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INtelligent Renewable Optical ADvisory System (INROADS)

Berichterstattung

Projektinformationen

INROADS

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Final Report Summary - INROADS (INtelligent Renewable Optical ADvisory System (INROADS))

Executive Summary:
The INROADS project, led by TRL with seven European partners, aimed to develop intelligent road studs containing lighting, sensors and communication technologies, which will enable enhanced traffic management and road user information.

This represents a major innovation over the existing retroreflective studs as not only do they have increased conspicuity, but they will also be able to communicate with each other and with a central control, making the system highly reactive and adaptable. They will also harvest energy from their environment.

Their greater visibility compared with standard retroreflective studs is a significant safety benefit, particularly on unlit roads. In such situations, they offer an extremely attractive and cost-effective solution to traditional street lighting, in that they offer many of the safety benefits, but with a much lower capital and operational cost.

After consultation with industry and research experts, the project team chose to focus on the most technically challenging applications, and demonstrate the feasibility of other simpler ones either by analogy or simulation. The applications chosen are as follows.

• active lane delineation on unlit roads where nodes detecting approaching vehicles send a command to illuminate the pavement and road edge on the section ahead
• smart pedestrian crossings, where a system enhancing the visibility of the crossing is activated when pedestrians are about to cross
• advanced hazard warnings, where sensors detecting the presence of obstacles on the pavement trigger a warning to road users
• pavement-embedded signage, which consists of an array of lights forming in-pavement signs or displaying fixed/scrolling messages.

A key task is to understand human factors through psycho-visual evaluation and behavioural studies to assess user acceptance of the applications. This was undertaken in 2013 with the results indicating

improved driver performance on roads delineated by lit studs. Experiments in TRL's accelerated Pavement Testing Facility to assess the robustness of the nodes and the performance of the energy harvesting technologies is took place in 2014. The results showed that the performance of the piezoelectric generators relied heavily on being trafficked directly with energy performance reducing considerably outside the wheelpaths.

A number of site trials focussing on the deliberately challenging active lane delineation application were undertaken in 2014 and 2015 to determine the acceptability of the system and integration of components. Rigorous trials proved the performance capability of the individual components although when integrated there were a number of performance issues. The final results showed high promise for the technologies although it was determined that the aim of being self-contained for power was unachievable for the application considered and it is considered that the supply of external power, possibly from a site based solar / wind solution would help overcome these issue. Recommendations for further development work have been prepared.
Project Context and Objectives:
Road studs are used around the world to delineate, along with painted lines, road space through retro-reflective spheres, which are illuminated by vehicle headlights. In recent years, the use of LED lights within road studs has been developed which has the significant advantage that the road studs are more visible due to active lighting than is achievable through reflection alone, can use dynamic colours and can be seen at angles that would not be reflected by headlights, e.g. the outline of a curve in the road which would only be illuminated by reflection as the car travelled around the curve. These properties make LED road studs useful for locations where there is an increased risk of accidents such as unlit country roads, but their use has been predicted to increase generally on unlit roads, both major and minor, as an alternative to traditional street lighting. Typically, the LED lights are a single colour, such as white for lane delineation or red for the hard shoulder for example, although the potential to have active lighting, such as blue in cold weather or red if a vehicle is travelling too close to another have been explored. There will be a trade-off between the potential additional information that could be achieved using additional colours, and the potential to confuse or distract drivers.

This project aims to develop new intelligent lighting applications, tools and methods, integrating LED lighting that will enable the more effective operation, planning, design, repair and maintenance of the highway network. It will improve safety and service level, reduce vulnerability of transport networks to incidents, assure high-quality process without data loss and errors and reduce CO_2 emissions by maximising the use of the existing asset and reducing the need for additional road construction. The integration of communication technology, and for certain applications, sensors within the individual units will enable enhanced traffic management and driver information and this is what will represent the significant step forward over existing systems, as the lights will be able to communicate with each other and with a central control. The potential for units to be powered by renewable energy, specifically solar or piezoelectric, to reduce carbon emissions and to be truly self-contained will be explored; this would allow for their use on sections of highway with no readily available power source. For certain applications, a wired power source would be required in order to have 24 hour illumination, or back up power.

The number of potential applications is considerable and the project team proposes to demonstrate a limited number of trials, each of which will provide proof of concept for other applications. Some of the basic functionality considered is adaptive road marking; where the lights could be used to delineate traffic flow, to enable more lanes to be operating in one direction depending on the time of day, or they could be used in tolling areas to direct traffic towards open booths. More advanced applications can be realised through the integration of sensors within the LED units; this would go some way beyond the current state of the art technology, as the integrated sensor and communications systems would enable the lights to monitor and adapt to certain traffic activities, to communicate with each other and with traffic control centres. The lights could be set to a low power / low lighting setting and brighten to full power as vehicles approached, warnings could be made based on real time monitoring of traffic flow and environmental conditions, such as temperature, rainfall and ambient light. Monitoring of real time traffic data would also enable advance warning of queues and to help smooth the concertina effect of stopping and starting at traffic signals.

Improved management of traffic flows is generally accepted to improve safety; in order to ensure that this is the case, the human perception of active lighting should be explored in order to ensure that the safety benefits are maximised and to avoid adverse effects such as information overload or confusion.

LED lighting technology is increasingly mature, and can be used off-grid when powered by a small integrated solar cell for example. Integration of communications and potentially sensor devices will increase the power requirements. The power requirements will be assessed with potential for a self-contained unit consisting of renewable power supported by a battery. The two main solutions to be investigated will be an integrated solar panel, and piezoelectric generation of power, although other options will also be explored, as will the potential for multiple technologies to be integrated to back each other up.

The ultimate aim of this project is the development of an intelligent LED road stud, with integrated communication and sensor systems, that is compatible with existing traffic management infrastructure, and which can provide some or all of its power needs through renewable sources.
The safety of such a system in terms of the lighting and information effect should be a key consideration. Human factors studies will be undertaken to assess the acceptability of the proposed solutions on selected participants, to help develop solutions that provide the optimum lighting and information levels, that help delineate the road and improve safety, but which do not dazzle or confuse road users. This will be undertaken through simulator based studies and through observations of participants in field trials. The robustness and performance of the individual units and multiple units will be validated through field tests, and subsequently a road trial. For any solution to be effectively implemented following completion of the project, it must be commercially acceptable, at least on a whole-life basis, and for this reason an outline cost-benefit analysis of the proposed system will be undertaken to ensure that there is clear potential for future commercial value to the participants and technology providers in the EC.

