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Amendments

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Applicable Documents

Description
NEARCTIS deliverable D6: Review of the state of knowledge and capability in relevant technologies
NEARCTIS deliverable D7: Review of available case studies and related scientific knowledge
NEARCTIS deliverable D8: Identification of Success , Gaps and Potential for Improvements in Traffic Management Applications
NEARCTIS deliverable D18: Evaluation and assessment of likely benefits of the harmonised research programme

Acknowledgements

Description

Table of contents

Abstract

The NEARCTIS Network of Excellence is addressing the potential for benefit directly to travellers and also to society as a whole that can be achieved by improvements to the transport system through adoption and use of cooperative ICT. This is being developed as a harmonised research programme on cooperative traffic management, with broad-based joint and separate analyses of current traffic management systems, cooperative ICT, objectives of traffic management, the state of knowledge in this area, and research needs that have already been identified. This is the substance of the present deliverable D14.

Traffic management has moved from an isolated technical problem to a more integrated vision of widespread mobility in which multiple criteria and constraints are considered. This recognises the overarching need for cost-effective, efficient transport systems that provide a wide range of attractive choices to all members of society. At the same time, continuing advances in technology, techniques and equipment for management of road traffic provide opportunities to develop and implement novel approaches to traffic management and control. The rapid development of communications technology provides new means to collect, integrate and use information, from vehicle positioning, identification and tracking, and bi-directional communication technologies to improve performance of the transport system. This opens up a wide area for research to take full advantage of the opportunities for improvements using cooperative ICT that can be integrated into a global vision for the transport system.

A key element underlying the development of ICT for cooperative traffic management is communication, and especially the emergent technology of dedicated short range communication (DSRC) that facilitates communication among vehicles and bi-directional communication between vehicles and infrastructure. This lies at the heart of cooperation, with various opportunities among users, and between users and components of transport system management.

Safety-related ITS applications will be the first priority in harmonisation and deployment on both intelligent segments: the vehicle (connected and networked) and the road infrastructure (road operators, traffic managers, services providers). In this context, these future applications will require high quality traffic models, efficient and reliable communication tools, and accurate measuring and monitoring systems. The role of technologies, in particular communication and positioning, will be essential in the enhancement of traffic management.

The harmonised research programme on cooperative ICT in transport is presented here within a framework that has 5 distinct dimensions that give complementary and cross-cutting views of research. These are:

1. Key objectives
2. Research themes
3. Areas of expertise
4. Areas of traffic management
5. Opportunities for innovative contribution.

The concept uunderlying this framework is that prospective research can be viewed within it in a way that highlights inherent commonalities and complementarities. The harmonised research programme was developed systematically through this to ensure that it is robust, extensive, shared and balanced. It draws on available knowledge and technologies, whilst remaining open to future ones. This involved planning and undertaking a series of consultations of consortium members that was repeated four times.

The resulting harmonised programme of research is organised according to the research themes of the framework. Within each theme, we introduce research and explore the underlying motivation, the premises on which it is based, and the research that will be required, including some of the major issues to be addressed. We then proceed to discuss the expected outcomes of researching that theme to identify some of the areas to be addressed in order to develop and exploit the potential benefits of cooperative ICT for traffic management. The agenda presented is extensive but remains open to extension and enrichment from complementary research ideas.

The 7 research themes that are addressed are:

1. Increased availability of mobile communications
2. Increasing data availability
3. Improved modelling at all scales
4. The need for communication between autonomous systems
5. An understanding of the consequences of interactions at various levels
6. Achieving effective large-scale management of transport systems and their efficient usage
7. Support for policy developers and decision makers.

Considering each of these in turn led to the formulation of a programme of research that addresses a broad agenda. By considering this as a whole, it could be harmonised in the sense that interrelationships among these themes could be recognised and explored. This will support the research effort by identifying commonalities and opportunities for cross-linkage, and by identifying the complementarities that will enhance the value of each contribution.

The approach presented here explores the potential contrbiutions of cooperative ICT to traffic management and control within a systematic framework. This led to formulation of an agenda for the research required to develop and exploit the opportunities for advances in traffic management that are furnished by ICT. This analytical approach achieves a perspective on future opportunities and identify the actions that will be required to realise them.

The broad base of expertise within the NEARCTIS consortium leads us to suppose that many of the main topics and issues have been identified in the harmonised research programme. Each research project and activity that addresses the programme will address one or more of the many combinations of descriptions within the framework. Because of their relevant expertise and established research interest in this field, we expect that partners of the NEARCTIS consortium will join in bids for research following any call of the kind proposed here. Joint research activity of this kind will have the effect of perpetuating the NEARCTIS network through collaborative research contribution.

1. Introduction

1.1. New context, new constraints, new problems, new opportunities

Continuing advances in technology, techniques and equipment for management of road traffic provide opportunities to develop and implement novel methods. The prospect of continuation of this trend presents opportunities for innovative research and solutions. In this context, the emergence of new objectives, new methods and new constraints give rise to novel opportunities, methodological approaches, technological applications, system architectures and solution formulations, which in turn will generate new opportunities for development and improvement. In order to anticipate and harness these advances for traffic management and control, a switch will be required from opportunistic (though nonetheless effective) exploitation of technological innovation to an approach to research that addresses these challenges in a planned and systematic way. The present document provides a rationale and formulation of a harmonised research programme for this.

It can be seen that:

- Traffic management has moved from an isolated technical problem (maximising vehicular flows on networks) to a more integrated vision, where traffic is only a part of the mobility system, in which road users are the 'actors' in the system and in which multiple criteria and constraints have to be taken into account; in particular, environmental and safety concerns have taken an increasing role in traffic management, with demand management being increasingly necessary to combat congestion.
- Technology has been developing rapidly, with various new methods now available to communicate information to road users (radio, satellite navigation systems, Internet etc). Related developments include new means to collect, integrate and use this information, with the appearance of vehicle positioning, identification and tracking technologies, and various new technical solutions to provide bidirectional communication between the vehicles and the control systems (*e.g.* DSRC, GSM, GPRS, Wi-Fi).
- Methodologies have also been improved: advanced measurement techniques together with the increased implementation of traffic measurements have made high quality traffic data available, which in turn has made it possible to improve the calibration and validation of traffic models and to go further into traffic analysis; optimisation techniques have also been improved, furthered by expanding computational capabilities.

Those improvements have made it possible to decrease the "granularity" for traffic optimisation, and so to take a better account of each vehicle or platoon. These developments have resulted in many system experiments and implementations, mostly on a local basis, involving multiple technologies and concepts. European cities and traffic operators have been particularly active, as has been acknowledged by the US administration. This has made it possible to test a wide range of methodologies, techniques and concepts, but leaving open a wide area for research and development to take full advantage of the opportunities for improvements that can be achieved through these diverse and individual activities.

There is an overarching need for cost-effective, efficient transport systems that provide a wide range of attractive choices to all members of society. Within this, five specific objectives can be identified for traffic management:

1. Safety (for users and for citizens)
2. Environmental impact (emissions of pollutants, noise, visual intrusion, reducing generation of greenhouse gases (mainly CO_2))
3. Efficiency of the transport system (enhancing deployment and delivery)
4. Traveller and system user experience, and
5. Societal impacts (including accessibility, costs and equity for all members of society).

Thus in brief, five issues have been identified: safety, environment, efficiency, performance and societal impacts. Each one of these has been addressed to different degrees by large research programmes on technological aspects, involving researchers and industrialists working together. In particular, there have been important European actions on each topic in the 6^{th} framework and before and the European scientific community is well organised. However, it is now clear that improvements cannot be based only on technological components but must integrate those technological breakthroughs into a more global vision for planning, organisation, management, operation and optimisation of the transport system.

The NEARCTIS project is addressing the potential for benefit directly to travellers and also to society as a whole that can be achieved by exploration and development in respect of these ways in which the transport system can be improved through adoption and use of cooperative ICT. The specific objectives of this programme of enquiry were set out in Table 3 of the NEARCTIS description of work. Within these objectives, a main purpose of this work package (WP1) is to develop a harmonised research programme on cooperative traffic management. Developing this research programme was based upon broad-based joint and separate analyses of current traffic management systems, cooperative ICT, objectives of traffic management, the state of knowledge in this area, and research needs that have already been identified. This information was synthesised from contributions made by members of the consortium, including their awareness and appreciation of the knowledge and know-how of other expert members of the community of transport researchers and practitioners. Alongside this knowledge comes an awareness of the gaps in knowledge that correspond to identifiable limitations of current capabilities. These lead to the formulation of a harmonised research programme on traffic management that integrates the use of cooperative systems.

