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TNO report

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Feasibility Study Intelligent Highways

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Summary

The project “Feasibility Study Intelligent Highways” was performed as part of ENTERPRISE. The project is looking at the concept of Intelligent or Thinking Highways using miniature, low cost and maintenance free sensors in the road surface. The aim of the project is to review and research the implications of such a new state-of-the-art data collection system for effective operational traffic management only and to perform a technological feasibility study. This was done by looking at two topics, namely applications and technology.

On a global scale the concept of intelligent highways is commonly seen as an essential part for the realization of so called cooperative systems, consisting of intelligent vehicles, intelligent infrastructure based systems, communication technology and nomadic devices. In general applications for cooperative systems can be classified by using the level of interference with the actual driving task: guidance, informing, warning and intervention (control). Most of the classes are within the focus area of both public as well as the private sector, both with different perspectives.

A survey held amongst partners of ENTERPRISE concluded that the most valued application areas or classes are travel-times calculations, incident detection, congestion detection, law enforcement and vehicle control, with enforcement being an application class not often mentioned in relationship with cooperative systems. Furthermore the respondents emphasized and valued the availability of more data and subsequently information needed for the named application classes. The most named requirements or issues to be solved were costs, interoperability and how this technology compares to other alternatives. One of the possible alternatives was specifically addressed, namely Floating Car Data. Most respondents anticipated that it would need more penetration and 10-15 years before FCD could provide the information needed for advanced Traffic Management.

The technology needed for intelligent infrastructure systems is part of various R&D programs all around the globe as well as for intelligent sensor networks in general. The concept of using large amounts of (different) sensors in order to determine and predict the state of the measured network is becoming available as we speak An important technology development for the Intelligent Infrastructure of the future is based on the use of sensor networks, where smart, light and cheap sensors are deployed and integrated with the infrastructure and communicate with each others and the remaining part of the infrastructure by means of (wireless) communication. This technology, which is being developed at TNO, is called Traffic Infrastructure Sensor Networks (TISNET).
The main technological challenges that lie ahead are power harvesting, communication, data-interpretation and efficient instalment. The sensing principle, the packaging and the algorithms however have already been thoroughly investigated. The challenges mainly arise from the fact that existing sensors are applied into an environment that consequently has very challenging and new requirements. The big technological issues are the use of Ultra Wide Band for communication and piezo electric power harvesting in order to provide solutions for maintenance free deployment.

Summarized we can state that the concept of intelligent highways is covered in various international R&D programs and that the specific idea of embedded miniature wireless sensor networks can open up a wide area of potential applications and is generally speaking feasible when three main technological issues can be solved: power harvesting, communication range and life-time (i.e. packaging).

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1 Introduction

Intelligent Infrastructure is a concept which is related to different developing areas: Information Technology, Security, Traffic & Transport and Buildings. Even though these areas are focused on particular subjects, they share some common grounds (for example, ambient intelligence[1] is a concept which is transversal to them).
Even this common ground, this study on Intelligent Infrastructure is mainly focused on Mobility, with a particular stress on Intelligent Highways of the future.

The project “Feasibility Study Intelligent Highways” was performed as part of ENTERPRISE [1], where the project is looking at the concept of Intelligent or Thinking Highways using miniature, low cost and maintenance free sensors in the road surface for multiple purposes. Within this study the main focus was on using embedded wireless sensor networks for traffic monitoring and detection.

The aim of the project is to review and research the implications of such a new state-of-the-art data collection system for effective operational traffic management and to perform a technological feasibility study for short term implementation.

The aforementioned feasibility study consisted of 3 phases:

1. Literature study after the State of the Art of know how and technology;
2. Identification of possible application areas;
3. Analyses of expectations and maturity of technology aimed at deployment.

These topics will be covered in this report. First we will give some more background information in chapter 2. In chapter 3 we will give a broad overview of the application classes and the potential and future applications that become available by the use of the Intelligent Highways concept. Chapter 4 will give more insight into the technological background of the concept covering the state of the art, the future and the maturity of the required technologies. The majority of the study was performed by desk research done by TNO. For phase 2 we also used a survey amongst the ENTERPRISE members to identify their expectations towards the impact of this technology and the potential application areas (see chapter 3 and appendix A). In addition to the mentioned phases we also provide some insights in parallel and complementing initiatives from an international perspective.

1.1 Scope of the study

The scope of this study is to review and research future implications and current status of development of data collection systems based on sensor networks, that can be fully integrated in the road network and constitute the basis of future Intelligent Highways. The scope of this study was limited to the applications for traffic management also because the majority of the answers from the survey stressed this as an important area for the success of the concept of Intelligent Highways. With the same concept or by using the same concept there might also be a big potential for asset management purposes. Some first initiatives in The Netherlands are now looking into the needs, requirements and problems to be solved around the relative lack of information about the state and the degradation of the infrastructure by using miniature low cost sensors.

[1] Ambient Intelligence refers to the fact that the environment is aware of the presence of the individual(s), is context sensitive and provides something for the individual(s). Ambient intelligence refers to electronic environments that are sensitive and responsive to the presence of people.

This concept is also known as Traffic infrastructure Sensor Network (TISNET) [2]. For the ease of reading in the rest of this report we will refer to the concept of large networks of small sensors embedded in the road surface by using TISNET.

2 Background

The worldwide problem in traffic and transport is the continuous increase in traffic demand. With this trend comes the increasing impact on environmental emissions and increased traffic safety issues. Those issues are being faced by using the concept of Intelligent Highways. Indeed, the total miles traveled by all vehicles in a specified area during a specified time have increased by 76% between 1980 and 1999 [3]. The problem looks even bigger considering that the world population in 2050 is expected to equal 9 millions [4]. Governments and institutions are facing the problem of reduction of throughput and safety on highways investing in new technologies that can solve, or at least limit, these issues. Such technologies are grouped together under the concept of Intelligent Highways.

Intelligent Highways are the new highway traffic analysis and response technology that will be implemented in the near future in order to decrease traffic congestions and accidents. Major highways in the US as well as other developed countries are being used by more or less 350,000 vehicles everyday. The traffic or congestion that results from such volume accounts for almost 78 billion dollars of wasted money every year because of lost man-hours and fuel waste. Consequently, billions of dollars have been spent trying to alleviate and eliminate this problem [5].

A globally accepted view on the future of our mobility system consists of so called cooperative systems which will in most views largely contribute to the reduction of the problems that arise from the increasing traffic demand. Cooperative systems consist of intelligent vehicles, intelligent road-side infrastructure systems and nomadic devices that cooperate together aimed at improved clean and efficient mobility of people and goods[2].

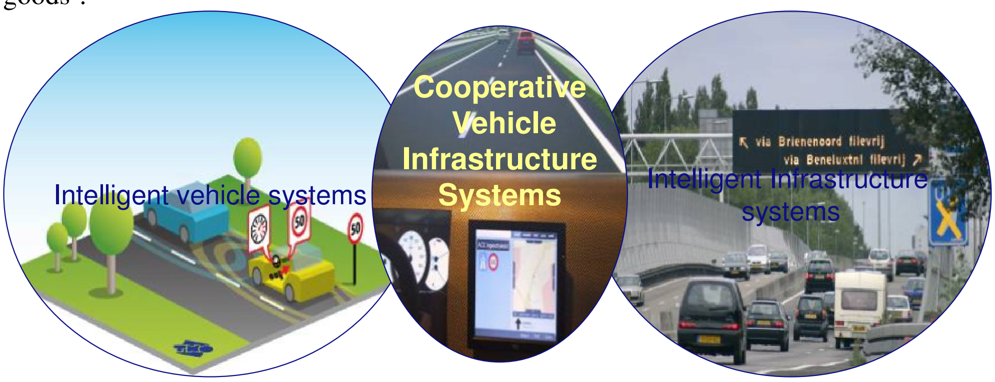

Figure 2: developments towards cooperative systems (© TNO)

Looking further ahead the *UK's Foresight Programme* [6] indicates a few scenarios for Intelligent Infrastructure Systems. Those scenarios are based on 4 main topics: Personal mobility, Cyberspace, Smart flows and Urban Environment. Considering those scenarios, Foresight individuates three horizons that will be gradually reached in the coming 50 years (see also § 4.2.1). In parallel TNO has presented its view of the future on mobility [7] with his 5 generations model, in line with the generations' model used for the developments in the telephone industry.

