in a circle with different surface structures. The demonstration system showed different signals on different surfaces.
Figure 47. Apollo project’s Demonstrator vehicle is a Mercedes-Benz S500 equipped with two different intelligent tyre prototypes on the front axle and the necessary receiver antennas and a laptop computer for displaying the information coming from the prototypes.

Figure 48. Apollo project’s final demonstration site on Nokian Tyres plc’s test track in Nokia, Finland.
5 Project results and achievements

5.1 Meeting the objectives

Overall, the project had a very ambitious target of both:

- Creating a prototype of mechatronic tyre system, a so called "Intelligent Tyre" comprising of a sensor, wireless communication and batteryless power supply and
- Showing in a vehicle demonstrator that the Intelligent Tyre system is capable of providing essential signals of tyre-road contact, later to be used to improve driving safety.

When assessing how the objectives of the project were met, it is stressed that this is the first attempt of this kind ever made. Tyre sensor and other development work on monitoring road surface properties have been carried out previously by other players too (see Chapter. 4.1.3 State of the art) but never before a whole mechatronic tyre system with all components included has been designed and prototyped. Moreover, compared to other developments in the area with much narrower scope, the project proceeded in the sensor system development in three years time further than comparable 'advanced' tyre sensors in ten years time.

The project met most of the objectives set in the TA. However, the most ambitious and difficult parameter to obtain, available friction could not be determined by using the approaches described.

The APOLLO project objectives as listed in the Technical Annex are shown in the Table 7 below.

<table>
<thead>
<tr>
<th>&quot;The overall- and R&amp;D-objectives of APOLLO&quot; as defined in Technical Annex, page 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
</tr>
<tr>
<td>Investigating the needs and expectations of various user groups concerning an intelligent tyre</td>
</tr>
<tr>
<td>Showing the added value the intelligent tyre can provide for driving safety and comfort as well as providing with other services for different user groups also outside the vehicle</td>
</tr>
<tr>
<td>Defining a reference application for the intelligent tyre prototype in APOLLO-project</td>
</tr>
<tr>
<td>Developing a novel sensor system mechanically integrated into the tyre such as capacitive sensors for sensing the following signals or parameters: - forces exerted on the tyre, - slip, - friction potential, - tread wear</td>
</tr>
</tbody>
</table>
5.2 Dissemination

APOLLO project's dissemination process can be regarded as conventional and reasonably active. Most customary means of providing and spreading information on projects results were used such as:

- Setting up public APOLLO www-pages:  
- taking part into seminars and conferences,
- submitting papers in scientific journals,
- organising press conferences on the topic and
- APOLLO results used in teaching technical university students (Germany, Finland).
The dissemination was working, since the project was contacted a number of times of having more detailed info or a possibility to join the consortium. The APOLLO project was notified even by the Russian press. Moreover, the project was contacted from Japan to buy one of APOLLO patents.

The main dissemination activities are summarised in the following table (Table 8). The list is not exhaustive, since, especially, all articles in papers are not known and listed here. Moreover, the list includes only activities having a presentation by the APOLLLO consortium.

Table 8. Main dissemination activities in the APOLLO project.