The present deliverable D14 of NEARCTIS provides the basis of this programme definition. This calls on specific contributions that:

- Elaborate a common vision of the state of the art, and identification of the fields of expertise that are relevant to this;
- Identify gaps in knowledge and within this the areas that are not being addressed by current research programmes. The gaps to be identified are generally at the intersection between research outputs (this work package) and complex issues that arise in practice (represented by case studies in WP2).
- Provide the knowledge basis to support the specification of a harmonised programme of appropriate research activities.

This document (NEARCTIS Deliverable D14) represents a major contribution to these objectives. It provides a review of the state of knowledge and capability in relevant technologies within members of the NEARCTIS consortium, representing their common view. This consortium has gathered together into a virtual research institute a substantial part of the European academic community working on the issues of road traffic management and cooperative systems. On the basis of this, the group can be considered to represent reasonably well the collective view of teams of researchers in the scientific fields concerned in traffic modelling, traffic control, communication and location technologies. In this document, a harmonised programme for future research is presented that is based on this group's examination and exploration of the current state of the art. This process identified research gaps, and hence key opportunities for future research and technological advance in cooperative traffic management. The resulting harmonised programme of research activities therefore represents work that will be required to realise the potential of ICT in transport management.

1.2. Communication and cooperation

1.2.1. Modes of communication

The basis underlying the development of ICT for cooperative traffic management is the emergent technology that will implement and facilitate communication among vehicles and bi-directional communication between vehicles and infrastructure. The different kinds of communication can therefore be described as

Vehicle –> vehicle
Vehicle –> infrastructure
Infrastructure -> vehicle
Bi-directional vehicle <-> infrastructure.

These services will be provided by dedicated short-range communications (DSRC) running under the IEEE 802.11p protocol, by satellite links and possibly by other mechanisms. The interest of the NEARCTIS consortium lies in the development of uses and applications for cooperative traffic management that the data, information and opportunities for communication of information that this technology will provide. This can be used to promote the interests and objectives of transport users and of system managers. Development of the communications mechanisms themselves is not in itself of central interest and so is not presented further in this document.

1.2.2. Common view of the state of the art

The deployment of future safety-based services for traffic management will be associated with the development of new technologies in communications. The ITS action plan [1] aims to accelerate and coordinate the deployment of intelligent transport systems in the road transport, including the integration of the vehicle into the transport infrastructure (action area 4). This area proposes some actions for the development and evaluation of cooperative systems with a view to define a harmonised approach, the specifications for I2I, V2I and V2V communication in cooperative systems and the mandate for the European Standardisation Organisations to develop harmonised standards for ITS implementation, in particular regarding cooperative systems.

The European Commission has also adopted a decision on the use of radio spectrum in the 5,9 GHz band for safety-related applications of ITS with the goal to harmonise the conditions for the availability and efficient use of this frequency band. European research projects on ITS have started within the 5th, 6th and 7th framework programmes of the European Commission. Most of the results are now transferred to the European Telecommunication Standard Institute (ETSI) and the European Committee for Standardisation (CEN) with the aim of writing technical standards and specifications. There are strong needs for standardisation, which requires a harmonised approach to ITS applications requirements, system architecture, transport protocols, location referencing and security issues for the implementation and deployment of cooperative systems.

The ITS safety-related applications will be placed in the first priority of harmonisation and deployment on both “intelligent” segments: the vehicle (connected and networked) and the road infrastructure (road operators, traffic managers, services providers). The traffic management based on cooperative systems is integrated in a global mobility policy and the improvement of road safety is a common goal for the development of new applications and services. In this context, these future very demanding applications will require high level traffic models, efficient and reliable communication tools, and accurate measuring and monitoring systems (*e.g.* vehicle positioning, speed measurements, emissions, noise, additional sensor technology, . . .).

The role of technologies, in particular communication and positioning, will be essential in the enhancement of the traffic management. One can consider the communication architecture to be a new component of the roadside infrastructure.

This application context leads the NEARCTIS partners to a common view of the state of the art on positioning, tracking and communications (PTC) technologies. Most of these technologies were recently developed or are currently under development or deployment (*e.g.* The Galileo satellite-based navigation system), which implies a huge effort for the validation and certification of components and procedures. This is a real challenge for safety-related applications and there is a great need in developing new methodologies in order to accelerate the validation part of communication and positioning systems.

Statement

The NEARCTIS consortium agrees with the following statement on the way that PTC technologies are approached within the traffic management domain:

- a better knowledge of PTC technologies is essential for the development of future traffic management applications based on cooperative systems
- the quality of traffic state information provided by PTC technologies must be high for adequate use in traffic models and for estimation of information on future traffic conditions
- accurate positioning and secure communications are key requirements for the deployment of high level traffic management applications based on cooperative systems
- the estimation of the quality parameters (positioning accuracy, integrity, availability, ...) must be integrated within innovative real-time traffic applications

1.2.3. Communication and cooperation

Communication is at the heart of cooperative systems. In order to help show how it has the potential to contribute to cooperative traffic management we have developed a simple taxonomy of communication and cooperation that we present here in terms of the two roles of User and System, with three modes of communication and cooperation between them.

By a *User* we understand any entity that is currently using or about to use the transport network. Thus a User may be an individual about to commence a journey, a driver of or passenger on a vehicle, a pedestrian or a consignor of goods. It sometimes facilitates analysis to consider a vehicle itself as a user, usually as a proxy for its occupants.

By a *System* we understand any entity that is concerned with the monitoring or management of the use of the transport system.

These roles can combine to produce complex interactions. We consider some of the opportunities for this.

1. User <--> User

   User to User communication may either be one to one, or may be broadcast as one to many or one to all. In the future, autonomous vehicle to vehicle communication is likely to play a major role the behaviour of traffic and in managing it. Communication may also be driver to driver as for example a signal of intention to change lanes.

2. User <--> System

   Communication between User and System encompasses a whole range of communications including data capture by the system, and in the opposite direction information, advice and guidance for users. These include vehicle to infrastructure communications as used, for example, in toll collection and traffic monitoring; requests from a driver for route guidance to systems such as the ones provided by the provider of traffic information for personal navigation devices (PND); advice about traffic conditions supplied through a wide range of channels such as variable message signs, radio traffic reports and independent information suppliers. This would also include communications between control centres of transport suppliers such as bus and freight companies and the vehicles in their fleets.

3. System <--> System

   System to System communication encompasses all communication between elements of systems concerned with the monitoring, management and control of traffic. Systems of this kind are becoming increasingly diverse, with many active components and distinct objectives. Information systems can be used to share data and information about current status, objectives, intentions and actions. Operational performance can be enhanced by the making of decisions that are better informed through this sharing of information. This offers the prospect of enhanced quality of operations and extended range of tasks within scope.

1.3. Cooperative systems for transport systems management

Technological context

A prominent feature of automotive technological evolution in recent years is the development of V2V (vehicle to vehicle) and V2I (vehicle to infrastructure) communication tools. The development of these tools came as a response to increasing safety concerns and also the projected development of automatic highways. The latter required vehicles to move in platoons at high speed and close spacing from each other, and implied that the relative position and speed of vehicles should be automatically controlled by communication devices. This evolution opens the prospect of information being shared and exchanged between vehicles, or ascending from vehicle to system or descending from system to vehicles, and thus of devising traffic management systems based on these new capabilities.

Scientific context

Since the introduction of synergetics there has been a growing interest in the applications of ideas from physics to social sciences and complexity issues. Statistical Physics have introduced various useful concepts, notably complexity, Brownian agents, mean fields, self-organisation and emergent behaviour. These concepts have carried over to other disciplines, with concepts such as distributed intelligence and multi-agents in AI (artificial intelligence), meta-heuristics in operations research and combinatorial optimisation, CA (cellular automata) and multi-agents in transport.

Context: summary
The convergence between new technological means and new conceptual frameworks has promoted the idea of cooperative systems in transport systems with many agents (vehicles, controllers, authorities) interacting towards an improved and more efficient management of the system. This leads to the requirement on traffic models that they be adapted and developed in accordance with this new perspective.