[2] This is one of the leading aims of the European Commission when it comes to Traffic, Transport and ICT.

In this view we are now between generation 0 and 1, with generation 1 being a first step with using intelligent vehicles for advanced traffic management. Generation 5 will then be the ultimate goal of autonomous driving cars. The generations in between will slowly show a transition where the autonomy of the driver is replaced by (autonomous) controlled driving led by the car itself.
An important feature in this model is the role for the infrastructure to enhance the penetration of intelligent vehicles into the mobility system. Intelligent vehicles that can communicate with other vehicles or with road side equipment aimed at improving safety are not yet available nor affordable for the general public. The benefit of having an intelligent car can be increased by providing information form sources that traditionally already collect this kind of information – namely the road operators. This is what we call the intelligent infrastructure (II). This II consist of traditional monitoring data and upcoming data like FCD but this will ultimately not be enough. Timely and locally relevant information on incidents, advice regarding speed and lane usage needs more intelligent use and combination of available data, more detailed data and data of higher quality.

2.1 International context

On all continents programs for cooperative systems have been running for several years. In the US several major Universities, governmental agencies and industries in California are working together within *PATH* [8], the Japanese government runs a special program on the deployment of infrastructure-to-vehicle communication named *SMARTWAY* [9] and in Europe all relevant parties are covering this topic within big European projects like CVIS[10[, Safespot[11] en COOPERS[12]. More specifically this topic is covered within the Intelligent Infrastructure working group of the *eSafety forum* [13] of the EU. A good overview of the global activities on the topic of vehicle-Highway Automation can be found in the proceedings of the International Task Force on Vehicle-Highway Automation, held in Versailles, France in 2007.

2.2 Infrastructure sensor networks

The first mention of the use of small sensors in a dense network for traffic monitoring was made by MIT but up to now no real application or deployment of this concept is known. The starting point of all discussions relating to intelligent infrastructure systems and cooperative systems will be the applications that we have in mind. These applications can have many and often contradicting interests or goals. Where road operators and governmental bodies will look at the benefit for traffic management aiming at better throughput, safer networks and less environmental pollution, service providers need to 'sell' their apps to the customer with a positive underlying business model and the car manufacturer wants to increase the comfort, status and loyalty of their targeted customers. In the end the general concept of infrastructure-vehicle information systems will have to cover all these interests of all these stakeholders. So where does this start? Many surveys and views support the idea that the development of cooperative systems will have to start with using all available data at the infrastructure side for reliable and advances traffic information. Only with dedicated and in-time traffic information aimed at increasing the drivers comfort, safety and travel times it will be useful to buy an intelligent car. In order to do so the Intelligent Highway concept can add great value to the required information needs coming from the defined applications.

2.3 The intelligent highways concept

In order to do this relevant, reliable and timely information is needed and consequently new ways of retrieving the data for this are subject of R&D activities all around the globe. Besides traditional detection systems like loops, video and radar new and upcoming technologies like GPS and other cell-based information sources (FCD), RFID tagging en even Wi-Fi tracking are developed in order to get qualitative better information about the state of the road network. Especially for applications like rerouting, real-time traffic and traveller information (RTTI) and travel time prediction these technologies are a feasible solution. For more advanced traffic management and vehicle control applications there is a need for more detailed information about individual vehicles in the network. The intelligent use of available information from large amounts of different sensors can fill this gap.

An important technology development for the Intelligent Infrastructure of the future is based on the use of sensor networks, where smart, light and cheap sensors are deployed and integrated with the infrastructure and communicate with each others and the remaining part of the infrastructure by means of (wireless) communication. This technology, which is being developed at TNO, is called *TISNET* (Traffic Infrastructure Sensor NETworks) [2].

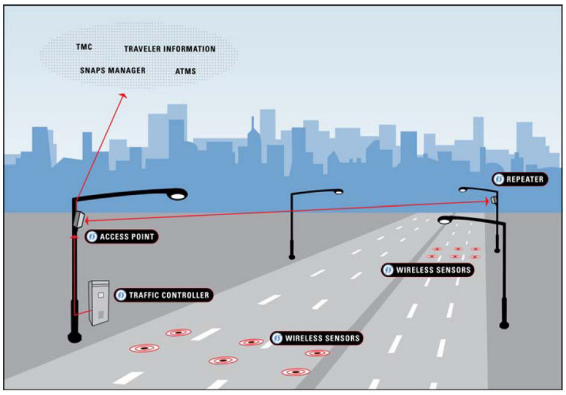

Figure 1: example of wireless sensor network for mobility (source: Sensys Inc.)

The TISNET concept is based on wireless sensor networks of extremely cheap and maintenance free miniature sensors (5x5x10 cm) in the tarmac. With a few sensors every square metre, 50% may be dysfunctional without affecting the robustness and reliability of the system. These sensors communicate with the road side units (RSU) via a wireless network and smart algorithms translate the various individual detections into vehicle trajectories. In this case every vehicle is detected the moment it enters the network and can be followed accordingly. Given the high sensor density, several vehicle parameters (presence, speed, lateral position) or road parameters (occupation, traffic jam position) can be determined very accurately. This boosts the information on what is happening on the road. Based on historical data we can also analyse and research the causes and effects of incidents or dangerous traffic situations. Typical intelligent infrastructure based applications are complementary to other related developments like car-to-car communication, Floating Car Data and cooperative systems for driving assistance. All these technologies are somehow using the available information to create situational awareness that is relevant to the applied application and in the future all these data sources will be combined with the communication technologies in order to reach the goals for clean and efficient mobility of people and goods.

3 Applications

In general applications for cooperative systems can be classified by using the level of interference with the actual driving task: guidance, informing, warning and intervention (control). Each of these classes consists of various applications. Intervention typically consists of Advanced Driver Assistance systems (ADA's) like Adaptive Cruise Control (ACC) and Lane Departure Warning (LDW), whereas the informing class has application for travel times, weather etc. Most of the classes are within the focus area of both governmental as well as private organizations but both with different perspectives (see figure 3)

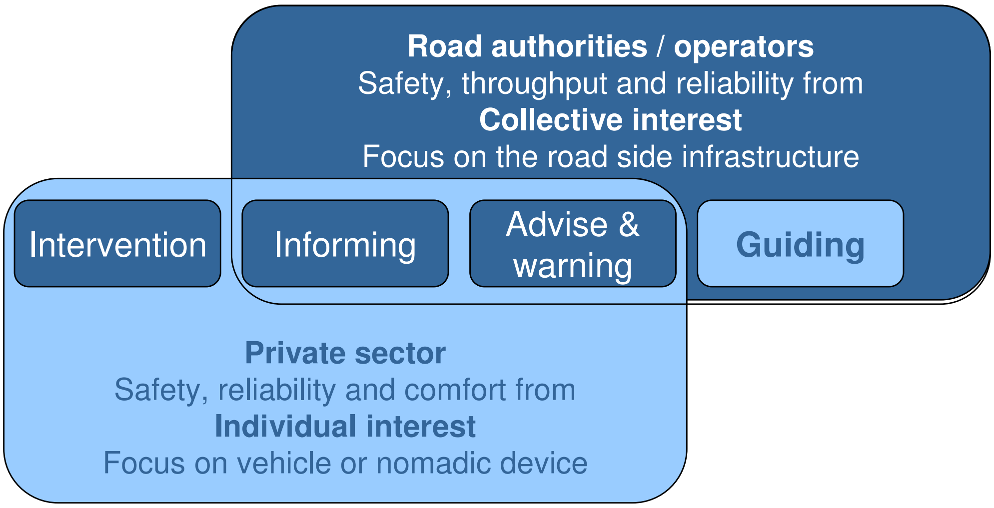

Figure 3: stakeholders and application classes for cooperative systems (source: Rijkswaterstaat)