The specific scientific and technical objectives of the project were to:
1. Determine a number of applications where embedded LED road lighting could benefit smart road infrastructure applications, improve safety and infrastructure performance.
2. Identify specific applications that could be developed, and when proven, would serve as a proof of principal for a series of similar applications. This means too the development of new methods and technologies for planning, design, construction, repair, maintenance and replacement of identified

applications elements as part of road infrastructure to improve its serviceability and reduce the impact on the environment
3. Determine the communication protocols between the lights and to/from a central control to enable a high-quality process over the life span of the road without data looses and errors.
4. Assess the power requirements of the communication, sensors and lights themselves and identify on-grid and off-grid (renewable) power sources to reduce the impact on the road infrastructure environment.
5. Identify a number of sensors that could be incorporated into an LED housing that would measure road, traffic or environmental conditions to generate real-time data for road users.
6. Consider human factor response to lighting to ensure that maximum safety benefits can be achieved, and that no unintentional adverse effects through, for example, information overload to enhance efficiency and road safety.
7. Design and develop prototype systems including tools for multi-functional smart and safe infrastructure monitoring.
8. Validate performance of LEDs in terms of communication, sensor, power generation and robustness under loading through field and full scale trials.
9. Disseminate the results of the project to a range of European audiences.
10. Report on findings.
Project Results:
The project developed S&T results in a number of areas as identified below:

1. Standards and requirements for intelligent road studs for a variety of applications.

In addition to a review of the specific standards and regulations that the solution and the individual components would have to adhere to, the project developed a set of operational and performance requirements as follows.

Dimensions, including height above pavement
The initial idea for the studs was to be roughly the size of a 330 ml drinks can, ideally flush with the pavement. However, this proved to be unpractical due to:
a) achieving good visibility of the LEDs at a considerable distance from the studs when they are level with the asphalt, and
b) providing sufficient transmission capacities between studs when the antenna for communication is located below ground. This would not be the case, should the studs be externally powered, as the transmission could be wired as well.
Raised parts of the stud should not be higher than 5 – 10 mm for reasons of driving safety (particularly for two-wheelers) and maintenance (snow ploughs in winter). Recommendations from a member of the steering group from Norway was that they should ideally be totally flush to the ground as snow-ploughs can even take road markings off if they are set too low, or that the lights should be on poles at the side of the road.

Construction material
The casing for the electronics needs to be durable enough to withstand axle loads from heavy goods vehicles as well as considerable environmental impacts such as temperature variations and humidity.
At the same time, the casing needs to provide ingress protection and chemical resistance while being

under these external strains, and support the electronic interior and make sure the PCBs stay in place even under the influence of vibration caused by traffic.
The lid needs to be transparent to allow enough sunlight onto the solar panels for charging up the batteries during the day.

Skid resistance
Smooth surfaces may be a problem regarding safety, especially for two-wheelers.

Retroreflective backup
In case the LEDs fail to light up (e.g. due to low voltage or faults in the electronics), a backup which would act as a passive lighting system (retroreflective) could be considered.

Operational requirements
Light output (illuminance day and night)
Good visibility needs to be guaranteed under various weather conditions while ensuring the avoidance of glare. The INROADS project has undertaken significant human factors studies to investigate appropriate light levels based on user response.

Control/setup/data collection
For maintenance and control purposes, the road studs should support an over-the-air firmware upgrade mechanism without physical interaction.

Activation of the system
The system needs to be easy to activate on site, as people responsible for installation are unlikely to be the same people who designed the electronics. The studs' electronics need to be smart enough to go into sleep-mode in case of low battery voltage, so that they can be reactivated once the batteries are charged up again.

Immunity to electronic interference
The possible bandwidths for transmission of messages between studs are either 868 MHz or 2.4 GHz. Interference issues would generally not be expected, but require final tests on site.

Security against hacking
To prevent the installation of malicious and illegal software, the firmware will be digitally signed using state of the art cryptographic methods. The communication between the studs should be encrypted to prevent manipulations and attacks from outside. For the INROADS prototype this was done using AES encryption and a pre-shared key within the studs. As an additional security feature and to prevent replay attacks a timestamp is added to each message.

Dependencies between subcomponents:
Adequate protocols need to be employed between the sensor, communication and LED control module (all designed by different partners in this project) to provide the required system logic and functionalities. Clear actions need to be defined concerning the following:
• day/night modes

• vehicle detection: positive relay message transmitted to neighbouring studs to active LEDs (which LEDs to activate?)
• automatic time out function for LEDs or turn them off when detecting vehicle at the exit of a section?
• functionalities in standby or low battery mode
• what information needs to be transmitted between individual components?

Maintenance/durability requirements
Environmental/mechanical impacts
The operating temperature range for all electronics should be -40 to +85 degC. Functionality needs to remain unaffected by humidity and possible condensation inside the casing.

Status monitor (battery, light output)
Ideally, the external control unit should provide access to information regarding the battery status, lighting colour or other status information of individual studs, so that over the air control/updates are possible where necessary.

Replacement options
The electronics (modular) was designed to be housed inside a plastic casing, allowing individual boards to be removed for replacement.

2. Communications
Having chosen the Active Lane Delineation application, low power operation was a key technological driver.
The principle of operation for active lane delineation is that the system lights a curve upon detection of a vehicle. Initially, a sensor stud detects the presence of a vehicle passing the message to a master stud. The master stud will then maintain the system logic such that, when appropriate, a system ‘ON’ message is broadcast causing the LEDs to ‘light up’.

In the proposed trial, this ‘ON’ message is sent to the area of the curve through a series of unlit relay studs, the rationale being that studs lighting immediately preceding a driver would be distracting. The area of unlit/relayed studs will mean that by the time the driver reaches the curve, the studs are already lit.

Deliverable 3.1 prepared during reporting period 1 documents the communications sub-system high level design. It contains:
A review of the RF chipsets available including key performance claimed, receiver sensitivity, transmit power, chipset power consumption, data rates supported, protocol support and availability of suitable real time OS.
Prediction of the link performance, consideration of stud to stud and stud to access point communications, influence of vehicle (interference).
Antenna options
Predicted power performance v output power, data throughput, packet length, connection interval
Recommendations and identification of further work

During Period 2, the main focus was on developing and implementing working hardware and software solution. Additionally an external interface to the studs was developed, allowing a user to analyse and/or control the Active Lane Delineations system.

One of the key issues identified, during the integration phase, was the interaction between the communications transceiver antenna and the LED control board. The antennae performance was severely reduced (~20dB) by various LED control board ground planes located directly beneath the wireless antenna. Ideally, only a single PCB would have used to contain all three system elements (communications, sensor and LED control); however DSTA preferred to develop their own LED control board.