1.4. Frame of reference

The harmonised research programme is presented here within a framework for research on cooperative ICT in transport: the particular benefit of establishing this is that proposed projects can be assessed and related to each other in respect of their combined coverage and their complementarity. The framework has 5 distinct dimensions of classification of research on cooperative ICT. These are:

1. Key objectives
2. Research themes
3. Areas of expertise
4. Areas of traffic management
5. Opportunities for innovative contribution.

These five dimensions give complementary and cross-cutting views of the research. The concept of this is that each prospective piece of research in the harmonised programme can be viewed with reference to each of these 5 dimensions of classification in turn, which will make explicit the inherent commonalities and the complementarities that arise. This will illuminate its objectives, motivations and relationship to other research and potential contributions. There is no intention to suggest either that all possible combinations should be researched or that overlaps should be eliminated from the research programme: rather, the classification is intended to help identify the relationships among different prospective research activities and to identify particularly promising combinations. Full details of this research framework and the associated dimensions of classification are given in section 2, together with a discussion of their content.

2. Methodology of our work towards D14

2.1. Introduction

The definition of the harmonised research programme is a fundamental task for the NEARCTIS project. So far, the activities in Work Package 1 (WP1) have elaborated the common view of the state of the art, identified the fields of excellence among the partners and delineated the gaps in knowledge. The final result of WP1 is the specification of the harmonised research programme that delineates the future research activities in the field of cooperative information and communication systems as applied in the form of intelligent transport systems. It is clear that the definition of this kind of programme gives rise to a set of issues that must be addressed. The substantial importance of this research together with these substantial issues makes the preparation of this deliverable a challenge for the entire consortium; therefore, a systematic approach and methodology for the development of the harmonised research programme that can address this challenge is needed.

This section sets out the methodology that was developed and adopted for this purpose. It starts from the process design, through the different stages, the sources of information used, the partners' involvements and the time frame that was followed. We specify and explore the framework within which the research programme was developed.

2.2. Methodology

The methodology was designed with the intention to ensure that the final research programme has certain specific characteristics that were viewed as being desirable and appropriate. In particular, it should be *robust*, *extensive*, *shared* and *balanced*. The programme should be *robust* and reliable in a way that transcends the individual research activities on which it was based and that it contains, and so provide a firm basis for the formulation of future research activity. It should be *extensive* in representing a comprehensive range of research topics that are relevant to cooperative ICT. It should be *shared* among the partners, in that it draws on their collective expertise, and their current and future interest. Finally, it should be *balanced* between coverage of a broad spectrum and focus on specialisms, it should look at the present necessity without neglecting the future ones. It should make full use of the available knowledge and technologies, but, at the same time, be open to future ones. The methodology that was adopted considers all of these in developing the research agenda.

To ensure a robust, extensive, shared and balanced research programme a phased approach was developed. This involved planning and undertaking a series of consultations of members of NEARCTIS consortium, each building on the results of the previous one. The process was phased in the sense that each consultation included a call for contributions that was followed by assimilation of the responses, synthesis of the resulting information and internal dissemination of the results. The first phase, *internal dissemination*, gives all partners an opportunity to express their point of view on the topic of the consultation. Subsequently, after the *receipt of contribution*, the crucial phase of *assimilation of the material* synthesised a view that was taken to represent a consensus of the consortium. During this phase, the topic of the consultation was developed in accordance with the inferred common view. This three-phase approach to consul-

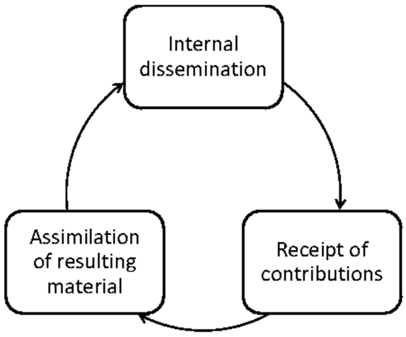

Figure 2.1: The Consultation Process

tation was repeated four times during the development of the research programme. The first and second times supported consolidation of the 5-dimensional framework for the research agenda, leading to a shared agreement on each classification dimension and defining every subtopic. The first consultation established the key objectives and areas of expertise, whilst the second consultation confirmed the thematic view of future challenges identified by members of the consortium. The third consultation provided the necessary information to populate the framework and to synthesise the harmonised research programme, thanks to the contribution on specific research project from all the partners. The final consultation reviewed the populated framework through the device of a round-table meeting with representative from all the partners, has provided the possibility to allow for flexible and dynamic discussion on the proposed research programme.

This consultation process to develop the harmonised research programme lasted more than one year. The preparation activities began at the end of 2010. The first consultation took place in January 2011, the second in July, third in September and fourth in November. Moreover, the research programme is deeply based on the information from previous deliverable and activities, *e.g.* elaboration of the common view, identification of the fields of excellence and delineation of the gaps in knowledge; therefore, the research programme is the outcome of a four year process, began with the start of the NEARCTIS project.

The purpose of the first phase of consultation was to establish a consensus on the major long-term challenges for the EU in traffic management. All partners of the NEARCTIS consortium were approached to elicit their views on this, and they were stimulated by provision of a specimen list. The two particular questions asked in this approach were to establish:

What challenges did partners envisage arising?

How did partners see their own areas of expertise contributing to research on these objectives?

The responses to this consultation were reviewed and a thematic view compiled of future challenges in traffic management with the consequent opportunities for contributions from cooperative ICT. In this, we identified themes for which there is a combination of strong support and potential for development. This approach to partners was successful in eliciting a broad forwarding-looking view of possible research contributions that would be based on sufficient knowledge, understanding and technology.

The purpose of the second phase of consultation of partners was to develop the thematic view that was the outcome of the first phase into a task-oriented research agenda. To achieve this, a summary of the thematic view was circulated to task leaders as the basis of a request for them to comment on this and, according to knowledge of their designated topics, to develop it into a task-oriented agenda. The response to this was used to draft a comprehensive document that unifies the contributions to the research agenda. The thematic view that was based on this identifies future challenges in traffic management that present opportunities for cooperative ICT. Elements of this were related to the expertise and capability of members of the NEARCTIS consortium.

The purpose of the third phase of consultation was to achieve a consensus on the thematic view of the research agenda that was compiled on the basis of responses to the earlier consultations. Partners were asked in particular for their comments on the draft thematic view, and for contributions of specimen research ideas placed within the task-oriented research agenda related to these themes. The responses, which are collected into the appendix to this deliverable, were compiled into a comprehensive document that develops the thematic view and unifies contributions to the research agenda. We will relate this to the expertise and research capability in the consortium. This material forms the framework for the harmonised research and development programme that is advocated in the present deliverable.

This process of synthesis of the harmonised research programme proceeded from the conception of the 5-dimensional framework for research through its creation and consolidation to its population. The specimen research projects that were contributed by NEARCTIS partners to populate the resulting framework have been analysed, and the harmonised research programme synthesised through this process. Part of this analysis was the identification of clusters, overlaps and links among the specimen projects. The result of this analysis is shown diagrammatically in Figure 2.2, which shows all of the contributed projects and indicates some of the principal relationships between them. Each contributed specimen project is represented by a circle that shows the project ID and a short title. Table 2.1 and Table 2.2 report, respectively, the correspondence between the project ID, the short title and the full one, and the glossary for the abbreviations used in the short title. The projects are positioned in the diagram so that proximity represents the degree of similarity. It is possible to identify affinities and overlaps among several projects, and so to create clusters. Some groups of projects are contained into square boxes that represent the general area to which these projects belong. These areas provide a logical classification, which gives a different view on the projects. In addition to these proximities and overlaps, some projects or areas of projects have particular connections, which could be defined as an interde-