Envisioned applications that would be possible with TISNET, a system based on wireless cheap sensors integrated in the asphalt layer, are summarized in Fig. 4. The applications are classified and compared taking into account two parameters:

- Coverage of the road, which reflects the extent of the deployment of the sensing. The more coverage an application needs, the more continuous the deployment of the sensors on the infrastructure should be, e.g. a full highway segment; while, an application needs a low coverage if the sensors are deployed on special places (road crossing, ramps, etc.), i.e. the coverage is "spotted".
- Accuracy, which – in case of TISNET – is proportional to the density of deployment of the sensors.

These parameters are especially relevant from a technological and functional point of view because they determine the possibilities for the deployment of the application classes. Without a high coverage and a high accuracy formation control can not be realized other than by full vehicle-to-vehicle communication. Besides these parameters also reliability, robustness etc are relevant for the deployment speed and potential.

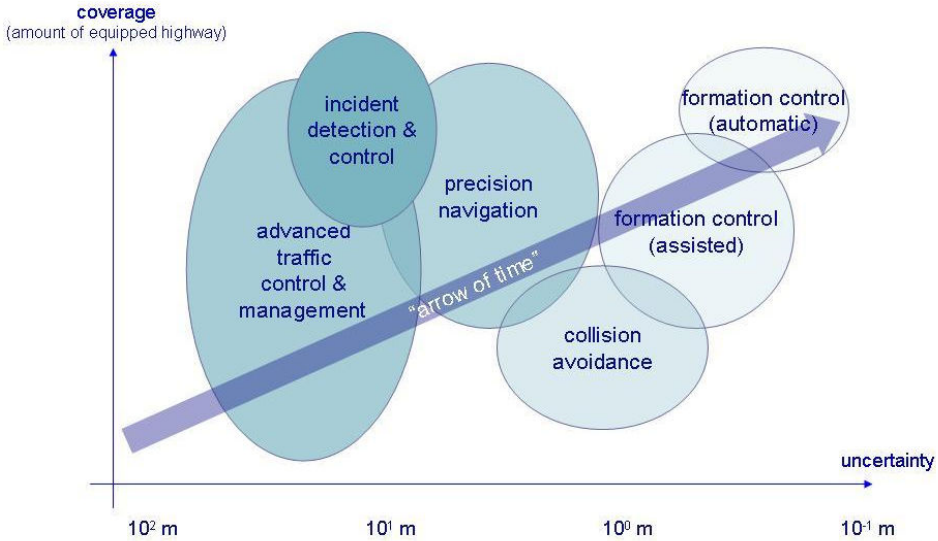

Figure 4: Application classes of TISNET with respect to sensing uncertainty, coverage of the sensing system and time.

The following application classes in which TISNET can find interesting applications are several and different:

- *Formation control*, which includes platooning, merging, overtaking and lane changing. This class of applications requires accurate sensing of position of the surrounding vehicles. This is the most exciting application class because it is the most effective to fight congestion. The formation control can be automatic or assisted:
    - *Automatic formation control* requires a high sensing accuracy because the human interaction in the driving process is completely avoided (autonomous driving) and thus requires dense and wide coverage deployment of sensors on the road.
    - *Assisted formation control* requires a less density of sensors because it is a human-in-the-loop scenario: the driver is assisted with visual, audio or haptic feedback.
- *Precision navigation*, which allows users to know in real-time and with relatively high accuracy what is the spreading and the localization of vehicles in a determined area, which can be relatively large. Particular applications can be the individuation of free spots in parking areas or choosing the right path/lane in urban or extra-urban environments.
- *Collision avoidance,* which draws the drivers' attention to invisible (occluded) danger situations and gives advice to avoid collision or mitigate its effect; more sophisticated implementations may initiate autonomous control actions.
- *Advanced traffic control and management*, which relying on monitoring traffic conditions in real-time both with high coverage (highways) and in local zones (near mobile bridges, semaphores or tunnels for example) enables the application of advanced traffic control solutions. The traffic control and management applications require a relatively low density sensor deployment.
- *Incident detection on highways*, which informs drivers (eventually just using radio-news) if and where an incident has happened and initiates the matching traffic control and emergency crew deployment processes.

Among these application classes, the most exciting is undoubtedly the formation control, because using a relatively cheap sensing technology (TISNET) and with simply-equipped cars (able to receive data on other cars' states) it can be possible to reach autonomous (or at least tightly assisted) driving, through which the most effective answer can be given to the problems of traffic throughput and safety.

In order to individuate the most promising and interesting applications for Intelligent Highways, a national (Dutch) perspective is important because of the particular needs and territorial characteristics that are distinctive of The Netherlands when compared to other countries, for example the high population density increases the problems with overcrowding of roads. However, an international perspective is even more significant because there is a more and more stressed tendency to globalization, especially in sectors like transportation and mobility becomes more stressed.

First the functionalities of different sensor systems which will be promising in the near future of Intelligent Infrastructure will be briefly compared, followed by some concrete applications with particular attention to the relative impacts on safety, throughput and environment. It is important to underline that in a short-term horizon (5-10 years), the possible applications that can be achieved by an Intelligent Infrastructure system are those based more on traffic-management than on vehicle-management. This means that the collected data would be made available to road-side-units or central-units for further elaboration and then would be used for traffic aims. Other more challenging and futuristic applications (like assisted or automatic vehicle control) that would require a real-time accurate map of vehicles' positions and speeds in a certain spatial region, would also be enabled by a system like TISNET, but they require sophisticated on-board-units for receiving data and properly control car dynamics. This means that car systems manufacturers most probably would start producing such a "car-control systems" only when the needed sensing technologies would be commercialized and broadly deployed on the road infrastructure. In the meantime, the main focus will be for applications related to traffic management, where TISNET can outperform other available systems in terms of accuracy of parameters' measurements and maintenance costs.

3.1 Different sensor systems

As a result of a survey for the ENTERPRISE project, which looks at the future of intelligent Infrastructure by using low-cost, miniature and low-maintenance sensors, some applications areas are individuated. The most promising applications for a 5-years horizon are in the field of traffic management. In fact, it is usually claimed that introducing a new Intelligent Infrastructure sensor system on the market, all the already available functionalities, which are currently in the field of traffic management, should be at least replicated (see appendix). In other words, a new technology should be able, at least, to measure traffic parameters like average speed, lateral position, occupation, traffic jam position, and traffic density. Anyway, an important property of the sensor would be the ability to be re-used in a customized way, which means that the same sensor technology can be used for different application scenarios. Traffic parameters that can be measured by a sensor system like TISNET and that can be directly used for traffic management are: traffic flow, vehicle ID, trajectory recognition. In Table 1 different technologies are compared with respect to different possible functionalities.