Measurements have shown that the wireless link was able to be functional over distances greater than 15m, when located at a subsurface depth of 1cm. However, this performance reduced to less than 7.5 metres when integrated with the LED control board. The system impact was not only a reduced separation between studs, increased the number of studs for a fixed system, but resulted in a large amount of additional work to make the system usable.

The communications sub-module was designed to be low power. The final design and implementation, of the communications sub-module, achieved an average current consumption of ~1mA at 3.3V. This power consumption could also be improved upon, if the wireless link could be improved

For the trial, all of the studs are identical type, i.e. they all contain LEDs, sensors and the communication equipment, but are programmed to perform specific tasks. However, sub-population of devices could be an option if taken to a price sensitive market,

A final activity was to develop a user interface for remote ‘control’ and service state monitoring/analysis of the system elements. This was achieved by the use of a roadside ‘Gemini’ unit which connects to the internet through a 3G mobile phone network. Additionally, a lightweight protocol was developed, in conjunction with DSTA, to allow the communications module to interrogate the LED control board for various statuses. These would include battery level, light level, temperature, LED control state and stud type.

3. Power

As indicated above, due to the deliberately demanding application of having a self-contained and self-powered stud, developing a solution with low power consumption was a key requirement.

The power consumed by the stud is broken down into three items:

$P_{tot}=P_{LED}+ P_{control}+ P_{comm}$

P_{LED} is the power consumed by the LED’s.

$P_{control}$ is the power consumed by the LED drivers, microprocessor, power supply system and the battery charger.

P_{comm} is the power consumed by the communications system.

In regard to $P_{control}+ P_{comm}$, the following consumptions energy consumption can be estimated:

Stud when the LED’s are OFF: $P_{control}+ P_{comm} \cong 1{,}65$ mW.

Stud when the LED's are ON: P_control+ P_comm≅14.85 mW.

The estimations for P_control have been undertaken based on Linear Technology and Energy Micro components. The estimation for P_comm has been based on Energy Micro and Microchip components with a 5% duty.

Finally, the LED road stud offers two options in regard to the power supply; batteries or connection to an external power source.
There are advantages with having a battery power source; firstly, some of the locations of critical road sections where the LED road studs will make a difference and contribute to safety are remote and it would be difficult and expensive to install a power line. The second advantage is that it simplifies the installation of the solution, reducing greatly the difficulties you might encounter, i.e. a standard road coring machine can be used to create a hole for the stud to be placed in with the requirement for grooves to be cut in the road to link the power supply, or connection to roadside power sources.
Equally, there are advantages to be gained from a wired solution, either where a mains power supply is present, or through a solar powered and/or wind turbine solution. Certain applications, for example, any application that required daytime lighting or 24 hour lighting would require an external power source due to the power required to get sufficient contrast and the requirement to recharge sufficiently respectively. The connecting wires could also be used for communications, removing the requirement for antennae, whilst batteries and solar panels would also not be needed reducing the size and unit cost of the solution.

For situations when piezoelectric power is generated, considering the speed at which the energy must be stored, the high number of charges and discharges that would be performed and the temperature to which the stud is going to be exposed, the only suitable energy storage systems that would be considered are super-capacitors.

However, given that the super-capacitors have a significant leakage current and that there could be long periods in which no energy is stored, it is convenient to use a backup battery that has the highest capacity possible in the smallest size possible and can resist a wide range of temperatures. For this, the project team identified Lithium-Thionyl-Chloride batteries with the following characteristics:
Operation voltage 3.6 V
Low self discharge (less than 1% per year)
Superior shelf life and operational life (up to 10 years)
Wide temperature range (-55 to +85ºC)
Capacity of up to 19 Ah in a cylindrical cell of 33.8mm x 59.7mm.
For example, the application for the INROADS LED road stud is Active Lane Delineation. LED automatically turns on when a vehicle has been detected

in order to outline the lane edges and highlight a curve which is poorly lit (LEDs are turned off when there is no traffic). For this we will considered the following requirements:
It works during the night.
Visibility: 1000 m.
Temperature range: -40 to 85ºC.
Roadside control (wireless communication).

Sensors: Light sensor and vehicle presence.
Stud and roadside control self-powered.
Colour: white or yellow.

Piezoelectric Generator:
Within WP4, INNOWATTECH (INNOW) evaluated and calculated the energy being produced by using the INNOW Piezoelectric energy generators (PEGs). The INNOW technology is based on the pressure (due to the weight) of the various vehicles driving on a given road, being applied on the piezoelectric based generators. A finite element analysis was undertaken during period 1, which determined that although PEGs would theoretically be able to provide the required energy for the active lane delineation application should vehicle wheels pass over the generators, when 30 – 50 cm from the stud, almost no electricity is produced. As the studs would be at the side of the road, away from the wheel path, PEGs were not an appropriate solution. However, the Smart Pedestrian Crossing could be a particularly suitable application as the PEGs could be placed directly in the wheel path of a vehicle, so maximising the energy generated.

Within task 4.5 INNOW suggested a new type of generator, a carpet type generator, having one layer of piezoelectric disks and capable of producing the required energy to light a warning signal to be placed before a pedestrians crosswalk. The sign will give a warning to both the drivers and the crossing pedestrians. The carpet will be easily placed and connected to the road at a distance to be decided, and can be removed when not needed. This solution of generating energy from the passing vehicles can be used in those places which need increased safety for the pedestrians. The carpet generator and standard generator were tested at TRL's accelerated testing facility.

4. Sensors
Work Package 5 was led by AIT and focused on developing a sensor sub-system to be incorporated into the stud for vehicle detection. This work package was necessarily closely linked with the power and communication work packages, as the sensors need to demonstrate low power consumption and for the results to be communicated effectively. The four main targets of WP5 were to:
Specification and selection of sensors
Sensor subsystem design
Subsystem functioning test
Embedding post-processing algorithms

General sensor trials
Task 5.1 was completed during the Period 1 and focussed on assessment and testing of a number of sensors to determine which would offer the optimum characteristics such as being appropriate for collecting information on traffic flow, meeting the requirements for energy efficiency and compatibility with other components, being able to embed post-processing functionality and testing applicability under realistic conditions.
A number of road tests and Finite Element testing was undertaken in order to determine the most applicable solution. Due to the generally poor detectability of strain sensors shown during the simulations, particularly when the wheel-road contact area was not in the immediate proximity of the strain gauge, this method was considered unsuitable and not pursued further. The focus was subsequently placed on magnetic field sensors, which showed the most promising results in terms of detectability of different types

of vehicles and also fulfilled requirements concerning low energy consumption and robustness to harsh environmental conditions.