ID	Short Title	Title
1	Platform for TM	AIM — Application Platform Intelligent Traffic Management
2	TT estimation	Real-time Travel Time Reliability Estimation and Prediction
3	ATM for corridors	Active Traffic Management Schemes for Integrated Corridors
4	Crash incident detection	Real-Time Crash Risk Detection and Prevention on Rural Roads
5	Data quality	Data Quality for Reliable and Efficient Traffic Monitoring and Control
6	Pedestrian in hubs	Pedestrian Movement in Multi-modal Mobility Hubs
7	Coop. for street design	Cooperative technologies to assist urban street design
8	DTA for TM	Cooperative dynamic traffic assignment models for co-modal sustainable traffic management
9	Coop. for logistics	A community system for cooperative sustainable city logistics
10	Coop. for network	Using cooperative data for knowing the real usage of the network
11	Urban modelling data mining	Spatial-temporal data mining for urban traffic modelling
12	Innovative cars	Using innovative cars to contribute to less congested traffic conditions
13	Multi-scale model	Multi-scale traffic modelling and control
14	DTA	Dynamic Traffic Assignment and collective real time users' information
15	Adaptive optimisation algorithms	Adaptive Optimisation Algorithms
16	Mainstream traffic control	Mainstream Traffic Flow Control
17	Ramp Metering	Ramp Metering
18	Urban Traffic control	Urban Traffic Control in Saturated Traffic Conditions
19	Feedback loops	Understanding Feedback Loops
20	Travel information	Improved Traveller Information
21	Signal control	Improved Signal Control
22	Innovative vehicle fleets	Evaluating the impacts of changing vehicle fleets and technologies
23	Incident detection in main road	Incident detection in main road networks
24	Pedestrian crossing	Optimisation of pedestrian crossing in multi-modal intersections
25	Differential road pricing	Differential Road Pricing
26	Real time traffic estimation	Real time traffic estimation
27	Multi-modal Coop. strategies	Multi-modal co-operative strategies
28	Operational strategies for network	Operational control strategies for network-wide traffic management

Table 2.1: Project IDs, short titles and full titles

pendency link. This means that the results from a project, or area of projects, could be used as predicates for other projects or areas of projects. This connection is shown by arrows, and the direction represents the logical flow of information, *i.e.* from the project that produces the results to the project that is predicated on them. The specimen projects contributed by partners have different scopes and scales: some of them are focused on particular aspect of cITS whilst others have a wider approach. The different scales are represented by different sizes of the associated project circles.

Abbreviation	Phrase
TM	Transport Management
TT	Travel Time
ATM	Active Traffic Management
DTA	Dynamic Traffic Assignment
Coop.	Cooperative

Table 2.2: Abbreviations in Short Titles

After a preliminary draft of the harmonised research agenda had been circulated to NEARCTIS partners for information and comment, it was discussed at a round-table meeting convened in London at which all core partners of the consortium were represented. The purpose of this round-table meeting was to refine and consolidate the draft harmonised research agenda. This provided partners with an opportunity to review and comment on the draft and so to contribute to its finalisation. This process recognised the substantial potential value in developing existing material to address opportunities that become apparent only in the context of the full draft. Through this, we achieved a fuller, more rounded and balanced presentation in the harmonised agenda of the research ideas in the context of the framework for this that had already been developed in consultation with NEARCTIS partners. This development of research ideas that had already been proposed with the partner who contributed them also enabled them to show how their ideas can be supported by shared resources that have been identified as part of Work Package 4 (Capitalisation and shared resources) of the NEARCTIS programme of work.

This entire process is set in the context of information provided by earlier NEARCTIS deliverables including:

- D6: Review of the state of knowledge and capability in relevant technologies
- D7: Review of available case studies and related scientific knowledge
- D8: Application possibilities and feasibility studies
- D11: Report on identified research topics due to assimilation of shared resources

In addition to this information, partners of the NEARCTIS consortium contributed at several stages during the consultation process that generated the present research programme. The programme draws on the expertise and interests of the partners, as well as the knowledge of

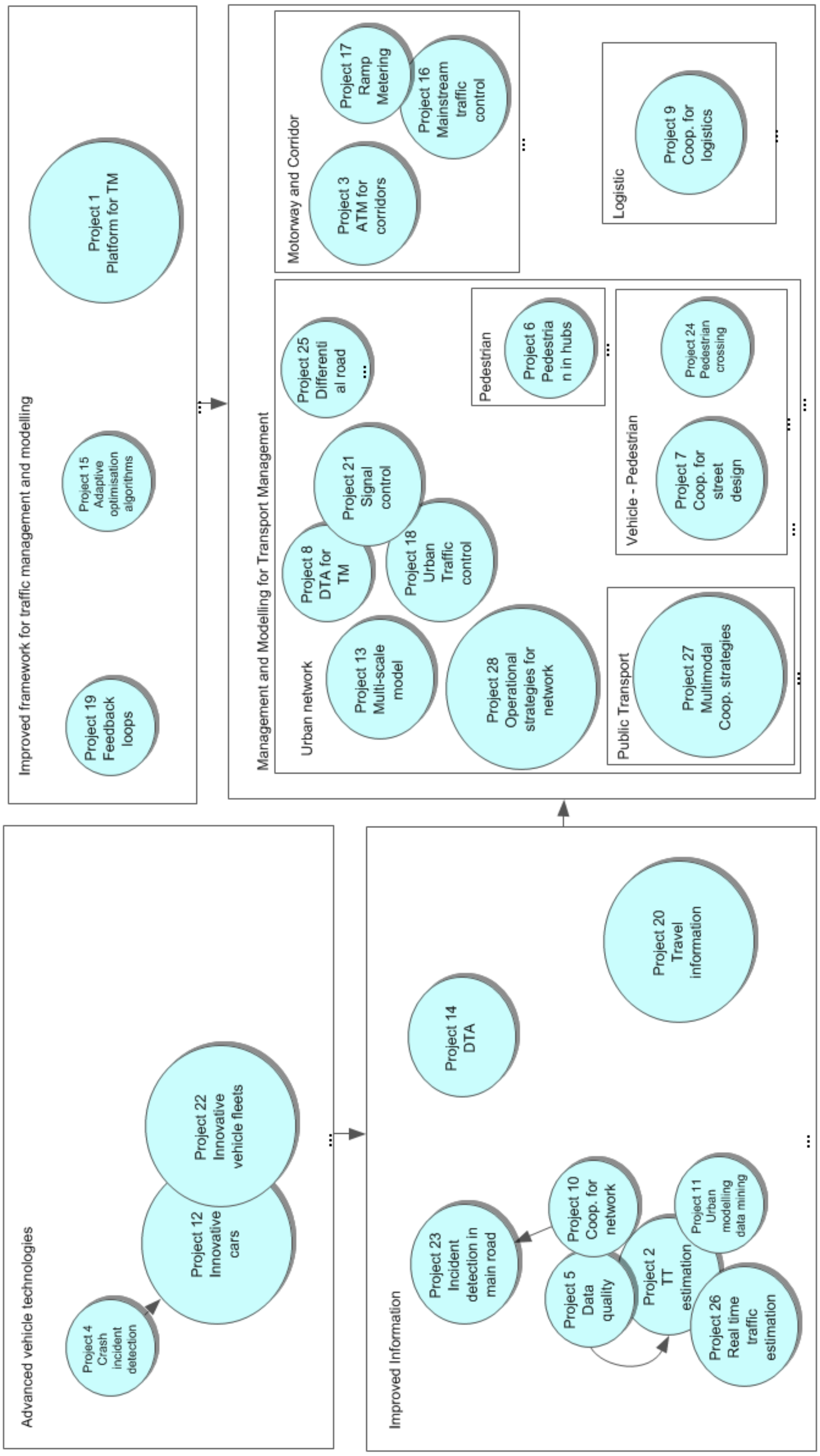

Figure 2.2: Partners Projects

the several national institutions, professionals and practitioners where the different NEARCTIS partners are based. This wide range of backgrounds and perspectives among the partners contributed beneficially to the research programme, giving to it a rich pan-European scale and composition.

In summary, the adopted methodology is appropriate for the characteristics that the final research programme is required to have, and it adds consistency, structure and coherence to the research programme. In light of the success of this approach, a similar one will be adopted to generate further deliverables from the NEARCTIS network of excellence.

2.3. The research framework

2.3.1. Introduction

In order to explore the relationships among the activities and contributions within the research programme, a framework with 5 dimensions of classification was developed, as described in section 1.4. In this section, we specify the dimensions of this framework and explore their elements. The purpose of this framework is to help to identify commonalities and complementarities within research and hence to structure and harmonise the programme. We consider each of the 5 dimensions in turn.