Sensor System	Traffic parameters (flow, density, average speed, etc.)	Vehicles Lateral positions	Stand-still Detection (accuracy <10m)	Vehicles Presence	Vehicle IDs	Vehicle sizes	System Cost	Maintenance costs	Environmental issues
TISNET[3]	High	High	Yes	Yes	Yes	Yes	Low	Low	High
FCD (PR=3%[4]) [14]	Low	No	No	No	No	No	Low	Low	Low
Induction loops	Low	No	No	Yes	No	No	High	High	High
Optical sensors[5]	High	High	Yes	Yes	Yes	Yes	Low	Medium	Low
GPS (PR=60%[6])	High	Low	Yes	Yes	Yes	No	Low	Low	Low
Radar	High	Low	Yes	Yes	No	No	Low	Medium	Low
Sensys[7]	High	Low	No	Yes	Yes	No	Low	High	High

Table 1: Comparison of different Intelligent Infrastructure sensing technologies. For the first 2 columns the values *high*, *low* indicate qualitative ranges dependent on spatial and temporal accuracy of sensing. The penetration ratio (PR) is the percentage of vehicles equipped with a certain technology.

3.2 Near-future application scenarios

Once the most promising functionalities have been recognized (see Table 1), some application scenarios linked to these functionalities can be consequently identified.
It should be noticed, however, that in order to elaborate and consider the huge amount of data that TISNET would produce, more complex traffic management decision algorithms would need to be developed and run. In order to exploit all the available data, an improvement of computational capabilities (hardware) on the road side units would probably be required. By the way, improvements of the micro-technology industry, would avoid this from being a bottleneck in terms of renovation costs of the road-side-units.

The most promising application scenarios that TISNET would allow on a short-term time horizon are described as following.

- **Dynamic speed limits.** Due to the amount of accurate and real-time data, it would be possible to change speed limits and advises at least one order of magnitude faster than with the current available technologies. It would be possible, for example, to install VMS panels with a higher spatial frequency and a higher update rate (on the order of a minute). Dynamic speed limits would enable to have more homogeneous traffic (less shockwaves) by better controlling the average speed of the cars.

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[3] *Sensors' deployment with a total spatial coverage of 1 sensor per squared meter (critical density which enables a position accuracy on the order of ten centimeters).*
[4] *Minimum penetration ratio (PR) required to achieve the same accuracy of common roadside detectors.*
[5] *Combination of different embedded sensors (stereo camera, VIS and IR sensors) with a total spatial coverage.*
[6] *Required penetration ratio (PR) which enables GPS applications to have a sensing accuracy comparable with TISNET.*
[7] *Same deployment of inductive loops*

- **Traffic prediction and rerouting.** Due to the higher quantity and precision of traffic parameters measurements, short-term traffic patterns prediction would be possible. Thus the availability of these patterns would improve the quality and the update rate of route advises (e.g. using a simple on-board unit on the vehicle side). Furthermore, due to the ability of detecting standing still vehicles with a precision on the order of 10 meters, TISNET would enable to instantaneously close a lane if an accident is detected.
- **Law enforcement.** Using a TISNET-sensors deployment in particular hot-spots (like close to on-ramps) would enable to retrieve accurately position and speed of every vehicle. This would allow to have vehicles trajectories available in real-time for detecting dangerous or unusual manoeuvres. When detected, the identification of dangerous vehicles can be done by cameras. Detection, identification and tracking of dangerous or hazardous drivers would be then possible.
- **Road pollution measurement.** The ability of tracking vehicles would allow to classify them on the basis of a predefined database where all the possible vehicle types and relative levels of pollutants are stored based on some distinctive features. Those features can be recognized by using different types of sensors (e.g. cameras) placed at each entrance of a road network. Then, once the vehicle has been recognized, it can be relatively easily tracked by TISNET. From that point on, the vehicle can be considered as a source point of pollutant that moves on the network and behaves like a pollution point. In this way, the pollutants produced by a network point in a particular time instant can be indirectly calculated [15].

3.3 Future application scenarios

The future of Intelligent Highways is in the field of automatic control. The *Vehicle Dynamics and Control* Lab at the University of Berkley [8] is carrying out an extensive research on this topic. The introduction of automatic control techniques on vehicles equipped with particular on board units would enable to use the accurate, real-time data coming from infrastructure sensor networks to automatically control vehicles' dynamics and/or supply high-precision manoeuvre assistance. The biggest breakthrough with such vehicle control techniques would be the removal of the human driver reaction time (which is 1.5 seconds on average). Organizing vehicle in automated platoons, the throughput would be 3 times greater then the currently achievable.

3.4 Summary of the survey

In order to define some potential applications envisioned by Intelligent Highways, a questionnaire has been made to all partners within ENTERPRISE. Representatives of the Departments of Transportation in the USA states of Ontario (MTO), Montana (MDT), Washington (WSDOT), Maryland (Mn/DOT) have provided us with their comments and feedback. The questions, with summaries of relative answers are listed below. All answers given are summarized in the attached appendix A.

1) **Given the concept of an intelligent highway, which potential and valuable applications can be identified?** A: Travel-times calculations, incident detection, congestion detection, law enforcement, vehicle control.

2) **Why would this be valuable or successful and to what extend does it solve present and daily problems?** A: Because this would produce real-time, low-cost and high-quality data.

3) **At what extent does the potential application add value to safety, throughput or environmental issues and user-friendliness?** A: Because the system is more robust, scalable and produces enough data for increasing the number of applications.

4) **Which requirements (ranked by priority) from an operational traffic management perspective are relevant when it comes to new data collection systems like this?** A: The applications of the systems should be, in order of priority: incident detection, congestion individuation, and real-time data; furthermore, it should be: cost-effective, easy to integrate, durable.

5) **The use of Floating Car Data (FCD) will undoubtedly increase in the future, when do you expect that FCD as a concept will be mature enough, used and implemented to its fully extent?** A: It is a difficult answer but, depending on privacy issues, there would be a need of 10% penetration ratio in high traffic-volume regions, which could be achieved in 15 years' time.

6) **Do you have information available about similar studies or technological developments that can enrich the study under consideration?** A: Information is known about cell-phones-based data, GPS-based probe vehicle data, and RFID-based data.

7) **Which questions arise as a result of this questionnaire and the general goal of this study?** A: The main question marks are: comparison with other systems, cost, life-time, system architecture, feasibility of proved applications.

4 Technologies view

4.1 State of the art

At the state of the art, Intelligent Highways are constituted by an ensemble of technologies which enable to evaluate current traffic situation and respond accordingly. Among others, those technologies include video cameras, loop detectors, electronic display signs.
Loop detectors are wires implanted on the road that allows calculating the speed and volume of cars in a certain highway by calculating the time elapsed between two consecutive crossings of a car upon two different wires. In this way, a slowdown in traffic can be detected and video cameras can be utilized to check the cause of traffic and carry out further processing. The interpreted data can be subsequently displayed on electronic signs (e.g. on VMS) to warn vehicles and reroute them properly.
Other emerging techniques use information from digital phones, GPS transmitters, PDAs for transmitting signals about locations of their owners that can be cheaply used by traffic management centers for determining the current traffic situation in a particular highway region by means of knowing the spatiotemporal dynamics of a few “instrumented vehicles”. The data sent by these devices and used for traffic management is called FCD (Floating Car Data) and has the big advantage with respect to the previously mentioned technologies to be cheap. However, the drawback of such a technology is that requires a high number of vehicles equipped with such transmitters (see chapter 3 for a comparison among different technologies)
Radio Frequency (RF) tags are also employed for toll pricing. A tag, required on each vehicle that enters a road section with toll, send information (unique ID of the vehicle) to fixed receiving stations in a particular spatial place. In this way, vehicles can enter and exit intersections with toll without slowing down the traffic flow.
Research and development programs in the field of Intelligent Highways, like the American ITS program [16] and the European CVIS project [10], are mainly focused on the Vehicle Infrastructure Integration (VII), which is oriented on developing wireless platforms to connect vehicles among each others and individual vehicles to the infrastructure.