<table>
<thead>
<tr>
<th>Type of activity</th>
<th>Description</th>
<th>Reporting period</th>
</tr>
</thead>
<tbody>
<tr>
<td>APOLLO www-pages</td>
<td>Public part</td>
<td>1st</td>
</tr>
<tr>
<td>Public deliverable</td>
<td>13 totally, describing most relevant aspects of the project</td>
<td>1st to 12th</td>
</tr>
<tr>
<td>Discussion - forum</td>
<td>Opened on APOLLO pages (use was slight)</td>
<td>1st to 12th</td>
</tr>
<tr>
<td>International Conference</td>
<td>The IEEE International Conference on Intelligent Transportation Systems, ITSC2002 Singapore</td>
<td>1st</td>
</tr>
<tr>
<td>Concentration meetings</td>
<td>2 in ADASE II</td>
<td>1st to 6th</td>
</tr>
<tr>
<td>Newspaper articles</td>
<td>4 (not all listed, since no tracking possible)</td>
<td>1st to 12th</td>
</tr>
<tr>
<td>HIGHTECH Report of DC AG</td>
<td>DaimlerChrysler dissemination; Issue 2/2003</td>
<td>4th</td>
</tr>
<tr>
<td>TV interview</td>
<td>Finnish TV</td>
<td>7th</td>
</tr>
<tr>
<td>Professional seminar</td>
<td>3rd International Tyre Colloquium, August 2004 in Wien/Austria.</td>
<td>10th</td>
</tr>
<tr>
<td>Professional conference</td>
<td>Tire technology conference, March 2003, Hamburg</td>
<td>5th</td>
</tr>
<tr>
<td>Nordic seminar</td>
<td>Finnish tyre forum, April 2003</td>
<td>5th</td>
</tr>
<tr>
<td>International Conference</td>
<td>ÖPET fuel saving forum, September 2003, Brussels</td>
<td>6th</td>
</tr>
<tr>
<td>International seminar</td>
<td>Intelligent Tyre System on chip seminar, October 2003 Tampere</td>
<td>7th</td>
</tr>
<tr>
<td>International Congress</td>
<td>FISITA Automotive World Congress 2004, Barcelona</td>
<td>9th</td>
</tr>
<tr>
<td>International Congress</td>
<td>SAE 2004 Future Car Congress, USA</td>
<td>9th</td>
</tr>
<tr>
<td>International seminar</td>
<td>Intelligent Tyre System on chip seminar, October 2003 Tampere</td>
<td>7th</td>
</tr>
<tr>
<td>International seminar</td>
<td>Finnish Rubber Association Seminar, November 2003, Tampere</td>
<td>7th</td>
</tr>
<tr>
<td>International seminar</td>
<td>TVMDA 04, Wien, August 2004</td>
<td>10th</td>
</tr>
<tr>
<td>International conference</td>
<td>13. Aachener Colloquium, Aachen, October 2003</td>
<td>7th</td>
</tr>
<tr>
<td>International Journal</td>
<td>Auto technology</td>
<td></td>
</tr>
<tr>
<td>IEE journal</td>
<td>A paper on preparation by VTT</td>
<td>12th</td>
</tr>
<tr>
<td>Professional conference</td>
<td>Tire technology Conference, February 2005, Cologne</td>
<td>12th</td>
</tr>
<tr>
<td>World Congress</td>
<td>SAE World Congress, April 2005, Detroit</td>
<td>12th</td>
</tr>
<tr>
<td>International Journal</td>
<td>Auto technology: “A Tyre Sensor System with Electronics for Data Transmission and Power Supply” by ika, DC AG, VTT &amp; PIRELLI</td>
<td>After the project</td>
</tr>
<tr>
<td>International conference</td>
<td>“Reifen - Fahrwerk - Fahrbahn”, October 2005, Hannover</td>
<td>After the project</td>
</tr>
</tbody>
</table>
6 Roadmap

Today, a number of intelligent driver support systems are already on the market with the trend being towards more proactive/preventive safety systems (Figure 49). From the roadmap for vehicle dynamics applications, it can be seen that already today, there are a number of driver support applications on the market. Especially, the number of various active safety systems will increase in short to mid term (< 10 years).

All these systems require several sensor signals for a precise functional operation. Until now, various driver assistance functions have mainly used signals from in-vehicle sensors such as acceleration, yaw rate, wheel rotation, steering wheel and brakes. During the past few years, also so called environmental sensors (77 GHz radar for ACC, machine vision for lateral control) have entered the market and now, also intelligent tyre technologies are under intensive development beyond pressure and temperature monitoring only.