2.3.2. Objectives of cooperative ICT

A review of the major long-term challenges for the EU in traffic management yielded a thematic view with the consequent opportunities for contributions from cooperative ICT. This led to identification of the following five **key objectives** of research on cooperative ICT in transport:

1. Safety
2. Environmental Impact
3. Efficiency of the Transport System
4. Traveller and System User Experience
5. Societal Impacts, Costs and Equity.

These objectives are viewed as having similar priority. Although the general consensus is that safety is of particular importance, there is also agreement that it should not be considered to the exclusion of the other key areas. Instead, we suppose that innovations and interventions should be considered provided that they are at least safety-neutral. Thus an innovation or intervention could be justified on grounds other than safety benefit provided that it is not expected to be detrimental to safety. Further objectives that are also relevant include accessibility, economic return, livability and sustainability, which can be incorporated within the five key objectives listed above.

Here, we summarise the goals and opportunities that cooperative ICT systems could promote and note some of the issues that arise in this. These are grouped under the 5 key objectives.

Safety
Prominent among the opportunities for cooperative ICT systems is the use of mobile communications to improve safety. These opportunities include:

- The collection and supply of real-time information about relevant road, traffic and weather conditions, especially where these result from incidents or give rise to other transient hazards. In particular the use of in-vehicle sensors to gather information that can then be transmitted upstream using communication from vehicle to vehicle (V-V) or bidirectionally between vehicle and infrastructure (V-I-V).
- The supply of information and warnings regarding road geometry, layout and other static hazards.
- The supply of information about speed limits and other traffic regulations.

The provision of tools and information to policy makers to assist decision making for this is recognised as being important.

Environmental Impact
A number of issues arise relating to environmental impact. There is a need to improve fuel consumption, pollution, noise emissions and air quality. These goals may be advanced by better traffic management and control. In particular the use of more, better and more timely data can facilitate inclusion of environmental effects to influence traffic control decisions. With knowledge of downstream traffic conditions, opportunities will arise to promote these objectives by better engine management and trajectory control that will smooth traffic flow and eliminate stop-go traffic.

Encouraging modal switching in particular, and to work towards truly inter-modal traffic and transport management is an important mechanism for this objective.

Efficiency of the Transport System
The purpose of the transport system is to facilitate the movement of goods and people between their desired locations. It is important that this be done effectively and efficiently, making good use of the resources available and with external effects that are managed and limited so far as is possible. Transport and traffic management aims to ensure that infrastructure is used

efficiently, and that users of the system and others who are affected are not subject to excessive and avoidable cost.

It is also important to identify where additional infrastructure resources, management resources and regulation will bring worthwhile additional benefits.

Traveller and System User Experience
Many opportunities arise for improving user experience. These include:

- Improved traffic conditions as a result of cooperative management.
- The effect and improvement of bus priority systems to encourage modal switching.
- Warning of incidents, hazards and other influences on travellers.
- Improved safety and security of transport systems and their usage.
- Improved and more efficient freight and goods distribution. With the rise of online shopping and home delivery the issues are expanding to a greater scale.
- Improved, more reliable and up to date information on the state of the transport system and the traffic using it.

Other issues that arise are the effect on user behaviour and choices in using the transport system of access to improved and more up to date information, the impact of instantaneous communication, and also the need for high-level reliable information.

Societal Impacts
The wider impacts of cooperative traffic management give rise to a number of issues. Topics and issues that arise in this include:

- The effects of improvements in vehicle tracking. Road user charging moving beyond charging for consumption through fuel duty then becomes more practical. There are also implications for enforcement of traffic regulations and wider enforcement. Commonplace vehicle tracking also raises issues of privacy.
- Improved accessibility for older drivers, and an increased comfort for all making driving safer.
- Payment for the costs of cooperative systems. Some benefits will be immediately clear to users but others may be less clear and in some case the benefits may accrue to others and elsewhere in society as a whole.

2.3.3. Research themes

The fundamental classification of opportunities to develop cooperative ICT for transport leads to a thematic view of future challenges to be addressed. Each of the emergent themes represents a way in which appropriate research can be oriented and focused. Working from contributions from members of the NEARCTIS consortium, we developed this view into the following 7 broad themes.

1. Increased availability of mobile communication
2. Increasing data availability
3. Improved modelling at all scales
4. The need for communication between autonomous systems
5. An understanding of these interactions at various levels
6. Achieving effective large-scale management of transport systems and their efficient usage
7. Support for policy developers and decision makers.

Considering each of these themes in turn:

Increased availability of mobile communications
The increasing ease of use and availability of mobile communications provides many new opportunities for cooperation, management and control of traffic. It offers the prospect of making available data on current and likely short-term future traffic, road and weather conditions. There is also the prospect of providing information of this kind to vehicles upstream so that appropriate decisions and actions can be taken by managers and travellers. This increased availability of mobile communications will play an important role in the development of cooperative traffic management.

Increasing data availability
A consequence of increased mobile communication is that as well as a providing a means of delivering information, it also provides an extensive source of data. This presents challenges for the timely collection, analysis, derivation of information, distribution and effective use of the data for planning, maintaining, operating and using the transport system: work will be needed on all of this. Using the data effectively will require a good understanding of its nature and content, and an ability to assess its reliability and accuracy.

Improved modelling at all scales
The availability of detailed data about traffic conditions will offer new opportunities and challenges for modelling at all scales. For use with cooperative systems, ease of transfer of results

between models will become increasingly important. Large-scale availability of diverse real-time data will offer new modelling opportunities at the small scale to assess the likely development from current traffic conditions, and the impact and consequences of incidents and of traffic management measures. At the other extreme, modelling on a larger, even regional, scale will be required to understand fully the operation and effects of autonomous but cooperative traffic management systems.

The need for communication between autonomous systems
Effective cooperation will require timely communication of traffic and other data, and also of traffic management and other related objectives and decisions. Work will be needed to identify appropriate information to transmit, and to develop standards for its communication and interpretation.

An understanding of the consequences of interactions at various levels
Cooperative interaction can take place at many levels. Because the communicating systems are autonomous the collective results of their independent decisions can be complex. Understanding the mechanisms of interaction, their potential benefits and the possible consequences that arise from this cooperation will be essential.

Achieving effective large-scale management of transport systems and their efficient usage
Results from the research programme that is specified here can contribute synergetically to this theme. But there are also requirements to address the challenges of large-scale management, to identify the tools needed to make this effective, and to address the issues of integration.

Support for policy developers and decision makers
Effective realisation of the concept of cooperative traffic management will require appropriate and relevant legislation and policies to be implemented. For this to happen, policy developers and decision makers will need to be properly informed and advised. This support must provide awareness of opportunities for application, the scope of technological development and capability, and the specific nature of benefits from implementation. Policy developers will need tools to facilitate evaluation of possibilities, identification of the range of possible benefits, and ultimately quantification of them.

2.3.4. Areas of expertise

Leading research in the area of cooperative ICT in transport will call on high levels of knowledge, understanding, capability and skills in each of analysis, engineering and social science. The effectiveness of cooperative systems will depend on an understanding of travellers' and other users' behaviour and their responses to increasing information and more flexible systems. The particular areas of expertise that are identified as being directly relevant and so to contribute to research on cooperative ICT are:

1. Modelling
2. Optimisation and control
3. Positioning, Tracking and Communication
4. Impact Assessment, Deployment and Implementation Issues
5. Evaluation.

Strong capabilities in these areas will be required to contribute to the research initiatives and technological developments that are envisaged within the research programme. These will be complemented by other knowledge and expertise, including that from practical implementation, industrial capabilities for manufacturing, planning and operation.

Considering each of these areas of expertise in turn:

Traffic modelling for cooperative systems integration
The varying role and use of models can be identified as including the key areas of: understanding the system, controlling the system, evaluation, transport planning, and infrastructure planning. Within these application areas, the nature and general properties of self-organising systems can be identified as being particularly relevant to cooperative systems in transport management and control. Three particular varieties of these systems can be identified as: cooperative individual agents (corresponding to driver/vehicle units), cooperative controllers, and integrated cooperative systems (associating vehicles and controllers). Each of these raises different requirements for the models that are used in their development and management. To put these models in perspective, we can consider what is their role and purpose, and what qualities they should have. Based on a review of the literature, the state of the art of model development and current modelling tools extends from multi-agent microscopic models through cellular automata to macroscopic mathematical models of traffic ranging from a single link model to system-wide models for traffic assignment. These modelling approaches and tools have substantial relevance and potential for development and management of cooperative systems. Several of these modelling tools are available as shared resources within the NEARCTIS network and are used in current projects. On the basis of this, and with reference to examples of current research applicable to cooperative systems, we have introduced some guiding principles for the development of future research.