4.2 Influence of future technologies

Though the aim of this survey is to provide information for the role of the intelligent infrastructure in the close future, longer-term predictions of the development of inherent technologies help to better place the short-coming events in a more distant perspective. Considering the Foresight view, TISNET can be inherently placed on three different horizons that help to understand how and when the new technology will take a role within the intelligent infrastructure. The focus here is on enabling technologies (like power harvesting, communication, and sensing principle) rather than on the application side, which was discussed in the previous chapter.

4.2.1 From 5 to 10 years ahead

The first horizon, slightly more than five years in the future, looks at the advent of new capabilities in order to solve problems by using already understood technologies.

The TISNET sensing and communication issues are apparently placed in this horizon frame, because they are based on already known and understood technologies (for example the employed sensors are commercially available magneto-resistive sensors, and communication protocols, like Ultra-Wide-Band, are already established technologies). Moreover, the power harvesting issue is also an actual concern, because technologies that enable energy harvesting are already available but require further scaling (minimization) and customization for ”in-tarmac” placement. Considering that the physical principle used for supplying energy to wireless sensor nodes generally changes depending on the particular application [17], in the case of TISNET the proper solution for reaching the first horizon time deadline seems to be a customized vibration-based energy harvesting solution [18]. Anyway, at the state of the art, commercialized systems that use the vibration principle for power harvesting solutions already exist.

4.2.2 *From 10 years to 20 years ahead*

The second horizon, around 20 years from now, addresses the need of new technologies (energy, materials, ambient intelligence), which means research and invention. TISNET can be positioned into this horizon as far as new power harvesting issues are concerned; those issues are closely related to new energy and materials-related capabilities that are strongly influenced by micro-electro-mechanical-systems (MEMS) advances [19]. As far as the ambient intelligence is concerned, the Intelligent Infrastructure HP-Lab [20], which works extensively on II, is challenged with new parallel-computing architectures, scalable network architectures and efficient data-storage systems, considered unavoidable for retrieval of information data, management and rerouting of data for supplying services.

Looking from a TISNET point of view, both MEMS and ambient intelligence technologies improvements would enable a new ”without-RSU” TISNET system, which would carry out the same functionalities of the traditional ”with-RSU” system, but without requiring the presence of any RSU (road-side unit), which would decrease the maintenance costs of the system. This means that installing the ”with-RSU” TISNET version today, would enable to substitute it in slightly more than 10 years (approximately correspondent with the asphalt lifecycle) with a ”without-RSU” version. In the meantime, application scenarios like incident detection, advanced traffic control, precision navigation, collision avoidance and assisted formation control would, in any case, be possible.

4.2.3 *From 20 years to 50 yeas ahead*

According with the Foresight view, the outcome of the horizon 2 is that the feasibility of II will not be driven by technological limits, because there will be enough technology to build the proper scenario. In other words, technology will not be the real bottleneck, but choices in ambits like life-style, socio-economics, law, environment, etc. will carry to different possible scenarios: from scenarios where an II system like TISNET would play a fundamental role (everybody at anytime can reach any place without any congestion problem) to cyber-scenarios where the II would be useless: everybody will virtually move from a place to another (e.g. from the office to the beach) without physically moving from a particular location.

4.3 Technology maturity

The system for real time monitoring of traffic and vehicles, TISNET, has been investigated under different points of view.

At the current status, as previously mentioned in the introduction, there is still a lack as far as issues like communication and power harvesting are concerned. However, the sensing principle, the packaging, the algorithms have already been investigated.

4.3.1 Sensing principle

TISNET uses the physical magneto-resistive principle for measuring variation of earth magnetic field. In other words, each sensing node placed within the tarmac layer measures the variation of the magnetic field along the longitudinal direction, which is the direction of the traffic flow. Every time a ferromagnetic material, like the iron which composes a road vehicle, passes over a sensor, the output voltage of the sensor circuit changes in time accordingly to the duration of the time that the vehicle "covers" the sensor. In this way, the time instants in which the car starts and ends to cover the sensor can be detected. Then, an algorithm obtains a binary signal (on/off) for the signal. The output is high (on) when the sensor starts being covered by the vehicle, and becomes low (off) when the vehicle uncovers the sensor. The achieved on/off detections are sent via wireless communication to the road side units. If a vehicle is just standing still on a sensor, the presence of a vehicle can be still detected. This principle is the same used by magnetometers and *Sensys* [21] detectors, but it differs form the principle used by commonly used inductive loop detectors.
With TISNET, a static variation of magnetic field with respect to the constant Earth magnetic field can be measured. A single vehicle must pass over the sensor for it to be detected. Consequently, a magnetometer can detect two vehicles separated by a distance of 1 foot (0.3 m). By the way, a single sensor is not a good locator of the perimeter of the vehicle. There is an uncertainty of about ±1.5 ft (45 cm); this is why a magnetometer is seldom used for determining occupancy and speed in a traffic management application. Placing more than one detector beneath the coverage area of a vehicle solves, anyway, the problem. This is why TISNET requires deployments of more than one sensor. The two biggest advantages of the magneto-resistive based sensors are that, first of all, they can detect bicycles when two detectors are placed at a distance of roughly one meter. When a vehicle passes over the loop or is stopped within the loop, the vehicle induces eddy currents in the wire loops, which decrease their inductance. The decreased inductance actuates the electronics unit output relay or solid-state optically isolated output, which sends a pulse to the controller signifying the passage or presence of a vehicle [22].

4.3.2 Radio technology

Nowadays, the standard technology for the standard communications in wireless personal area networks (WPAN) uses the IEEE 802.15.4-2003 standard and the ZigBee specification. The ZigBee performs better than the concurrent specification Bluetooth with respect to applications that require low data rate, long battery life, and secure networking. Intelligent transport system applications developed in the EMMA [23] (Embedded Middleware in Mobility Applications) project makes, for example, extensive use of the ZigBee approach. The same specification is currently being used with TISNET in order to send binary detections from the nodes to the road-side unit.

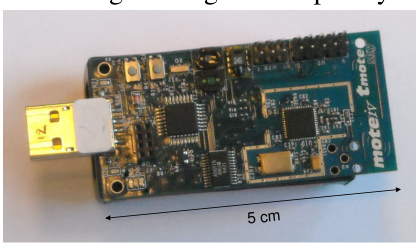
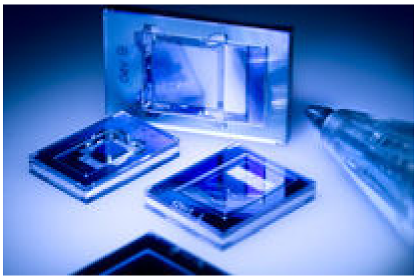


Figure 5: Example of a Zigbee wireless sensor mode

However, a new technology for efficient short-range communication is currently being developed. Such a technology is called UWB (Ultra Wide Band) and promises to be the substitute for traditional narrowband communication. The difference between UWB and commonly used systems is in the modulation principle; because the new technology transmits information by generating radio energy at specific time instants and occupying large bandwidth (time modulation), while the traditional technologies use amplitude, frequency or phase modulation. Essentially, the main advantages of such a technology with respect to traditional standards are the higher data-rate, the lower transmission energy, a better radio-jamming resistance (where the radio jamming is the deliberate transmission of radio signals that disrupt communication) and superior penetration properties through different materials.
For an Intelligent Infrastructure application where low-energy transmission of high data-rate signals through different materials is needed, the UWB technology would be highly suitable. These technologies will become widely available within the next 3-5 years.