The final specification of the sensor sub-system design was the Magnetoresistive (AMR) for detection of moving metallic objects causing local changes in the Earth's magnetic field. It demonstrates very low power consumption (< 4 mA given a supply voltage of 3.3V (@ 25oC) and 0.5 A set/reset pulse for 2 µs once a day to restore nominal sensitivity). In addition it has an operating temperature range of -55oC to +150oC

Initial sensor board design

In Period 1, a draft layout for the sensor board was designed which would accommodate all the hardware needed to run the sensor. It was agreed that the final board layout will contain one mutual micro-controller for both the communication and the sensor subsystems, which reduces energy consumption and hardware costs. As mentioned previously, the chosen PCB design includes a sensor subsystem in every stud, rather than having two different sets where one is exclusively employed for vehicle detection and the other one exclusively for lighting (with only the communication board being a mutual feature). Producing only one type of stud simplified the design and production of the prototype.

Operation

The principle of operation that the sensor aims to achieve is as follows. As a vehicle drives near the road stud, the magnetic field lines are concentrated in the car's body and cause a change in field strength detected by the magnetoresistive sensor. If the detection value surpasses a predefined threshold, a positive detect message is passed on to the communications module. This threshold can be set at an arbitrary value depending on the desired application. Reducing the threshold makes the studs highly sensitive to small or distant moving metallic objects, for example, motorcycles on the nearby lane or bigger vehicles across several lanes. High threshold values, on the other hand, would only allow large or very close objects to be detected.

Metallic objects on pedestrians or even bicycles were found to be below feasible threshold levels and would thus not trigger the LEDs as the detection value needed would be very close to the sensor circuit's noise floor. The way the sensor is currently programmed is to detect moving vehicles only. Stationary metallic objects are filtered out, as the sensor works on the basis of detecting changes to the prevalent magnetic field.

Proof of concept

In order to assess the functionality of the system when the initial sensor circuit was combined with the communication circuit on a mutual PCB in-situ tests were conducted in three stages. The foremost aim of these experiments was to test the performance of the magnetic field sensor in the presence of other electronic components and their potential interference with the signal. The second aim was to find reasonable threshold values for the calculated parameters for successful vehicle detection, given different vehicle types, velocities and drive-by distances from the sensor. These thresholds (peak-to-peak or variance) can be adjusted in order to compensate the components' respective effects on the magnetic field.

Functionality tests of stand-alone of sensor board – version_1

These tests involved only the sensor- & communication board (version_1, received December 2013) being placed inside a borehole on asphalt pavement, with the communication circuit deactivated throughout the test. The borehole was located at the edge of an asphalt driveway, with two lanes of equal width marked on the pavement for the drive-by tests. A small car (Toyota Yaris) drove by in both lanes at speeds between 20 – 45 km/h. These initial tests aimed to show whether vehicles are detectable when the sensor was placed level with the pavement, or even slightly below the surface. Furthermore, the on-board detection algorithm was compared against post-processed data to see if the simplified version designed for the micro-processor would suffice for detection.
It was found that the vehicle could be seen in both sensor axes in the form of slight peaks/troughs.

Stage 2: Functionality tests of assembled electronics – version_1
The second stage of testing involved the sensor/communications board (version_1) together with the fully assembled electronics inside the stud housing. The stud was placed in the borehole, with the sensor board being mounted on the battery/control board but powered externally via a laptop's USB interface.

A large car (Jeep) passed the stud on both, the nearby and distant lane (each 4 m width), at varying speeds (20, 30 and 50 km/h). Again, only the sensor board was activated and the aim was to show possible effects on detectability due to the presence of other electronic components. Furthermore, the exact vehicle signatures were studied to see if improvements were needed regarding parameter computation and thresholds.

Tests along hard shoulder of a motorway
In order to test the sensor board and detection algorithm during fast vehicle passages (> 100 km/h), the stud was placed on the hard should of a motorway (A6, between Vienna and Bratislava) where the local speed limit was 130 km/h for cars and 80 km/h for lorries. The housing was placed on the pavement surface as shown in Figure 6; the board was powered via a laptop's USB interface.

The stud was placed behind traffic cones to warn drivers about the setup on the hard shoulder, which led to some vehicles moving over to the second lane as they drove by.

Stage 3: Functionality tests of assembled electronics – version_3
The circuit of the sensor/communications board was modified slightly in the course of 2014 and two samples of the new PCB (version_3; version_2 was only used at Siemens) were sent to AIT for testing in January 2015. Some further modifications were subsequently needed in order to stabilise the sensor circuit's power supply, as the sending/receiving of messages caused a drop in voltage and thus a false signal in the sensor which triggered a positive detect message. To test the adaptations of the two available boards, the electronics were fully assembled and the board powered via the stud's battery pack. On-site experiments were carried out using a small electric car (iMiev) for drive-by tests at different distances from the stud.

Post-processing algorithms
Each sensor channel is sampled at 64 Hz and a running window of length 0.5 sec (32 samples) is passed over the data to compute the variance. The threshold value set for vehicle detection applies to the sum of the two channels' variances.

An alternative detection algorithm implemented on the sensor board computes the peak-to-peak values of the signals produced during a vehicle passage. However, the running variance method has shown to be the more stable during testing, but given its inherent smoothing of the signal it is less sensitive to vehicles further away from the stud than the peak-to-peak method. Given that vehicle detection will only have to occur across the nearby lane, variance was seen as the more reliable threshold parameter for the site trials.
Depending on the number of sensors activated in the stud layout, the data could be used for a number of further applications, for example:
Traffic counts: assuming each peak is caused by a vehicle, the number of positive detects could be used as an indicator for the traffic flow. Careful setting of the thresholds and positioning of the stud locations would be required in order to avoid double counts or misses for closely spaced vehicles.

Speed: Measuring the time difference between signal peaks in two consecutive studs caused by the same vehicle would allow the computation of an average speed along a road section.

Directivity of traffic: The raw data signature produced by a vehicle may differ as it drives past the same stud in different directions. This effect could potentially be used to detect the driving direction; a possible application could be to warn vehicles on exits/ramps in case of driving in the wrong direction.

Subsystem functioning tests
In addition to testing of sensor sensitivity, physical and mechanical testing of the sensor was undertaken using shaking table tests were undertaken in accordance with EN 50556 and climatic chamber tests to assure sensor performance. The purpose of the shaking table tests was the verification of the studs' vibration resistance corresponding to the following specifications: Vibration test EN 60068-2-64 using the vibration specifications from EN 50556:2011 Class AM2 over a duration of two hours.