The tyre-road contact and the available friction therein has a great impact on vehicle control. All forces for vehicle dynamics will be transferred through a contact patch about the size of a man's palm. Without the tyre-road contact and under very low friction conditions no forces can be applied to the vehicle making steering and braking very difficult. For this reason, more information on tyre-road friction and road slipperiness is needed to enhance ADAS functions that are not yet mature enough to exploit their full potential.

The main future intelligent tyre features are depicted as follows:

1) Ability to sense friction potential of driving surface
2) Ability to sense current wear status (tread depth)
3) Ability to sense forces, accelerations and deformations needed by vehicle control systems
4) Ability to sense concealed damage (future blow out)

Figure 49. Road map of intelligent driver support systems of which many can be improved by intelligent tyre technologies (RWTH Aachen, 2005).
5) Ability to sense overload

The best technology that allows these new properties, has not yet been invented. The "killer" technology will:

1) Require minimum (or no) electronics in the harsh tyre environment, all intelligence should be located outside the tyre (good example: Continental's Side Wall Torsion system),
2) Require no battery,
3) Cause no imbalance or tyre mounting problems,
4) Cause no major additional cost and
5) Can be disposed with the tyre in the end of life.

Although monitoring friction potential seems the most difficult, it is also the most desired new feature from the driving safety point of view. However, this parameter is still some years ahead (Figure 50).

Figure 50. State of the art of intelligent tyre technology (TPMS) and future applications.

7 Deliverables and other outputs

The project reporting followed closely to the deliverable list drawn up in the Technical Annex (Table 9). There were some deviations from the planned time table, but overall, also the planned reporting schedule was reasonably well observed.

An extra deliverable was produced. That dealt with the Deliverable 4 "Test plan and the guidelines for the interpretation of measurements". The deliverable was named Test plan and the guidelines for the interpretation of measurements - extension. The reason was that the timing for the deliverable was planned too early. The extension specified in more detail the actual testing plan.
Table 9. Project deliverables.