4.3.3 *Power Harvesting*

In the previous paragraph, communication issues for a system based on a wireless sensor network have been considered. Another issue closely related with wireless systems is power harvesting. Indeed, wireless sensor networks are widely used in applications where sensors are needed in places that humans can hardly reach (typically, wireless sensor networks are widely used for military applications). In such systems, an important constraint is the power scavenging, which is the way how power can be saved using different sources of energy. Batteries are perceived as inadequate for long-term operation and changing batteries in many applications is just as costly as a total failure of the device. A wireless sensor for in-tarmac placement is highly sensitive to this issue. For these reasons, a recent study about the state of the art of power harvesting solutions, with a particular attention to the TISNET sensor node, has been recently carried out within TNO [24].
Due to the location of the deployment of the sensors, ambient energy sources can be mechanical, thermal or electromagnetic field. Using different energy sources means designing completely different approach in the design of the power harvester devices; this can be translated in a large variation of performance characteristics and cost if a particular principle is chosen instead of another.



In power generation, the main focus is on ‘harvesting’ unused ambient energy. Potential sources can be:

- Thermal
- RF
- Mechanical / vibration
- Small, indoor photovoltaic’s

The ultimate goal is micro-power modules that can be easily integrated into complete sensor node designs. The Holst centre [25] – a cooperation between TNO and IMEC – is world leading on this subject.

Thus, for the TISNET case, the best performance in terms of energy supplied can be achieved using thermal energy: when the difference of temperature between the tarmac surface and the underground is higher than 5°C, then a power density on the order of 10 $\mu W/cm^2$ can be achieved.

However, this solution is expensive if compared with vibration-based micro-generators, which can use efficiently mechanical vibration in the acoustic frequency-range with efficiency on the order of 1 $\mu W/cm^2$. This last solution has been individuated as the best solution as far as TISNET is concerned.

4.3.4 *Connectivity / interoperability*

One of the important design principles for the intelligent highway concept must be the connectivity requirement with existing installed road side equipment. First of all because we will only deploy the concept in situations where the additional information can and will be used for better control (e.g. incident detection on dedicated or priority lanes) but most of all from a practical point of view that the embedment takes time and the installed based should be able to fulfill its functions whenever. Wherever existing road side infrastructure is using detection systems like induction loops or camera's the additional applied sensors should be able to feed information - or better said data – into the road side equipment for the execution of present and new applications in basically the same way. Although with the embedment of large amount of miniature sensors in the road surface new opportunities arise for vehicle identification and tracking, we should not forget that most of the equipment (hardware and software) is designed to use input signals like 0 or 1. With the use of 'non-intelligent' sensors which use the same detection principle like loops we can always identify one or a group of sensor that function like loop detectors and thus be interoperable with road side equipment. The only additional needed hard- and software is some kind of wireless communication unit with an interface to the present processing unit.

4.3.5 *Sensor installment*

The conditions under which the sensors are installed and the forces and influences they have to stand during their designed life cycle – and that of the road surface – are an essential research topic for the feasibility of the Intelligent Highway concept. In The Netherlands the average economic life cycle of the road surface is 10 years (based on the most frequently used right lane). First of all the most efficient way of embedment is during the laying of the asphalt. After the under layer is applied the sensor can be added after which the final top layer will be applied. During this process the sensor must be able to stand temperatures between 150 and 180 degrees Celsius and the pressure of the equipment used. After the successful embedment of the sensors, the sensor will be able to stand high vertical but most of all horizontal pressure, water and moist, temperature deviations of around 70-80 degrees Celsius between seasons. On top of that within Europe the asphalt has to be in line with EU regulations for the strength and the use of the material components in the asphalt. All these requirements and regulations will determine the design of the sensor.

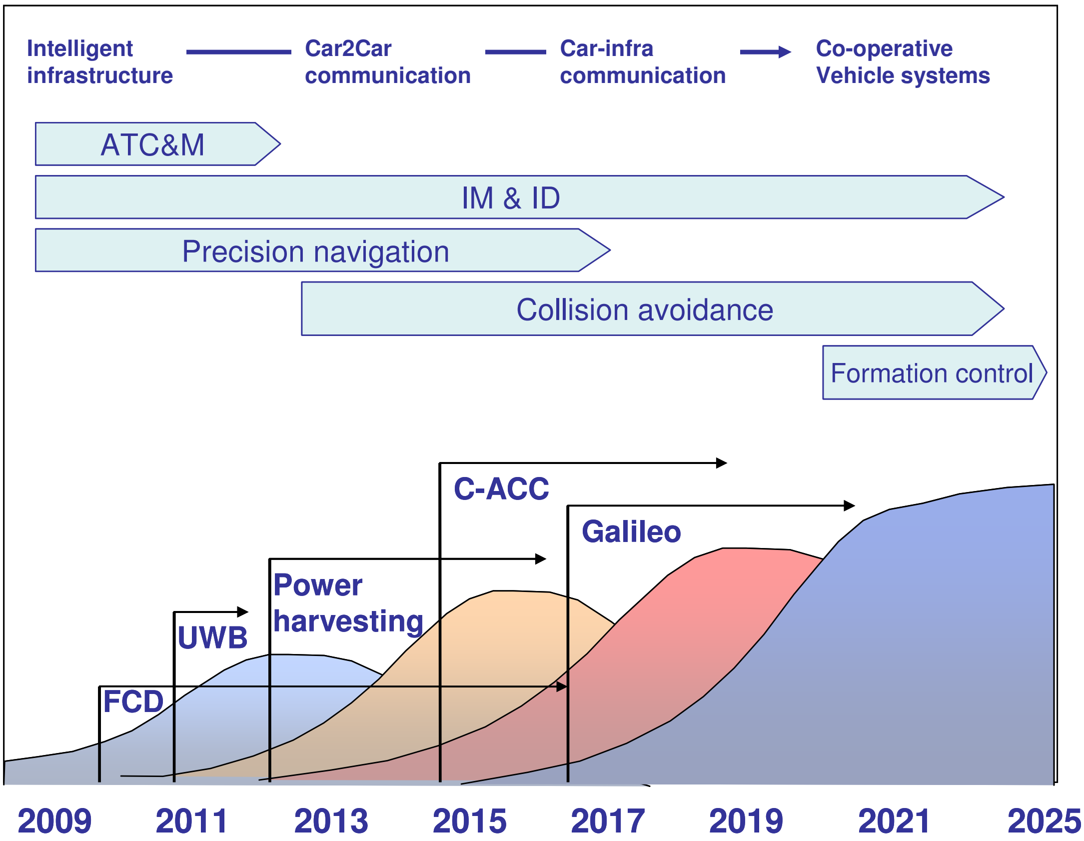
5 Conclusions

All around the globe several projects, initiatives and programs focus on Cooperative Systems, consisting of intelligent vehicles and intelligent infrastructure systems. Often the potential of car-2-car communication is thereby stressed as one with the highest potential and impact on safety and throughput. Though this might be true and enabling technologies are becoming widely available and are demonstrated on a small scale, Cooperative Systems need advanced and intelligent infrastructure systems first, which can provide the required high quality detailed information which can be used for new I2V applications. Several studies in addition predict development towards ambient intelligence using ‘smart dust’, the internet of everything and autonomous driving using highly automated vehicles and traffic systems.

The possible new technologies to provide us with this infrastructure based information vary from the upcoming cell-based FCD, to RFID technology and the large installed base of video camera’s and detection loops. By using data fusion and data mining techniques we can already make better and smarter use of the available data. Due to the low density or the aggregation level of the data gathered this information can mainly be applied using general broadcasted messages for relatively large networks. This can be used to inform travelers on travel times or downstream incidents or traffic jams which can have its impact on throughput and the better use of the available capacity. For increasing traffic safety and individually designated advice or guidance we need more timely and spatiotemporal information about the state of the network and the individual vehicles. The use of networks of small miniature sensors might be a solution. In The Netherlands we work on this concept within the TISNET project, which is short for Traffic Infrastructure Sensor NETworks.