During and after the tests no visible damage was observed. Further tests showed that the sensor board's functionality was also unaffected by the shaking table experiment.

Climate tests
In order to account for seasonal climate variations which the stud may be exposed to in asphalt pavement, tests in a climate chamber were carried out to simulate extreme temperatures and humidity. Testing was undertaken for cold (-40oC), dry heat (+85oC) and change in temperature (-40oC to +85oC), each with a test period of 16 hours. Sensor performance was found to be satisfactory under all conditions.

5. Human Factors
A key INROADS contribution will be the undertaking of human factors research, specifically pyscho-visual evaluation of road user response to embedded LEDs and behavioural studies using a driving simulator. This work was undertaken by IFSTTAR and CIDAUT.

In Period 1, IFSTTAR engaged in two main actions in 2012. The first one was to improve the computer graphics performance of their driving simulators in order to be able to control a large number of small light sources in real time. The second task was to design a driving simulator experiment, in order to assess potential applications of the new road studs developed in the project, for the Active Lane Delineation experiment, whilst CIDAUT focused on the Smart Pedestrian Crossing application.

During Period 2, IFSTTAR focussed on undertaking the two human factor trials, which would subsequently feed into recommendations for the field and road trials. This was split into two distinct areas:

Cognitive (understanding the required behaviour) and behavioural (speed, positioning etc.) undertaken in a driving simulator developed in period 1
Perception issues including visibility and glare at night and during the day

Cognitive and behavioural
The cognitive and behavioural assessment was undertaken using a driving simulator at the IFSTTAR facility in Paris and involved an assessment of the driver's behaviour on a simulated environment of a country road with two kinds of curves; the first 400m long and 300m radius and the second, 150m long and 200m radius. There were three separate scenarios for participants to experience, an unlit road lit by headlights, a road where standard streetlights were used on the curves and a section illuminated using active road studs.

Eighteen participants were used for the experiment, with the instruction to 'drive as you normally drive', with IFSTTAR monitoring speed, lateral position and time spent across the centre line. The results were extremely positive for road studs, showing:

Better control of the lateral position with road studs, compared to road lighting and automotive lighting alone.
In curves, the time spent across the lanes is shorter with road studs.
Road studs do not increase the speed in straight sections(with regard to automotive lighting), whereas road lighting does.
Subjective feeling: driving comfort improved with studs and road lighting, compared to automotive lighting alone.

The overall conclusion was that active lane delineation improves road safety in curves.

Visibility and glare
Another important factor to consider with regard to road safety is the visibility and glare of the studs, i.e. they have to be bright enough to be seen from a reasonable distance, but not to induce glare or dazzle. For this, IFSTTAR undertook a number of experiments to complement the contrast measurements undertaken by CIDAUT in Period 1. The questions to be answered were:
In daylight, are the road studs visible ?
At night, do they induce glare?
Do these issues depend on environmental factors:
Sunny vs. Overcast
Dry vs. Wet road surface

A psycho-visual experiment was undertaken at a non-trafficked road track in Guerville, France, with participants under various illumination conditions. A single illuminated stud was observed with a 1° of observation angle and random illumination intensity values.

Daylight conditions
During daylight, on both a wet and dry road surface, forty two participants were asked to rate the road stud as follows:
Switched off
Switched on, barely visible
Switched on, uneasy to see
Switched on, visible enough
Switched on, with glare

The results indicated that the visibility threshold (light intensity needed for the road stud to be visible) depends on the road surface state (wet vs. dry), on the road surface illuminance (i.e. the weather) and on the sun position (azimuth (with regards to the observer) and elevation angles).
Based on the collected data, a quantitative model was proposed, in order to compute, for any sun position, road surface illuminance and wetting condition, the visibility threshold (fair visibility for more than 95% of the drivers).

Glare (at night)
A second psycho-visual experiment was undertaken with thirty six participants, under simulated night conditions, (undertaken indoors), with an amber road stud again illuminated at random luminous intensities at a 1°of observation. The participants were asked to rate the subjective glare intensity on the following scale:
No glare, unnoticeable
Just acceptable
Glare, disturbing
Glare, unbearable

The results indicated that the participants found the visibility acceptable at the lowest level of illumination (0.10 candelas (cd)) with participants starting to experience uncomfortable glare from a relatively low level (0.14 cd) with a corresponding reduction in the acceptability. It was recommended that at night a reduced intensity of < 0.14 cd would be acceptable in avoiding glare, whilst maintaining visibility.

In addition to visibility and comfort for the drivers, there is an operational cost element to these results, with IFSTTAR demonstrating an example of potential energy savings (Vaulx-en-Velin, France), where tuning the light level according to the quantitative model would result in energy savings of 80% compared to the LED operated at the maximum intensity 24/7.

The overall results from IFSTTAR were that the main goal of undertaking a priori human factors evaluation of LED road studs was complete, photometric recommendations were made and a behavioural test of the chosen test application (Active Lane Delineation) was undertaken.

Additional areas of further research were identified, namely; for ALD, a priori evaluation of additional factors (traffic, target visibility, etc.); assessment of application in low visibility conditions (rain, fog); rating

the visibility and glare for a series of studs lined up; suitability of LED for other applications (public lighting, high beams) and additional identification and testing of more road/urban applications.
In addition to the work undertaken by IFSTTAR, CIDAUT also undertook a priori evaluation of the smart pedestrian crossing application, with the objective of understanding the perceived hazard level, acceptance of the prototype system and detectability and conspicuity of the advanced warning. From this, CIDAUT aimed to determine the most preferable lighting configuration based, targeted to provide information about the presence of pedestrians crossing on the crosswalk.

The evaluation was undertaken using simulated video clips of the different scenarios using thirty three users. In addition to the range of participants a number of different potential pedestrian crossing applications were considered.
In-pavement LEDs in pedestrian crossing.
Eight configurations comprising four colours of yellow, amber, white and red in both flashing and steady state modes.
Pedestrian crossings with in pavement signage.
OLEDs (Pedestrian crossing).

The experiment examined ten options, focussing on the use of LEDs in front of the crossing, with the eight configurations identified above, plus one each for the pavement embedded signage and OLEDs. The participants were asked their perception of the rating of the perceived hazard level of the stimulus and rating of acceptance of the different solutions.

The results indicated that:
White is in general perceived as less dangerous and urgent than the other type of warnings, but the nicest, the most likeable and pleasant
Flashing amber is perceived as the most conspicuous as well as more detectable and raising alertness than other options
Danger warning is considered less effective than any other modality, and less assisting than most of them
Flashing-redis perceived as more dangerous than other modalities, and more undesirable

The main conclusion from this work was that steady and flashing white, and flashing amber are considered as the most appropriate alternatives to inform the driver about the presence of pedestrians.