<table>
<thead>
<tr>
<th>Del. no.</th>
<th>Deliverable name</th>
<th>WP no.</th>
<th>Lead particip.</th>
<th>Estim. person-months</th>
<th>Del. type*</th>
<th>Security**</th>
<th>Delivery (project month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Project presentation</td>
<td>1</td>
<td>VTT</td>
<td>12</td>
<td>Report</td>
<td>Pub.</td>
<td>3</td>
</tr>
<tr>
<td>D2</td>
<td>Project fact sheet</td>
<td>1</td>
<td>VTT</td>
<td>12</td>
<td>Report</td>
<td>Int.</td>
<td>3</td>
</tr>
<tr>
<td>D3</td>
<td>Project website</td>
<td>1</td>
<td>VTT</td>
<td>12</td>
<td>Website</td>
<td>Pub./Int.</td>
<td>3</td>
</tr>
<tr>
<td>D4</td>
<td>Test plan and the guidelines for the interpretation of measurements</td>
<td>3</td>
<td>RWTH Aachen</td>
<td>77</td>
<td>Report</td>
<td>Pub.</td>
<td>3</td>
</tr>
<tr>
<td>D5</td>
<td>Dissemination and use plan</td>
<td>9</td>
<td>DG AC</td>
<td>7</td>
<td>Report</td>
<td>Pub.</td>
<td>4</td>
</tr>
<tr>
<td>D6</td>
<td>Needs of various user groups, the interview method and results</td>
<td>7</td>
<td>HUT</td>
<td>30</td>
<td>Report</td>
<td>Pub.</td>
<td>9</td>
</tr>
<tr>
<td>D7</td>
<td>Intelligent tyre systems – State of the art and potential technologies</td>
<td>2</td>
<td>DC AG</td>
<td>37</td>
<td>Report</td>
<td>Pub.</td>
<td>10</td>
</tr>
<tr>
<td>D8</td>
<td>Potential applications, requirements and reference application</td>
<td>2</td>
<td>DC AG</td>
<td>37</td>
<td>Report</td>
<td>Int.</td>
<td>10</td>
</tr>
<tr>
<td>D9</td>
<td>Dynamic tyre behaviour with respect to sensor technologies</td>
<td>3</td>
<td>RWTH Aachen</td>
<td>77</td>
<td>Report</td>
<td>Rest.</td>
<td>13</td>
</tr>
<tr>
<td>D10</td>
<td>Description of design concept, specifications and test results of communication interface and a power supply</td>
<td>5</td>
<td>MM</td>
<td>62</td>
<td>Report</td>
<td>Rest.</td>
<td>21</td>
</tr>
<tr>
<td>D11</td>
<td>Communication interface and a power supply prototype(s)</td>
<td>5</td>
<td>MM</td>
<td>62</td>
<td>Prototype</td>
<td>Rest.</td>
<td>21</td>
</tr>
<tr>
<td>D12</td>
<td>Prototype of novel sensors</td>
<td>4</td>
<td>VTT</td>
<td>78</td>
<td>Prototype</td>
<td>Rest.</td>
<td>22</td>
</tr>
<tr>
<td>D13</td>
<td>New types of sensors for tyres, their preliminary specifications and fabrication instructions</td>
<td>4</td>
<td>VTT</td>
<td>78</td>
<td>Report</td>
<td>Pub.</td>
<td>23</td>
</tr>
<tr>
<td>D14</td>
<td>Scenario description: safe traffic, safe vehicle and safe tyre</td>
<td>7</td>
<td>HUT</td>
<td>30</td>
<td>Report</td>
<td>Pub.</td>
<td>30</td>
</tr>
<tr>
<td>D15</td>
<td>Mechatronic tyre-wheel system prototype</td>
<td>6</td>
<td>PIRELLI</td>
<td>72</td>
<td>Prototype</td>
<td>Rest.</td>
<td>32</td>
</tr>
<tr>
<td>D16</td>
<td>Overall tyre-vehicle-system behaviour and test results</td>
<td>3</td>
<td>RWTH Aachen</td>
<td>77</td>
<td>Report</td>
<td>Rest.</td>
<td>32</td>
</tr>
<tr>
<td>D17</td>
<td>Description of design concept, specifications of mechatronic tyre-wheel system</td>
<td>6</td>
<td>PIRELLI</td>
<td>72</td>
<td>Report</td>
<td>Rest.</td>
<td>33</td>
</tr>
<tr>
<td>D18</td>
<td>Test vehicle equipped with mechatronic tyre-wheel system</td>
<td>8</td>
<td>NR</td>
<td>55</td>
<td>Prototype</td>
<td>Pub.</td>
<td>35</td>
</tr>
<tr>
<td>D19</td>
<td>Verification system description including a test report</td>
<td>8</td>
<td>NR</td>
<td>55</td>
<td>Report</td>
<td>Rest.</td>
<td>36</td>
</tr>
<tr>
<td>D20</td>
<td>Video and/or a CD-ROM animation of the verification system</td>
<td>8</td>
<td>NR</td>
<td>55</td>
<td>CD-ROM</td>
<td>Pub.</td>
<td>36</td>
</tr>
<tr>
<td>D21</td>
<td>Exploitation plan</td>
<td>8</td>
<td>DC AG</td>
<td>7</td>
<td>Report</td>
<td>Pub.</td>
<td>36</td>
</tr>
<tr>
<td>D22</td>
<td>Final report (including TIP)</td>
<td>1</td>
<td>VTT</td>
<td>12</td>
<td>Report</td>
<td>Int.</td>
<td>36</td>
</tr>
<tr>
<td>D23</td>
<td>Final report for publication</td>
<td>1</td>
<td>VTT</td>
<td>12</td>
<td>Report</td>
<td>Pub.</td>
<td>36</td>
</tr>
<tr>
<td>D24</td>
<td>Quarterly management reports</td>
<td>1</td>
<td>VTT</td>
<td>12</td>
<td>Report</td>
<td>Int.</td>
<td>3 -36</td>
</tr>
</tbody>
</table>

* A short, self-evident description e.g. report, demonstration, conference, specification, prototype...
8 Project management and co-ordination aspects

8.1 Communication Between Partners

Overall, project management and coordination was carried out and progressed routinely.