The TISNET concept has been shown to be a feasible concept, although particular technological issues have to be solved for proper deployment. Most of these issues are indifferent from the defined potential application areas, like power consumption and communication. Looking at the applications which are becoming feasible, incident detection was mentioned by a majority of the respondents. Features or requirements that were marked as being important were reliability, accuracy, (maintenance) costs and identical functionality to loops. The widely accepted parameters to be measured like speed, vehicle classes and intensity were also mentioned frequently.
From a more foresight perspective we conclude that incident detection is just the start of the application spectrum together with advanced traffic management and control. We also see important benefits in areas like collision avoidance and formation control.

Summarized we can visualize the relationship between state-of-the art, technological maturity and the potential application classes as follows:


Intelligent infrastructure
Car2Car communication
Car-infra communication
Co-operative Vehicle systems
ATC&M
IM & ID
Precision navigation
Collision avoidance
Formation control
C-ACC
Galileo
Power harvesting
UWB
FCD
2009
2011
2013
2015
2017
2019
2021
2025

6 Signature

Delft, 27 November 2009

P. Hendriksen, BSc.
Head of department

TNO Science and Industry

M. Lagioia, MSc.
M.E. Oonk, MSc.
Authors

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Appendix A

In order to define some potential applications envisioned by Intelligent Highways, a questionnaire has been made to representatives of the Departments of Transportation in the USA states of Ontario (MTO), Montana (MDT), Washington (WSDOT), Maryland (Mn/DOT). The questions, with relative answers, are entirely reported in this section.

Question 1: Given the concept of an intelligent highway, which potential and valuable applications can you identify?

Respondent	**Answer**	**Classification**
MTO	The hope of this technology in the short term is that it will replace the expensive vehicle detection systems with a much more cost effective system.	Cost effective, cheaper
	The maintenance free aspect is also very beneficial in reducing system down time and all impacts associated with road closures required to repair and / or replace equipment.	Reduction integral maintenance costs
	This technology will eliminate the need to cut loops into pavement reducing the negative impact on the pavement integrity.	Pavement integrity
	This technology could also be used to provide vehicle detection in construction zones if they were place deep enough to prevent being milled out when the surface pavement is removed or the lane arrangement is temporarily adjusted.	Continuous monitoring during road construction
	Traditional loop technology in Ontario fails about 1% of the time whereas 25-30% of loops are lost annually due to pavement removals during construction.	Robust applications
	If this technology is more cost effective than conventional technology, the hope is that further deployments would be possible providing ITS benefits on more of our road network.	Enhance deployment of ITS
	In the longer term, this technology could also be a valuable tool for Vehicle Infrastructure Integration.	Tool for Vehicle Control
Respondent	**Answer**	**Classification**
Mn/DOT	On ramp coverage to accurately count the vehicles, determine actual wait times for individual vehicles and accurately identify the back of the queue.	Ramp metering
	Signalized arterial coverage at intersections to accurately determine the number of vehicles in the queue and its length for through and turn lanes.	Waiting length at arterials

	Accurately count turning movements.	counting
	Wrong-way detection for one-way sections, ramps, etc.	Wrong way detection
	Incident detection.	Incident detection
	Travel times (especially on arterials) assuming vehicles can be individually tracked.	Travel times
Respondent	**Answer**	**Classification**
MDT	Vehicle travel time calculations, either real-time or historical.	Travel times
	Incident detection and management.	Incident detection / IM
	Detection of congested or stopped traffic.	Congestion detection
	Incident Management, Warning tied into the sensors to warn traffic of conditions ahead such as stopped traffic, icy road, etc.	IM, (embedded software for signaling vehicles)
	Incident management, congestion information, travel times and speed enforcement.	IM, congestions information, travel times, speed enforcement
	Travel time information.	Travel time
	Incident detection.	ID
	Queue dissipation information that can be analyzed and provide as travel delays on future similar incidents.	Queue dissipation information
	Aggressive driving areas to focus on for mitigation.	Speed enforcement management
	Areas where drivers are continually speeding.	
	Icy or slippery road conditions.	Road conditions
	Travel Time Reliabilities. Real Time congestion and speed information. Traffic Counts.	Travel times, speed, congestion
Respondent	**Answer**	**Classification**
WSDOT	All of the parameters listed above are important (presence, speed, lateral position, occupation, traffic jam position, density and size). The sensors should be able to replicate the functionality of other sensor technology on the market, anything less will make the sensors less attractive. To obtain all the parameters a family of sensors could be developed which could be custom mixed based on the needed data collection.	Same functionality as present sensors
	Not listed above is the need for environmental data collection. Of most important would be road surface temperature and surface condition (wet, dry, etc). This would allow the direct observation of traffic patterns in relation to environmental conditions on a lane by lane basis.	Environmental data, road surface temperature and conditions

Question 2: Why would this be valuable or successful and to what extend does it solve present and daily problems?

Respondent	**Answer**	**Classification**
MTO	See question 1	NA
Respondent	Answer	Classification
Mn/DOT	Accurate queue detection is important but very difficult to do economically so this could solve the problem.	Queue detection
	Travel times on arterials is very difficult but the data could be very useful.	Travel times
	It is difficult to assess the potential for success at this point because there are many questions after reading the brief description (how do you handle the huge amounts of data that would be available, can they be mixed in asphalt, would they last long enough to remain available between repaving projects, etc.).	How feasible?
Respondent	Answer	Classification
MDT	The cost of installing and maintaining non-intrusive detection devices, such as radar or microwave sensors, is relatively large, especially when the costs associated with supplying power and communications are considered. A lower cost solution would allow a larger detection area with the same amount of funding.	Lower cost solution
	The information can be used to help the public make informed decisions and warn them of any immediate issues.	Better information, warning system
	Can help identify and locate incidents faster, can help identify speeding areas and can help congestion management and improve mobility.	Incident management, congestion management
	All of this information will allow us to better manage the system as it will provide us with an accurate account of the baseline conditions and how the system is operating. This will enhance safety and mobility. Many of the things above are self explanatory on what they will accomplish.	Baseline conditions
	Provide information to the general public and freight to better plan their trips. Currently, this information is limited in Michigan. Adding sensors is expensive.	Cheaper for mass distribution of data
Respondent	Answer.	Classification
WSDOT	If realized as stated the effort would provide a leap forward for infrastructure based data collection in a way that is comprehensive and redundant.	

Question 3: To what extend does the potential application add value to (i) safety, (ii) throughput or (iii) environmental issues and user friendliness (iv)?