6. Development of Prototype Intelligent Road Stud for Selected Applications
The work on power, communications and sensors, as well as the defined characteristics led to the development of a prototype road stud. In addition to the development of the stud itself, from the laboratory, site and field trials, an installation and maintenance manual has been prepared for system operation. This details the mechanisms for the coring, installation and fixing of the physical stud housing and also the start-up process for the electronic components, stud identification and communications.

7. Validation Testing and Field and Road Testing

Different Technologies Integration
The aim of this task was to test the different technologies developed during the project to ensure a smooth

integration leading to the road demonstration. This proved by some distance as the single most difficult and time consuming item on the INROADS project due to the issues identified earlier including based on the individual components working separately, but issues surrounding the LED board interfering with and reducing the range of the wireless communications and interfering with the sensor and communications in general.

Siemens spent considerable additional effort in attempting to resolve these issues and a number of separate individual trials were undertaken, which are detailed below.

Laboratory Testing of Different Applications

During 2013-14, TRL undertook testing of the stud housing and cover and two types of piezoelectric generators (PEGs) in its accelerated pavement test facility (PTF). One of the PEGs was a standard, buried unit, and the second was a 'carpet' unit developed for the INROADS project which is designed to be fixed to the surface of the road, and could potentially be used in any future development of the smart pedestrian crossing application.

Stud Housing

The pavement test facility is able to replicate repeated vehicle loads at a variety of loadings to test road components. For the road stud and housing, trafficking was with a 385/65R22.5 wide-based single tyre, with the wheel centred over the stud at 10km/h, thus providing a worst-case scenario of repeated vehicle passes directly over the stud.

At a relatively early stage the top cover cracked upon repeated trafficking, although there was no catastrophic failure, i.e. although cracks developed, the cover remained intact, until eventually at around 22,000 passes, it developed a steady state, where there was flexing of the cover. The lower casing was undamaged throughout. Whilst this was a demanding test, there was a redesign of the top cover for the units developed for the site trial.

Whilst there was a failure of the components under repeated vehicle passes, at an installation of ten studs at the Siemens factory site, with only occasional vehicle overruns, the studs displayed no obvious signs of damage.

Performance of piezoelectric generators

Two types of piezoelectric generator were trialled. The IPEG measured 44cm x 35cm x 12.5cm and was buried in the surface of an asphalt pavement, whilst the carpet measured 40cm x 60cm x 0.5cm and was bolted to the surface of the pavement. Both generators were installed in the same asphalt pavement.

Installation of the IPEG

Installation of the IPEG was performed by taking seven 300mm diameter overlapping cores to form a rectangular shape in the existing pavement surface in the PTF. This was filled with sub-base and concrete to a depth of 180mm upon which the IPEG was placed. The hole was then backfilled with concrete to the top of the IPEG and surfaced with 50mm of asphalt to the surface level. The installation is shown in the following figures.

Installation of the carpet PEG
To install the carpet a template was used to mark out the location of the fifteen fixing holes; threaded sockets were installed were placed in the fixing holes into which the PEG was screwed into position.

Method for measurement of energy generated
As a vehicle travels over a pavement, the pavement deflects resulting in energy being wasted by the vehicle (conceptually it can be thought of as the vehicle continually having to drive slightly uphill, the hill being due to the deflection). The PEGs recover a fraction of the energy expended by the vehicle due to the deflection. Each time a vehicle passes over or close to the PEGs a pulse of energy is generated. For the purposes of these trials these pulses where recorded. This was achieved by logging the voltage formed across a resistor connected to the PEG outputs.

The resistance (Rt) chosen was based on the manufactures recommendation of 300KΩ as the optimal load of the PEGs.
The PEGs produce high voltage (approximately ±4KV peak-to-peak) and low current signals and so the voltage could not be directly measured using the available logging equipment. For this reason a voltage divider was used to step down the voltage into the ±10V range.

Test programme
A test programme was developed to investigate the effect of several parameters on the performance of the PEGs, namely:
Speed,
Wheel load, and
Vehicle (load) position

For each parameter, a total of 10 passes was made using the PTF at each parameter setting. The average energy was calculated from these ten passes.

In addition, the durability of the PEGs was assessed by trafficking continuously over a period of several hours.

Speed dependence
For the speed dependence tests all the passes were carried out with no offset in the line of trafficking (i.e. the wheel was set up to pass directly over the centre of the PEGs). The results for the IPEG, shown below indicated a clear trend in the energy generated per pass reducing with speed. In contrast, the energy generated by the carpet PEG increased with speed when going from 5km/h to 10km/h, however there appeared to be little correlation between speed and energy for speeds of 10, 15 and 20km/h.

The results have been presented in terms of the energy generated per pass (single axle) over the PEGs. For the IPEG the energy decreased with speed. This would suggest that for roads with equal flow, the road with the slower vehicle speed would produce more energy. However, another way to present the results is in terms of the energy per unit time (or power). Clearly, a road with a high average vehicle speed has the potential for more passes in the same period of time (a higher flow), and therefore the potential for a higher power output. For example, for a 25KN axle load, at 5km/h the energy per pass was ~0.65J while at

20km/h the energy per pass was ~0.35J. If it is assumed that 4 times as many vehicles can travel along a 20km/h road as a 5km/h road, then the equivalent energy at 20km/h would be 0.35J x 4 = 1.4J i.e. more than double that generated at 5km/h.

Wheel load dependence

For the load dependency tests, as for speed dependency, all the passes were carried out with no offset in the line of trafficking. Both the IPEG and carpet PEG showed increased energy generation with increasing wheel load.

Vehicle offset dependence

The influence of offset between the centre of each PEG and the path of the wheel was examined. The energy generated by the PEGs is related to how much they are flexed as the wheel passes over or near to them. For both devices, the energy generation dropped off dramatically once the wheel was completely off the PEG. For the IPEG, which is buried below the surface of the pavement, the significant drop in energy generation was believed to be due to the backfill having become debonded from the existing pavement, resulting in a discontinuity in the load transfer through the pavement. The cause of this debonding was assumed to be due to the presence of the IPEG. It was noted that the installation method chosen for these trials, to core a hole only slightly larger than the IPEG, may have allowed for this debonding and had a larger area of pavement been milled off, as is common when multiple IPEGs are being installed, this debonding may not have occurred. This issue would need to be addressed if a small number of the IPEG design were to be considered for an installation alongside the INROADS technology.