The management was assisted by an external quality control person. The duties of the quality control person was to ensure the quality of reporting, monitor that the project is on track and the work is proceeding towards meeting the objectives.

In addition to the meeting discussions, a major part of the communication between partners has been made by means of electronic mail (E-mail) and by phone. The formal information between Partners has been however on paper especially when official signatures have been needed. The Coordinator has been the link between the Partners and the Commission.

The project Internet sites were available on June 2002 and are located in the address: http://www.vtt.fi/tuo/projects/apollo/index.htm. Apollo web- pages have been worked interactively with users via the web survey, which was launched at the beginning of the project.

Apollo project also has internal intranet pages for distribution of confidential information to the partners. These pages locate in the address: http://proxnet.vtt.fi/apollo/ and need a user name and password to be able to log in. Apollo pages have been actively in use throughout the duration of the project and have been the main channel of distribution of project information and knowledge.

8.2 Meetings

The following meetings were held during the project:

Table 10. List of the project meetings held.

<table>
<thead>
<tr>
<th>Type</th>
<th>Time</th>
<th>Place</th>
<th>Attended by</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Pre-kick off meeting</td>
<td>25 January 2002</td>
<td>Aachen</td>
<td>All partners)</td>
</tr>
<tr>
<td>Project Kick-off Meeting</td>
<td>21-22 March 2002</td>
<td>Ivalo, Finland</td>
<td>All partners, EC</td>
</tr>
<tr>
<td>Consortium meeting</td>
<td>18-19 April 2002</td>
<td>Milan, Italy</td>
<td>All partners</td>
</tr>
<tr>
<td>Consortium meeting +Technical WP meetings</td>
<td>26-27 June 2002</td>
<td>Espoo, Finland</td>
<td>All partners</td>
</tr>
<tr>
<td>Additional meeting for sensor system discussion</td>
<td>25 September 2002</td>
<td>Frankfurt, Germany</td>
<td>Sensor group</td>
</tr>
<tr>
<td>Consortium meeting</td>
<td>9-10 December 2002</td>
<td>Frankfurt, Germany</td>
<td>All partners</td>
</tr>
<tr>
<td>Small Group meeting</td>
<td>20 January 2003</td>
<td>Aachen, Germany</td>
<td>VTT, DC, IKA</td>
</tr>
</tbody>
</table>
In the project kick-off meeting, guidelines for the project administration and management were introduced. Regular consortium meetings handled progress of the project and issues related to milestones, project deliverables, periodic reports and management. Three annual project reviews per year were held during the project. Generally, partners have actively taken part in the meetings as well as the project work.

Three dedicated workshops/small group meetings were organised to speed up resolving some specific issues. These were agreement on a reference application, integration of sub-systems into a mechatronic tyre and the evaluation of tests results.

Moreover, a number of bilateral work meetings were held when sub-systems were being tested & optimised and in the integration of the electronics in the mechatronic tyre.

### 8.3 Contract Amendment

Three contract amendments was made during the project. The first Contract Amendment concerned changes in contact details of the contractors and change in VTT's bank account. The amendment was accepted by EC on 16th October 2003.

The second Contract Amendment concerning changes in contact details of the contractors and budget transfers between contractors was accepted by EC on 13th October 2004.