Respondent	Answer	Classification
MTO	The system should be operational more of the time as a failure of one sensor will not be critical, therefore all of the system benefits mentioned above will be provided without interruption.	Robust System (i,ii)
	If the technology is more cost effective, then potentially there is more opportunity to expand the system further, again extending all of the benefits mentioned above	Scalable (i,ii,iii,iv)
Respondent	**Answer**	**Classification**
Mn/DOT	This cannot be assessed without more information.	N.A.
Respondent	**Answer**	**Classification**
MDT	The ability to provide travel time information to motorists allows them to predict how long it will take them to arrive at their destination, or to use an alternate route to avoid congested traffic conditions. Travel times also allow commercial fleet companies to better schedule their deliveries to avoid times when congestion is most likely to occur. Automatic detection of incidents can lead to quicker emergency response times, thereby reducing incident durations and improving safety for the involved motorists. Motorists approaching the incident can also be alerted, reducing the likelihood of secondary collisions and allowing motorists the opportunity to completely avoid the incident area. In addition, by reducing incident durations and congestion, the consumption of fossil fuels is also reduced, resulting in environmental benefits.	Travel times reduction by rerouting and real-time incident detection (i,ii,iii)
	The application would help all the categories above due to the help of the sensors to aid in creating an efficient transportation system.	More efficiency (i,ii,iii,iv)
	It could regulate speeds via variable speed limits and help reduce emissions. Can help mobility and reduce congestion through other ITS applications such as DMS and traffic signals. Also can help alert motorists of incidents and congestion ahead.	Dynamic speed limits (ii,iii)

	It adds value to each of the areas dependent on the application. The extent of the value will be determined by the available data and the ability to share information.	More data availability (i,ii,iii,iv)
	Better knowledge of the operation of the road will better identify areas of improvement. This will help manage our network and improve all three categories.	Better road-networks monitoring (i,ii,iii,iv)
Respondent	**Answer**	**Classification**
WSDOT	Since this proposal is more about data collection, the value to safety, throughput, and user friendliness will only be realized if the data is put to productive use. However, more data, properly utilized will provide a clearer awareness of what is happening on the road in real time for both operators and the public.	More applications of data post-processing (i,ii,iii,iv)

Question 4: Which requirements (ranked by priority) from an operational traffic management perspective are relevant when it comes to new data collection systems like this?

Respondent	**Answer**
MTO	Benefit cost must be much better than current system
	1) Integration with the system 2) Accuracy 3) Reliability - data quality and communication / data transmission 4) Ease of installation 5) Durability for extreme climates 6) Timely data / real time
Respondent	**Answer**
Mn/DOT	Ramp data – queue location, wait times, counts
	Travel time data on arterials
	Intersection data – queue location, counts, turn movements
Respondent	**Answer**
MDT	1) The ability to receive and use data in real-time 2) The ability to archive data for future use 3) Data reliability 4) System reliability 5) System cost
	1) Traffic Incident 2) Work-zone congestion 3) Travel Times 4) Traffic Counts 5) Vehicles Classification
	1) Incident detection 2) Congestion presence 3) Travel times 4) Speed data

	Real time and accurate are the key requirements but I am not sure that I am addressing this question appropriately.
	1) Travel Time 2) Real-Time Speeds and Travel Time 3) Traffic Counts 4) Vehicle Classification 5) Congestion
Respondent	**Answer**
WSDOT	1) Presence 2) Occupation 3) Speed 4) Surface Temperature and Condition 5) Traffic Jam location 6) Density 7) Vehicle size 8) Vehicle lateral position

Question 5: The use of Floating Car Data (FCD) will undoubtedly increase in the future. When do you expect that FCD as a concept will be mature enough and used and implemented to its full extend?
(For example 70% of all vehicles are able to provide travel and trip information)

Respondent	**Answer**	**Classification**
MTO	I think trials are needed to identify this number. Some probe vehicle trials are demonstrating success with 10% penetration. Some transponder trials are good during the day when volumes are high but leave large gaps in the data and conditions during the night when volumes are low and / or in more remote areas.	10% of penetration ratio needed in high-volume traffic regions
Respondent	**Answer**	**Classification**
Mn/DOT	This depends on the availability of other data with which FCD can be fused so it is too complicated to answer at this point without considerable work.	Unknown
Respondent	**Answer**	**Classification**
MDT	It is impossible to say when such technologies will be used to their full extent, in part because there will most likely be uses for the data in the future that we are not even considering at this time. For example, we do not fully know today the data that will be needed in order to run the VII technologies of the future.	Unknown

	This would depend on the replacement of the US vehicle age population. 15 years	15 years
	10-15 years	10-15 years
	I don't fully understand the question. I think it will be awhile before this concept is mature enough. The privacy concerns will be paramount and need to be addressed up front. I think if we could get 60 percent of the vehicles detected we would have some good implementation.	unknown
WSDOT	There are real questions on the viability of in-vehicle data in the future given many efforts around the U.S. to block the collection of data from vehicles or other devices (blue-tooth) without the expressed consent of the owner/operator. If substantial effort is achieved to block data collection then infrastructure data collection will still have a significant role.	Depending on law issues

Question 6: Do you have information available about similar studies, technological developments that can enrich the study under consideration?

Respondent	**Answer**	**Classification**
MTO	Cell phone studies and transponder studies are underway.	Cell-phones
Mn/Dot	Nothing that approaches the density of detection discussed here.	No
MDT	The I-95 Coalition is currently using GPS-based probe vehicle data to provide travel information to motorists. The Michigan DOT will also begin receiving and using similar data later this year.	GPS
	Houston TranStar uses data collected from toll tags to calculate travel times. In addition to being located along toll roads in the Houston area, toll tag readers have also been installed along non-toll freeways for the purpose of travel time calculations.	Toll-tags
	Michigan is going to be buying probe data from a third party source to use.	Buy data for testing
WSDOT	None that I am aware of.	No

Question 7: Which questions arise as a result of this questionnaire and the general goal of this study?

Respondent	**Answer**	**Classification**
MTO	This technology would have to be compared to the other more cost effective detection systems that are currently being assessed / implemented including transponders, cell, others?	Comparison with other technologies
	How will the large number of sensors be polled and utilized to provide information for effective traffic management in a timely and accurate manner.	System architecture design
	With all of this instantaneous data it would be beneficial to instantaneously update predictive models such as travel time.	Travel times
	What other applications are possible for this technology should it prove effective.	Proved applications
Respondent	**Answer**	**Classification**
Mn/Dot	How long will the detectors last?	Life-time
	Are they hardy enough to handle all of the harsh conditions present in Minnesota (low temps, high temps, deicing chemicals, vibration from snow plow operations).	Resistance to environment
	If this will be unlicensed wireless data transmission from the devices to roadside, what assurances are there that this system could be rendered useless by some other unlicensed wireless system?	Integration with other systems
	How is the location of each of the devices accurately identified?	Methods for sensors localization
	How would the huge amounts of data be collected, assessed and transmitted to a TMC?	Data transmission and gathering
	Can the detectors be mixed with asphalt and concrete?	Sensors positioning
	Is it really necessary and useful to have this level of density of data when considering the level of control, or lack thereof, over the traffic?	How to use new data
Respondent	**Answer**	**Classification**
MDT	Is there an expectation that a large number of the sensors would eventually fail? Would it be more efficient to install far fewer sensors (such as one per ¼ mile) and maintain only those locations?	Robustness
	What is the cost of these sensors? Assuming only one sensor per square meter of pavement, there would be over 5,000 sensors per lane-mile of roadway.	Cost

	Is there an advantage to using in-pavement detection, as compared with some of the non-intrusive options that are available?	Comparison with other technologies
	The maintenance and initial cost of this system would seem prohibitive. That is the first blush comment based on the limited information.	Cost
Respondent	**Answer**	**Classification**
WSDOT	I think the study needs to look at the potential maintenance implications for such sensors. Would it be better or worse then current sensor technology given similar functionality?	Maintenance

Appendix B

Based on the draft report send out to all members there was one additional question from Matt Radulski, P.E.:

> *My only question is how would the sensors follow a vehicle through out the system to determine speeds, occupation, etc,? Is there some kind of identification process?*

All the individual detections of the sensors are collected by the road-side unit where a state-estimation and state-prediction algorithm determines first the presence of an object – i.e. vehicle. This unique identification requires a certain amount of sensor to be simultaneously active. The number of sensors that need to be activated in order to distinguish a car from another depends on the density of cars that are running on a certain area at a certain time (i.e. the more dense the traffic, the more sensors you will need to distinguish between cars). Furthermore, the prediction algorithm predicts the vehicle state after which the estimation algorithm updates the vehicle position considering the measurements from the sensors. Important to mention is that the cars itself do not need any kind of equipment for this identification; it's completely vehicle-independent.