Durability

Durability tests were carried out on both the PEGs. This involved continuous trafficking of the devices over several hours at 10km/h, resulting in several thousand passes of the wheel. During this continuous testing the energy generated by the IPEG was seen to be gradually decreasing, with a sudden drop at around 3,250 passes. To examine the cause of this change in the energy generated per pass the IPEG was exposed and the device opened up by removing its top lid. An inspection of the internal components of the IPEG suggested that the change in energy generation was due to a gradual shaking apart of the device, including the shearing of bolts. It appeared that the sudden drop in energy generation was caused by a dramatic failure in which half of the piezoelectric material inside the IPEG became detached preventing the load (applied by the wheel) from acting on it. The carpet PEG showed no obvious durability issues.

Conclusions on Piezoelectric Generation

The results of these trials showed that the amount of energy produced by each PEG, from each pass of a wheel, was very dependent on the wheel load and to a lesser extent the speed of the wheel. For this reason the energy generated by a PEG installed on a live road will depend greatly on the make-up of the traffic. In addition, the two designs of PEG produced energy levels that were orders of magnitude different to each other. The carpet PEG, designed specifically for this study, produced substantially less energy than the below ground IPEG.

The suitability of the PEGs to provide energy to power the INROADS studs will be dependent on the traffic flow and the make-up of the traffic, as well as the energy requirement of the studs; including the overall energy requirement, such as the number of studs and the usage pattern.

One way to analyse the usage patterns is to separate them into those in which the lighting illuminates in response to a passing vehicle and those in which the light illuminates due to a separate trigger, such as pedestrians for a pedestrian crossing.

Assuming the PEGs are the only source of energy, in the former case, the energy generated by a PEG (or a series of PEGs) due to the passing of a single vehicle would need to be sufficient to meet the energy demands of the intelligent studs. If the standby energy requirements of the intelligent lights was ignored and it was assumed that the lights consume 1 watt when illuminated, with a typical set-up consisting of 10 lights lit for 5 seconds, then the total energy requirement for this set-up would be 50J, per vehicle pass. Even if it were assumed that the traffic type consisted of a large proportion of heavy vehicles and so an optimistic 0.5J were generated per IPEG per vehicle pass, an estimated 100 IPEGs would be required for this usage pattern. Using the carpet PEG design would need considerably more devices to meet the energy demand.

In the case of the usage pattern where the lights illuminate due to a separate trigger, the above analysis would suggest that a high ratio of vehicles to trigger events would be required to confidently be able to meet the energy demands of the intelligent lights using the IPEG design.

8. Scientific findings from Field Trials

Initially, it was planned that there would be one track trial of the studs, followed by a road trial. Due to the issues regarding integration of components and interference of the LED control board with the antennae, a series of field trials were undertaken in order to understand and refine the performance of a series of intelligent road studs. The first of the mini trials was undertaken at a CIDAUT test track in Spain to understand initial performance of the integrated components, which initially highlighted the communication and interference issues. Following a substantial amount of work by Siemens, a second trial was attempted in Spain which again did not fully resolve the issues.

A demonstration event in November 2014 in the UK provided some addtional information, before a permanent installation of ten studs at the Siemens factory site in Poole, UK demonstated acceptable detection and messaging performance, although due to the winter conditions, the studs had to be charged externally as the solar panels received little light..

Following this, several active studs were installed on a controlled test track to evaluate the performance of the studs in the delineation of a curved lane. Each stud needs to be placed at 5 meters or less from its neighbours to be able to properly communicate with them. The sensor demonstrated a great sensitivity and it rarely missed a passing vehicle. Its performance was however affected when big metal objects were nearby, such as parked vehicles.

A series of mini-trials on this set-up were performed during the execution of the project with the aim of studying the effectiveness of the active studs and their impact on drivers' behaviour and feelings. These tests involved a heterogeneous group of drivers, whose impressions were registered through several questions addressing different aspects, such as safety, comfort or workload. As a result of the studies, the use of intelligent studs showed to be capable of reducing the fatigue produced by night driving, increasing at the same time the sensations of comfort, driving quality, vehicle control and safety. Additionally, none of the consulted drivers reported discomfort related to the possible glare produced by the studs.

The GPS trajectory and speed of the vehicle used by the participants were also recorded to allow a deeper analysis of the behaviour of the drivers with and without the Active Lane Delineation. Speed turned out to increase a little with the use of the studs, although the difference wasn't found to be statistically significant. This is directly related to the drivers' self-confidence and their capability to predict the next situations.
A thorough photometric study was performed as well to quantify and assess the visibility of the studs in use and the disability glare they may produce. In this sense, it was found that not only did none of the drivers report any discomfort glare during the subjective analysis, but also the measured disability glare was totally insignificant with a T.I. of only a 1,24%. Regarding visibility, it was verified that the studs comply with the minimum values established by the European Standards to guarantee their correct visibility from up to 200 metres.

Besides, the distribution in space of the luminous flux of the studs was measured in laboratory by means of a goniophotometer. This is very useful to determine the variations in luminance that can be expected depending on the stud orientation and the observation angle.

The light cast by LED is quite directional, although some mirrors placed under them and the diffuse cover help scatter the light. The luminous intensity is concentrated on <5º. Therefore, the visibility of the ALD can vary depending on the orientation of the stud in relation with the observer. It is suggested that the studs should be placed so that one of the LED faces points towards the middle of the lane in unidirectional roads, although in bidirectional roads, studs should be placed so that each LED face points towards a driving sense.

A deeper analysis was undertaken comparing the active studs with the usual road delineation elements. Particularly, they visibility of road markings and retroreflective studs was studied. The luminance of the active studs was proved to be much higher than newly painted road markings, meaning better visibility and conspicuity. The advantage of active studs is that their performance does not depend on the cars' headlights, and therefore they are clearly visible at a much longer distance than can be achieved with car headlights, clearly identifying the road geometry, allowing drivers more time to predict and adjust their trajectories.
Potential Impact:
Socio-economic impact
The results of the project have shown that intelligent road studs can improve driving performance and so road safety, with a cost-benefit analysis demonstrating that the two applications considered in greater detail, i.e. Active Lane Delineation and Smart Pedestrian Crossings.

The CBA considered bends and pedestrian crossings where at least one accident had been recorded in Spain. There are around 100 run-off fatalities on unlit bends in Spain per year, whilst pedestrian crossing fatalities represent between 1.2% and 7.6% of all pedestrian fatalities across Europe (2005 figures). There is an average of around 50 fatalities per year in Spain at pedestrian crossings (2008 – 2010 figures).