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Date</th>
<th>Location</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consortium meeting</td>
<td>17 February 2003</td>
<td>Frankfurt, Germany</td>
<td>All partners</td>
</tr>
<tr>
<td>Steering Committee meeting</td>
<td>26 May 2003</td>
<td>Turin, Italy</td>
<td>Steering committee</td>
</tr>
<tr>
<td>Review team meeting</td>
<td>26 June 2003</td>
<td>Brussels, Belgium</td>
<td>Review team</td>
</tr>
<tr>
<td>1st Annual Review</td>
<td>27 June 2003</td>
<td>Brussels, Belgium</td>
<td>Review team</td>
</tr>
<tr>
<td>Consortium meeting</td>
<td>29-30 September 2003</td>
<td>Helsinki boat meeting, Finland</td>
<td>All partners</td>
</tr>
<tr>
<td>Consortium meeting</td>
<td>2-3 February 2004</td>
<td>Milan, Italy</td>
<td>All partners</td>
</tr>
<tr>
<td>Consortium meeting</td>
<td>28-29 June 2004</td>
<td>Tampere, Finland</td>
<td>All partners</td>
</tr>
<tr>
<td>Steering Committee meeting</td>
<td>9 September 2004</td>
<td>Brussels, Belgium</td>
<td>Steering Committee</td>
</tr>
<tr>
<td>2nd Annual Review</td>
<td>10 September 2004</td>
<td>Brussels, Belgium</td>
<td>Review team</td>
</tr>
<tr>
<td>Workshop</td>
<td>17-20 November 2004</td>
<td>ika, Aachen</td>
<td>HUT, ika, PIRELLI</td>
</tr>
<tr>
<td>Steering Committee meeting</td>
<td>29 November 2004</td>
<td>Aachen, Germany</td>
<td>Steering Committee</td>
</tr>
<tr>
<td>Consortium meeting</td>
<td>14 December 2004</td>
<td>Brussels, Belgium</td>
<td>All partners</td>
</tr>
<tr>
<td>Workshop</td>
<td>2-3 December 2004</td>
<td>PIRELLI, Milan</td>
<td>ika, PIRELLI, MM</td>
</tr>
<tr>
<td>Workshop</td>
<td>22 March 2005</td>
<td>Espoo, Finland</td>
<td>HUT, IKA, VTT</td>
</tr>
<tr>
<td>Consortium meeting</td>
<td>4 April 2005</td>
<td>Turin, Italy</td>
<td>All partners</td>
</tr>
<tr>
<td>Final Review</td>
<td>20 May 2005</td>
<td>Nokia, Finland</td>
<td>Review team, EC</td>
</tr>
</tbody>
</table>
The third Contract Amendment concerned three months extension to the project. The amendment was signed by EC on 30th December 2004. The duration of the project is after the extension 39 months.

9 Conclusions

9.1 Driving forces for an intelligent tyre system

The APOLLO project was set up for an obvious need to meet the increasing needs to improve active vehicle safety. Today, potential applications and systems that can benefit from more precise information on road slipperiness and tyre-road contact are control systems for driving dynamics and driving safety are numerous such as Slip Control Systems, Emergency Braking System (EBS), Electronic Stability Programme (ESP), Adaptive Cruise Control (ACC) to name a few.

Vehicle safety systems on the market using information on road conditions - even indirectly, are still few. These are Slip Control Systems (e.g. ABS) and Electronic Stability Programme (ESP). Current Advanced Driver Assistance Systems contain/provide no information on a safe driving speed. If the speed is too high, the vehicle cannot be controlled even with the help of advanced systems such as ESP, since the friction available between the tyres and the road is simply too small.

Collision Avoidance Systems (CAS) and EBS calculate steering angles and braking needed to avoid collisions, but without information on friction forces available, the vehicle can not execute the calculated manoeuvres in an optimal way. When there is no information on friction, EBS will brake too late on a wet or icy road.

Today, when any given Active Safety System is activated only when the driver has made manoeuvres which lead to wheel slippage or in an extreme case to a collision, one of the key functions is driver pre-warning of dangerous conditions.