Optimisation and Control
The efficient, safe transport of persons and goods with minimal pollution calls for optimal management and use of the available infrastructure via suitable application of a variety of traffic control measures. This trend is facilitated by the rapid developments in the areas of communications and computing (telematics), but it is evident that the efficiency of traffic control depends directly on the efficiency and relevance of the control methodologies that are employed. The methodological domains of optimisation and control offer reliable, robust and powerful generic techniques and algorithms that are explored in section 3.3. This can be used to select the most appropriate approaches for each particular traffic management application at hand.

Positioning, tracking and communication
The deployment of future traffic management services will be supported by the development of new technologies of communications and positioning. In the context of road safety, future applications will require accurate measuring and monitoring systems as well as high quality traffic models, and efficient and reliable communication tools. This application domain will call for multidisciplinary research activity with strong links between positioning and tracking technologies, and traffic modelling and monitoring, which will in turn be supported by developments in telecommunications.

This broad field of knowledge is largely covered by the NEARCTIS network, which includes relevant expertise and competence in these specialist domains. Most of the institutions are already involved in research activities in cooperative systems. However, there is a requirement for integration of this wide ranging specialised knowledge into a common view of the needs of future traffic management systems based on cooperative technologies.

Impact assessment, deployment and implementation
Four areas relevant to successful implementation and deployment of ITS applications are: impact assessment, system architecture, interoperability and transition effects, and uncertainty and robustness. With the use of detailed simulation models, significant impact assessment for some indicators such as travel time, travel time variability, fuel consumption, emissions, vehicle speed, and traffic conflicts becomes possible. These advances in system architecture are seen in applications to traffic measurement, incident detection, and information transmission in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications respectively, with increased reliability, capability, and efficiency of different cooperative systems. The improvements in interoperability and transition effect of ITS applications have been revealed in the areas of map matching, traffic surveillance and inter-vehicle communication. Last, for the issues of uncertainty and robustness, achievements are revealed in the applications to traffic measurement, travel time prediction and incident detection with increased detection rate and reduced false alarm rate.

Evaluation
The aim of NEARCTIS is to improve the long-term performance of the transport system by the use of ICT for the deployment of cooperative traffic management. Contributions will be required in three key areas:

1. Assisting in the formulation and evaluation of policy objectives
2. Identifying appropriate traffic management techniques as potential contributors to these objectives
3. Developing effective tools to design and evaluate these measures.

The knowledge required for the evaluation task differs from that for the other tasks in this work package. Four distinct areas that need to be considered and understood for evaluation are:

1. The users and stakeholders, including providers, managers and users of the transport system, and their interests. The users and stakeholders identified are those on whom the NEARCTIS research will have a direct impact. A separate class of users and stakeholders who have a role in the assessment of the performance of the transport system is identified.

2. The role of technologies and research activities in progressing effective integrated transport systems through cooperative deployment.

3. Techniques and methods for identifying and evaluating the available technologies for achieving identified ends.

4. Assessment of the performance of the transport system. This requires:

    - Performance Criteria: Outcomes that will be used to assess the benefits and disbenefits of ICT for the affected groups
    - Interested Parties: Identification of those who will benefit or be disadvantaged and in what ways
    - Transport System Components: The means by which technologies will deliver benefits.

Focus should be restricted to areas that are relevant to the particular instances of cooperative traffic management that are the subject of the research being evaluated.

The fifth task, Evaluation, is a cross-cutting task aimed at evaluating and identifying the benefits that will arise from the final research programme. The work of this task is formulate a common view of how and against what criteria the research programme should be evaluated to show that it will contribute successfully to achieving the goals of the NEARCTIS project. (This will be explored more fully in D18)

2.3.5. Traffic management applications

This dimension of the 5-dimensional framework identifies areas of traffic management according to the role they play in the management of the transport system as a whole. The work done in the development of the case study deliverables D7 and D8 contributed to the identification of areas of **traffic management** (TM) where research in the future programme could contribute. These are:

Global services
The state-of-the-art of global service implementation on advanced traffic management, with respect to shadow toll systems, fleet management, door-to-door travel support and individual cooperative systems were identified. The functionalities of GPS applications on individual traffic participant management were revealed. Based on the identified knowledge gaps, case studies of

pilot projects of GPS implications on European road network management were described, assessing the operational and economic feasibility of integrated traffic management systems with global services. Besides this, the impacts on mobility, safety, environment, and user acceptance of GPS implementations of this kind were evaluated. However, it was found that coordinated enhancement of specifications for low level and system level data exchange will be crucial to the successful international interoperability of applications in the future.

This application area includes, but is not limited to:

- Shadow toll systems and road pricing
- Fleet Management
- Door-to-Door Travel Support
- Individual Cooperative Systems
- Coordination on network level
- Integrated traffic management
- Coordinated traffic control
- Coordinated ramp metering
- Use of control scenarios
- Need for large field operational test

Large highway corridors

Case studies presented in deliverable D7 illustrate state-of-the-art traffic management methods for large highway corridors. These case studies covered the topics of driver information systems, route guidance, local and coordinated ramp metering, variable speed limits, vehicle-to-vehicle and vehicle-to-infrastructure communications, tunnel management, and traffic surveillance. Each one of the case studies was presented following a common structure and was assessed based on various criteria including efficiency, user acceptance and operators views. While each case study has reported measurable benefits, it is seen that further enhancements are possible. The efficient, safe, and less polluting transport of persons and goods calls for optimal use of the available infrastructure via suitable application of a variety of traffic control measures. These include driver information systems, route guidance systems, ramp metering and variable speed limits. Daily varying demands, changing environmental conditions, exceptional events and incidents may change the typical daily traffic conditions in an unpredictable way. This may lead to under-use of network capacity, whereby some links are heavily congested while capacity reserves are available on alternative routes. Route guidance and driver information systems may be employed to improve the network efficiency via travel-time displays or direct recommendation of alternative routes.

Dense urban networks
Case studies show that advanced ITS systems have been implemented in several European dense urban networks. These covered the topics of urban traffic control, congestion management, traffic information collection and provision, congestion charging and public transport priority. Further advanced implementations exist world-wide. The analysis of case studies in D8 shows that the traffic management applications in these areas would benefit from more effective cooperative systems.

Local main road networks
Management here is concerned on one hand with managed lanes operations and on the other hand with incident management on road local networks. Managed lanes operations develop more and more in Europe. Various practices are implemented including additional lanes, hard shoulder running, high occupancy vehicle (HOV) and reserved lanes. Many case studies confirm the positive impact of these practices on the traffic congestion and the environment: local pollution and CO_2 emissions. However the conclusions as regards safety are sometimes contradictory. The development of suitable cooperative systems would have a beneficial impact on managed lane operations

The effective management of incidents is essential on local main road networks. Case studies suggest that well thought out measures have a positive benefit in reduction of non-recurring congestion, reduction of emissions of pollutants, and improvement of road safety. Cooperative systems offer potential to provide additional benefits.

Multi-modal networks
Multi-modal management applications are primarily concerned to promote sustainable transport by encouraging wider use a range of means of transport. This includes potential priorities to these modes, to support the movement of people rather than vehicles. Advanced applications of this kind have a significant ITS (Intelligent Transport Systems) component, particularly regarding the need for road user detection, communications and advanced control strategies. Examples include ITS-dependent bus priority, improved pedestrian crossing facilities and multi-modal traffic management.

2.3.6. Opportunities for innovative contribution

The four **technical opportunities** for innovative contribution by cooperative ICT are:

- Evolving methodologies
- Emerging technologies (sensors, communications)
- Enhanced traffic management applications
- Novel traffic management approaches.

Applications of combinations of these opportunities to address traffic management needs and requirements are considered to be most appropriate where improvements can be made to one or other of:

- Efficiency of a TM activity that is currently undertaken
- Effectiveness of traffic management
- Scope of traffic management activity.