The study was a preliminary approach to estimate the maximum allowable cost for the two selected applications in order to achieve a cost benefit ratio of 1:1.

Many assumptions had to be made in order to obtain these costs and there remain other areas of uncertainty that will not be resolved until the two applications are fully developed. Effectiveness and reliability will be a key factor in maintaining the reduction in accidents as it has been assumed in the analysis that the applications will be 100% reliable. The applications will therefore need to be carefully designed since their implementation is to have a large impact on road casualties.

In practice the typical costs in the UK for a standard conventional street lighting column -including service connection- is between 1800 and 3100€, plus about 75€/m, if any extra cabling is required for electricity supply. Regarding pedestrian facilities, a simple refuge including electrical works and all associated works is between 7500 and 10000€ and 25000 to 30000€ for a typical Zebra crossing with high friction surfacing There were other examples of installations with prices three-fold, and this does not take into account any maintenance and operation costs. In terms of lighting costs, the light from an intelligent road stud uses a fraction of that from a standard streetlight, and a reduction in energy use, cost and associated carbon of around 90% would be achievable.

Indeed authorities spend much more than could be defensible from a purely economic perspective for lighting and pedestrian crossing facilities. In other terms the cost-benefit ratio is likely to be somewhere between 5:1 and 10:1 for these two applications. This means that self-powered active lane delineation could be worthwhile from 15000 to 30000€ per bend equipped and smart pedestrian crossings between 25000 and 50000€, which further justifies the amount of efforts invested into the development of such applications and their commercialization.

The analysis in the report concluded that there is a case for active lane delineation development in terms of accident reduction on unlit roads and savings in the cost of street lighting on lit roads. An examination of how active lane delineation best be implemented has concluded that self-illuminating white lines is a better option than self-illuminating road studs given the increased conspicuity the former can provide combined with the fact that there is no comparable product available.

It was also concluded that even greater benefits are likely to be achieved with the development of Smart Pedestrian Crossing. Furthermore, the proposed fabrication of this equipment can be adapted to the client’s specification, which is a further advantage, and similar pedestrian facilities are in place all over the world, which represents a huge potential market.

Main dissemination activities

Project Website and Newsletters

A web-page was established in Period 1 as part of Task 9.1 with details of the project, and additional documents such as newsletters and reports available. There is a public and private area to the website, where deliverables are available for the project team. This has been updated regularly with project deliverables and more recently with videos of the site trial activities. LinkedIn has been used to share details of updates on the project, most notably by FEHRL who have an extensive reach.

Case Studies

Two page case studies have been developed for both the active lane delineation and smart pedestrian crossing applications in a common format which could be used for future applications.

Preparation of journal articles in the scientific and technical press
In addition to the data available on INROADS' web-page, the project has been widely publicised in the national and international press, at scientific conferences and on television. In addition, it has been the subject of newsletters of various project organisations. Highlights of the activities undertaken in Period 2 are presented below.

The project appeared on national television in France on TF3, with an article on future road concepts and IFSTTAR's Route 5iéme Generation. Amongst various features, there was an article on human factors work and the IFSTTAR driving simulator with the INROADS rendering, and an interview with project participant Celine Villa who spoke about the use of the simulator and new road concepts.

Technical Press
There were articles in Traffic Technology International on the project in 2013 and 2015 in addition to the one in Period 1 in 2012, an article in an edition of FEHRL's 'FIRM Magazine' which has a wide reach across European research organisations in printed and electronic form, including links on FEHRL's e-newsletter.

Academic Articles and Conferences
Two papers were accepted by IFSTTAR on the simulator work to TRA in 2014, which were presented at the conference. It was not possible to prepare a paper on the overall project as it was a requirement that the results had to be complete which was not the case at the time the abstract was required. However, a poster detailing the project was prepared and accepted (shown on the left), and more notably the project was one of a select few that was selected for the Outreach Marketplace area of the conference by the organisers. For this, a specific additional poster was prepared to an EC template, a stud was on show at the event and a 15 minute presentation was given

In November 2013, a presentation was given to the UK Road Safety Marking Association conference, along with an exhibition space at the event where flyers on the project were available, and the INROADS video prepared by NTIC in Period 1 was played on a loop with a number of other project videos.
In November 2014, seven INROADS studs were temporarily installed for a demonstration at the 'Seeing is Believing' event. This is a major UK event held every two years and organised by Highways Magazine; it is undertaken over two days that has a conference area and an outdoor exhibition area. The key feature is that in November, with darkness falling at around 5pm, visitors to the show can see the outdoor exhibits during the day, dust and in darkness. The studs attracted some interest from other stud manufacturers who have not yet added intelligence to their products, and also from representatives from the Highways Agency (now Highways England). The conference was publicised widely on the Highways Website, in Highways on-line and hard copy magazine and the dedicated seeing is believing website.

Most recently, the project was presented to the FIRM 15 in Brussels main conference as well as hosting the INROADS final conference as a 'side' event. A poster was prepared for the main exhibition area and IFSTTAR brought a desktop version of their driving simulator.

Exploitation of results
There have been a number of enquiries regarding potential application of the technology which are being

followed up, and there is the potential to use some of the individual components in various applications. TRL has recently been awareded a contract from Transport for London to undertake a simulator study for a variable use transport lane, that came about as a direct result of the INROADS project.

Whilst the system as developed is not ready for immediate roll out, there are areas that could be exploited in the short term. For example, a combined sensor and communication board was developed which was tested extensively and good performance proven in field testing in Austria and in laboratory tests. A web-based communication database was developed that allowed the status of the studs to be reported remotely.

For a future development of the system in a commercial application, there are a number of recommendations:
• In the short term an external power source would be required for the active lane delineation. In an area with no close power connection, it is possible that the use of a commercially available external solar panel and wind turbine would be sufficient to achieve this. Whilst this would require a thin slot for a channel to be installed, it would enable sufficient power to be delivered and the cable could potentially be used to transmit messages. In the medium term improvements in batteries and solar panels, in addition to refinement in the control boards could lead to the self-contained application envisaged.
• The electronics, antennae and sensors should be developed as a single board. Siemens have provided suggestions as to how the existing two could be better integrated with a modified LED board, as well as different position of the antenna.
• The physical dimensions of the stud could be modified to make it more commercially attractive. At 200 mm diameter it is larger than many similar studs. As it is, there is potentially scope to reduce the diameter with the existing internal configuration, but a modification to the internal components (possibly by making it deeper) could reduce it further. This would have three immediate benefits in that it would inherently make the top cover stronger, by giving less area under which to flex; it would also reduce the surface area with limited skid resistance and would reduce the number of screws required to remove the cover for maintenance activities.
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