The examples above served as motivating forces to engage in work towards an intelligent tyre system.

On the other hand, a Tyre Pressure Monitoring Systems (TPMS) standard was passed in 2002 in USA. It requires an installation of a TPMS to warn the driver if the tyre is significantly under-inflated. This legislation has also been a strong driver for the overall development of advanced tyre technologies.

The APOLLO project engaged in an ambitious task of creating an intelligent tyre system with all sub-systems and components needed for the realisation of it. The requirements of the system concerned providing (i) information to drivers, (ii) external users, (iii) vehicle control systems and (iv) Advanced Driver Assistance Systems.

9.2 Prototype of a mechatronic tyre

The project was realised by developing sub-systems for communication from tyre to vehicles systems, power generation for communication and the actual sensor for tyre-road contact monitoring. The realisation and integration of all these sub-systems into a mechatronic tyre prototype required innovative approaches and a new deep understanding of tyre phenomena and tyre-vehicle system level behaviour.

The target of the project was a prototype of a mechatronic tyre capable of providing information on various parameters of tyre-road contact such as forces exerted on tyre, slip information, friction potential, tread wear, prediction of tyre damage and road surface qualities. Many of these target
information can be obtained by the new tyre but not all. Especially, friction potential seems to be out of reach by the system developed using acceleration sensor only.

Power supply development showed the following: two methods were developed to meet the goal of a batteryless operation. Inductive transmission was found to be capable of remarkable power availability. Piezo generator has a limited power capability below 1mW and can be considered only if the amount of data to be transmitted, decreases a lot in the final application. Concerning the sensor development, by using the acceleration sensor, the contact length can be determined fairly accurately on road conditions either from the radial velocity or tangential position signal. In the former the standard deviation is 5 per cent and in the latter 3 per cent on normal asphalt. This uncertainty is low enough for determining the contact length. It also allows the determination of the wheel load if the pressure is measured independently. One of the main results of this study is that even if the acceleration sensor is located on the inner liner, its output indicates the roughness of the road surface. This is particularly true for the lateral sensor. The tangential deflection signal was different on the high and low friction surfaces. Therefore, it might be used for the evaluation of the friction coefficient.

The other two sensors, piezo and optical showed promising performance, even better than that of an acceleration sensor, but so far, they can not be considered for automotive use due to lacking robustness.

In the course of the project, three versions of the communication system were developed in order to manage different sensor system configurations. After the first version able to manage three acceleration signals, a four-channel for optical sensors and an eight-channel communication interface for mixed acceleration, optical and piezo sensors have been developed and used. For such different versions specific transmitter devices have been designed while the hardware receiver chain has been the same. The software were changed in order to manage different frame configurations.

Furthermore, different versions of transmitter, receiver (RF interface) and antennas have been developed in order to facilitate the mounting on the mechatronic demonstrator and to guarantee good data transmission in drum and car tests. A circularly polarized antenna has been designed for the receiver to eliminate transmission failures due to particular reciprocal orientations with transmitter’s rotating antenna. For vehicle tests, an Ethernet connection to a second PC has been set up in order to visualize in real time acceleration signals and process the data.

After these sub-system developments and integration, a mechatronic tyre was created and verified. Even the integration of electronics in the tyre proved to be a challenging task. The project had to acquire a custom made dividable rim to ensure the integration in a reasonable time and effort.

Overall, the project faced a number of challenging tasks all the way from system requirements to the first verification tests of the whole system. It is clear that many of the technical solutions are possible in the first prototype only. The weight and size of the electronics parts and components need to come down and the durability improved concerning series production. Moreover, better understanding of sensor signals is still needed and the theoretical model improved to have more precise information of tyre road contact and associated tyre deformations.