On the other hand, there is agreement that where a traffic management activity is currently undertaken adequately and development of cooperative ICT applications does not stand to improve any of efficiency, effectiveness or scope, then research into this activity this should not be a high priority.

3. The Harmonised Research Programme

In this section, we propose a harmonised programme of research in the form of a thematic agenda. This is organised according to the seven research themes that were introduced in section 2.3.3 as part of the framework discussed in section 2. We discuss the nature and interpretation of each of these themes and synthesise the relevant contributions. Within each theme, we introduce research areas that were identified by considering and building upon contributions from partners. For each of these areas, we address each of:

- Motivation for researching this area
- Premises
- Research required, including some of the major issues to be addressed

We then proceed to discuss the expected outcomes of researching that theme.

This thematic presentation of a research agenda is intended to form the basis of a harmonised programme of research. This programme identifies some of the areas of research to be addressed in order to develop and exploit the potential benefits of cooperative ICT for traffic management. Although the agenda as presented here is intended to be extensive and includes a wide range of topics, it is not considered to be exhaustive: it remains open to extension and enrichment from complementary research ideas. Although the genesis of this specification for the research programme lies with ideas contributed in the form of specimen projects, these were not intended to cover all possibilities and are not believed to do so. The programme therefore includes scope for many more projects, each with specific objectives.

The programme presented here identifies research needed to ensure that cooperative transport management achieves its full potential. The wide range of themes identified and the diverse research requirements included illustrate the ambition for cooperative transport management. The programme lays out what needs to be accomplished to achieve full-scale effective cooperative transport management. Progress towards that goal will be made by work on imaginative, ambitious projects motivated by the programme. Many, if not most of these projects will include research that contributes to several of the themes presented here. A successful project or sequence of projects has many stages in bringing an idea from initial development through field trials to successful application and implementation, which are illustrated in Figure 3.1. Depending on its scope, a single project might address one stage in this process, or might address several (typically sequential) ones.

3.1. Increased Availability of Mobile Communication

The increasing availability of mobile communication offers a number of opportunities for use with cooperative systems. Many of the anticipated benefits and much of the research needed

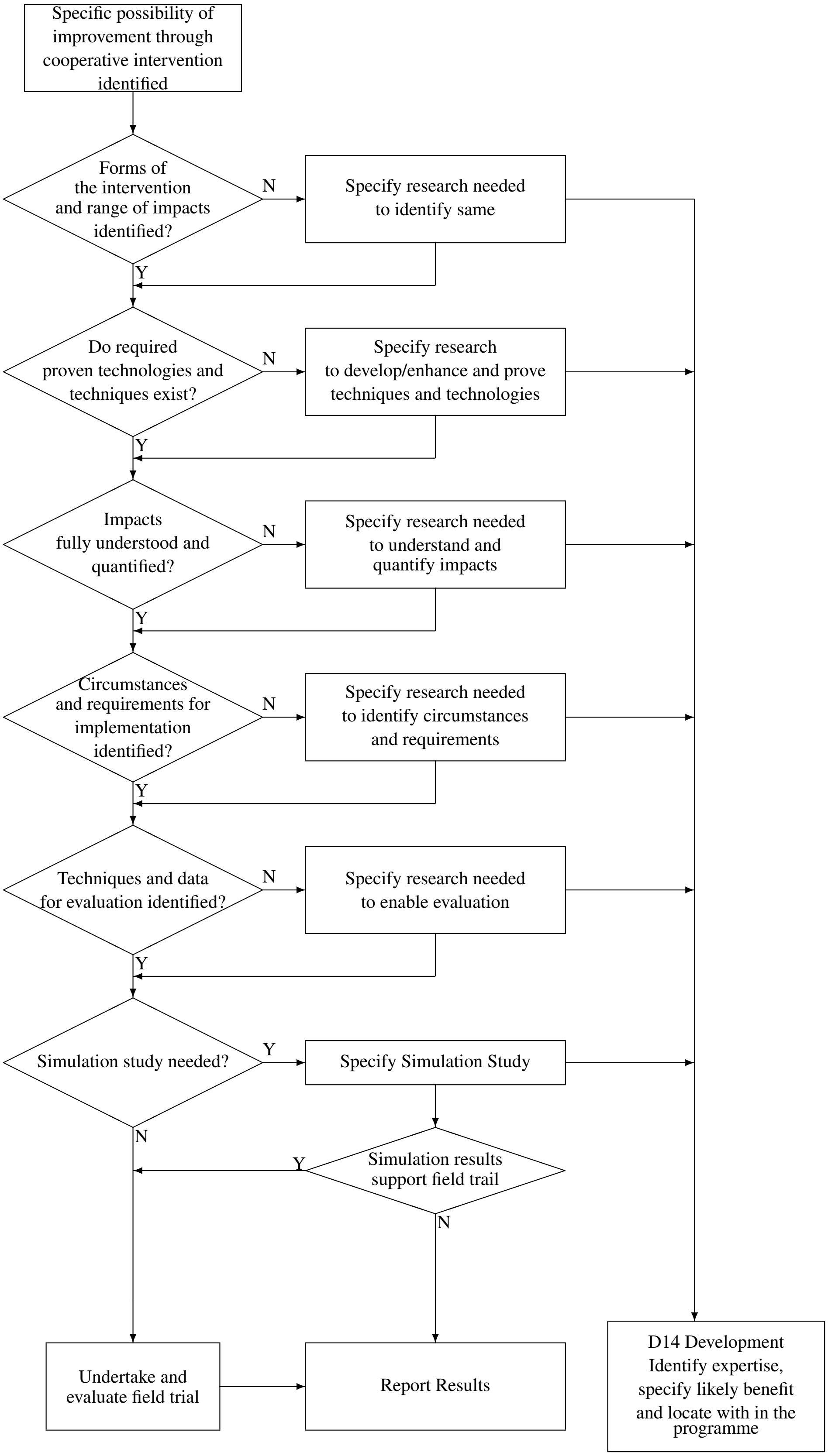

Figure 3.1: Project Life Cycle

to realise those benefits are predicated on the uses and availability of mobile communications. In order to exploit these opportunities successfully, there are two kinds of origins of communication and the same two kinds of recipients of communication to be considered. The first of these, either as an origin or a recipient, corresponds to the users of the transport system, whilst the second corresponds to the managers and operators. The primary forms of communication therefore correspond to the three modes that involve some mobile element of V2V, V2I and I2V. In discussion of the present theme, we consider these modes of communication according to the recipients. Thus we consider in turn communication to the system, as received by infrastructure, and communication to users, as received by vehicles or directly by users in them.

The capture of data by operators through making measurements from transport operations and the extraction of information from that can be used to facilitate its effective management. This can include macroscopic measurements of quantities that correspond to usage such as mean speed, flow and density of traffic. Measurements of usage can also include microscopic measurements of individual positions, speeds and travel times achieved. Other measurements can be made to monitor performance of the infrastructure to achieve good operation and control, and rapid detection and effective management of any incidents that affect this. The information extracted from this can be used to monitor transport networks and to support control and management of traffic operations. The second class of recipient is the users, so we also consider transmission of data and information to them. This can be used in various ways to inform, manage and control traffic and network operations.

3.1.1. Data Capture

Motivation Effective management of the transport system requires up to date information on both the current state of traffic on the network and of traffic management measures in operation. Beyond this, the capture of further information can be envisaged that concerns the current disposition of traffic in the network, commitments to actions that have been made implicitly, and intentions for further travel activity that will influence decisions and choices made in the short-term future. This information can be used in routine management and also in detection and management of incidents. In the longer term it can be used to develop a record of historical information that can be used as reference for management and, ultimately, for planning.

In practice, knowledge of the usage and traffic state of the road network is not homogeneous across different kinds of road. Effective knowledge about the traffic state of motorways is often readily available, whilst that for arterial roads and local road networks is not. The total length of local roads is too great and the traffic flows in places too low to justify the ubiquitous installation traffic sensors. For arterial roads the extent of urban networks can be so great that the cost to install fixed sensors throughout them can be excessive. Even for motorways the supply of real-time data may be limited, and the installation of additional sensors can be both expensive and disruptive. Thus alternative means of gathering information are required, which will call for use of vehicle-based mobile sensors in the form of either special-purpose devices or of implicit sensing based on devices such as GPS-equipped mobile telephones that have other primary purposes. Effective combined use of data from all sources of these kinds will entail fusion and other strategies of integrating diverse data. Low latency positioning with millimetre accuracy will be required for some applications to achieve appropriate levels of management and control, and ultimately this will become available. The relevant issues include that the existing monitoring infrastructure in arterial roads is less dense than on motorways. Beyond this, the traffic dynamics on arterial systems differ in important ways from those of motorways, and fixed sensors cannot always give the required level of information.