### 9.3 Future

The future work faces one fundamental question: is one tyre sensor sufficient for monitoring tyre-road contact. Should we carry on the work based on a more enhanced theoretical model, or should there be more empirical approach adopted. Furthermore, more work in the signal processing area is needed to better understand the tyre behaviour. Some test results are indeed promising also for the accelerometer, since clearly different signals are obtained on different road surfaces.
Another question posed is: are there other sensors available that can be used to support or even substitute the accelerometer as a tyre sensor in determining friction available.

On-line monitoring adverse road conditions seems to be more of a technical problem than a marketing issue. Owing to a great potential of friction information to enhance the functioning of a number of driving dynamics applications, there is demand for a road surface monitoring system in the automotive sector - provided the costs for such a system are reasonable. Also external users, especially road operators are in a need of continuous information along the road network rather than on cross-sectional points as turned out in the project by Finnish Road Administration.
REFERENCE LIST

1. Bosch, 2005 (http://www.bosch-presse.de)
2. Deliverable D4: Test plan and the guidelines for the interpretation of measurements
3. Deliverable D6: Needs of various user groups, the interview method and -results
4. Deliverable D7: Intelligent tyre systems – State of the art and potential technologies
5. Deliverable D8: Potential applications, requirements and reference application
6. Deliverable D9: Dynamic tyre behaviour with respect to sensor technologies
7. Deliverable D10: Description of design concept, specifications and test results of communication interface and a power supply
8. Deliverable D11: Communication interface and a power supply prototype(s)
10. Deliverable D13: Scenario description: safe traffic, safe vehicle and safe tyre
11. Deliverable D16: Overall tyre-vehicle-system behaviour and test results
12. Deliverable D17: Description of design concept, specifications of mechatronic tyre-wheel system
13. Deliverable D19: Verification system description including a test report
**APPENDIX**

**Used Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ABC</td>
<td>Advanced Brake Control</td>
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<tr>
<td>ABS</td>
<td>Antilock Braking System</td>
</tr>
<tr>
<td>ACC</td>
<td>Adaptive Cruise Control</td>
</tr>
<tr>
<td>ADAMS</td>
<td>A commercial software package for the analysis of mechanisms and complex mechanical structures</td>
</tr>
<tr>
<td>ADAS</td>
<td>Advanced Driver Assistance Systems</td>
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<tr>
<td>AIAG</td>
<td>Automotive Industry Action Group</td>
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<tr>
<td>ASK</td>
<td>Amplitude Shift Keying</td>
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<tr>
<td>CAS</td>
<td>Collision Avoidance System</td>
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<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
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<tr>
<td>DIS</td>
<td>Driver Information System</td>
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<tr>
<td>EMC</td>
<td>Electromagnetic compatibility</td>
</tr>
<tr>
<td>FCD</td>
<td>Floating Car Data</td>
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<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
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<tr>
<td>Finnra</td>
<td>Finnish Road Administration</td>
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<tr>
<td>HGV</td>
<td>Heavy Goods Vehicle</td>
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<tr>
<td>HMI</td>
<td>Human-Machine Interface</td>
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<tr>
<td>IPR</td>
<td>Intellectual Property Rights</td>
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<tr>
<td>MATLAB</td>
<td>A commercial general purpose mathematical software package</td>
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<tr>
<td>PSD</td>
<td>Position Sensitive Diode</td>
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<td>ROI</td>
<td>Return On Invest</td>
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<tr>
<td>RF</td>
<td>Radio frequency</td>
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<tr>
<td>RFID</td>
<td>Radio Frequency Identification</td>
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<tr>
<td>SAW</td>
<td>Surface acoustic wave</td>
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<tr>
<td>Simulink</td>
<td>An optional simulation tool package for MATLAB</td>
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<tr>
<td>SWT</td>
<td>Side wall torsion</td>
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<tr>
<td>TPMS</td>
<td>Tyre Pressure Monitoring System</td>
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<tr>
<td>v2v</td>
<td>Vehicle to vehicle communication</td>
</tr>
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