Premises Cooperative systems should aim to exploit on the whole range of different kinds of sensor information that are available. In particular, location-based sensors, such as GPS based mobile sensors, are becoming widely used and Automatic Vehicle Location (AVL) mobile sensors are found in abundance in commercial fleets such as UPS, FedEx, taxis and public transport vehicles. Furthermore, intelligent vehicles have many additional sensors as well as location sensors, including environmental sensors (weather conditions), proximity sensors, image-based sensors, and several kinds of internal monitoring and management sensors. These additional sensors offer the opportunity to capture a much richer set of data than that supplied by conventional road sensors. In addition to data from in-built sensors, trip-specific information such as intended destination and route may be available either explicitly or implicitly. This information is also potentially useful in the development of cooperative traffic management systems and their use in practice.

Research Required The amount of real-time information that is potentially available is enormous. However, this will only be useful if it can be captured, processed and delivered to traffic management systems in a timely manner and with adequate quality. Research is therefore needed:

- to identity potential sources of information and means by which the data can be gathered;
- to identify the data that can and should be captured. The appropriate data may vary from location to location and for different times of day. Thus data gathering software will need to be flexible and its configuration manageable. Identify the monitoring needs (type, location and sampling frequency of sensors) to provide data for efficient real-time management of road networks and traffic on them.
- to ensure that data can be made available in a timely manner. For example, some kinds of information such as intended turning and other movements may only have immediate use for a short time.
- to develop standard means of communicating the data from sources to collectors, and the distribution of information to traffic management applications, to other systems and to relevant groups of users.
- to understand how travellers and other owners of potential sources of data can be motivated to contribute. Individual drivers or commercial fleet operators may be reluctant to contribute data unless they can be persuaded of the benefits and that the use and distribution of their data will be managed properly.

- to identify and develop means to collect data on pedestrian movements in busy mobility hubs, multi-modal sites and multi-modal transport systems using smart phones and other personal devices.

3.1.2. Improved Traveller Information

Motivation Within any information-based system, the issue of dissemination is key in realising the potential benefits. Traffic information and control systems are typical in this respect, and indeed suffer the added difficulty that information will usually be based on the predicted future rather than the current measured traffic conditions. Cooperative systems provide the potential for both a more comprehensive and detailed understanding of current traffic conditions and information on current traveller destination and route intentions to improve predictions. However, it is not yet clear how best to impart this information to travellers to achieve the greatest system-level benefit. Cooperative systems also enable more targeted dissemination activities, with the potential to tailor specific information to individual travellers based on their current travel intentions.

Premises Provision of appropriate amounts of information, presented in helpful ways and qualified according to its accuracy and reliability will be valuable to travellers. The distinctions between data, information and advice are important in specifying the architecture of systems and in designing them. Especially in the case of explicit advice to travellers, differentiation between public and individual delivery will be important.

Research Required To ensure that information useful to users of the transport is delivered effectively will require research in a number of areas.

- Investigations of how traffic and travel information, particularly when targeted at drivers, can be delivered safely to the intended recipients. In particular, identification of the best methods and formats to convey travel information within vehicles. This should include investigations into the appropriate levels of detail to include and how this should vary according to the forecast horizon.
- Understanding of how information and advice can be personalised and made specific to the interests and preferences of individual recipients, particularly with the aim of improving personal mobility.
- Development of integrated inter-modal traffic information platforms.

3.1.3. Expected Outcomes

The increased availability of mobile communications will play a central role in realising ICT in traffic management and control and hence in implementing cooperative systems as envisaged here. Mobile communications will provide the means for vehicle to vehicle and vehicle to infrastructure communication, and hence will be required to implement systems involving vehicles that cooperate in real time. Measurements made from vehicles can be communicated to infrastructure-based systems for use in real time. This will result in better quality of management and control in normal conditions, and will facilitate rapid detection and response to incidents. Information generated by control systems can be disseminated directly to vehicles using mobile communications. This can either be common information broadcast to all users or information targeted to individuals according to their usage and profile. Traveller information can also be sourced directly from other travellers and communicated directly.

The effects of this mobile communication will be greater levels of information for system operators and for users. For the system, this will be beneficial in achieving more effective monitoring, and better quality of control and management of road networks. For users, this will be beneficial in providing greater levels of information and so supporting better choices in using the transport system safely and effectively.

3.2. Increased Data Availability

Data that could be used for cooperative traffic management can come from many different sources and will relate to the current traffic and system states. Beyond this, data are becoming available on actions to which travellers and vehicles are committed and on the travel intentions that underlie choices and behaviour. Some examples of current and prospective sources are:

- Traditional traffic sensors in both motorways and urban areas
- Data transmitted from individual vehicles using on-board technologies
- Image processing techniques are available that can track moving objects including pedestrians
- The vehicle fleets using AVL as discussed in section 3.1.1 are also a valuable source of data
- Smart phones and other personal devices with WiFi and GPS technology, which are becoming ubiquitous. They represent a further source of data, and are particularly valuable in cases where pedestrian movements are of interest.

In several cases, these sources can be used to provide data about plans and intentions as well as current state. Information of this kind can be used to anticipate developments of the system and hence to lead to better dynamic modelling and management.

3.2.1. Data Quality

Motivation The concept of cooperative traffic management is based on several technologies with augmented capability to measure and to transmit large amounts of data between vehicles, traffic centres and road operators. The deployment of new traffic models and strategies will benefit from multiple sources of information. The main motivation for the research proposed here is the development of a quality concept relevant for future cooperative traffic management models and applications.

Premises Data will be available from multiple sources with varying degrees of quality and different approaches to management of this quality. Most of the more traffic-related research identified in the programme depends on the timely availability of reliable data, in some cases to resolution within lane or finer.

Research Required Most of the more traffic-related research identified in the programme depends on access to reliable source of data. Research is therefore required to ensure that data of the quality required can be generated and communicated promptly to applications and users.

- The data quality must be adequate for the intended application or use. Tools to assess the data quality therefore need to be developed. Quality needs to be understood and communicated at both the level of data from individual sources and also for estimates resulting from data fusion. The relevant characteristics for the quality assessment and how these vary according to the field of application will require investigation.
- Vehicle positioning is particularly challenging in urban areas. Future positioning systems will combine multi-sensor systems and will perform continuously. What is the methodology for assessing the positioning accuracy and how can we monitor the positioning integrity of large numbers of vehicles?
- Identify appropriate levels of accuracy and timeliness of data in light of intended application and determine suitable technology to achieve this.
- The investigation and determination of means of collecting traffic state data from novel sources, in particular using mobile communications to obtain data from travelling vehicles. While the communication of collected data to collection points can be easily achieved the challenge is the identification of the appropriate data to collect and the development of the means of distributing it to relevant systems. (see also section 3.1.1)
- The development of tools for data capture and retrieval that will ensure data is of the required accuracy and reliability. In general, all these data-sources have to be exploited with regard to the applications that use them. For instance, automated vehicles may need their location and the instantaneous distance from other vehicles with millimetre accuracy, while estimating a traffic state from these data only requires an accuracy of around 10 meters. When determining origin-destination information from the same data, kilometre-scale accuracy is sufficient and even advisable in light of privacy issues.

- Continuing research effort to monitor novel sources of data in order to identify emergent opportunities that arise from them. Consider, for example, floating car data (FCD) from vehicle fleets in which travel times are estimated for the links of the network. Internal self-evaluation can be achieved by removing the data of a randomly chosen vehicle from the fleet and not processing them: the system can then be tested by using it to predict the travel time of this vehicle – the difference between the two provides a measure of quality and accuracy.

3.2.2. Data Collection and Fusion

Motivation With the potential for obtaining data from a large number of sources, some of which may be intermittent or sporadic, the consistency and reliability of collected data becomes an important issue.

Premises Data may be collected from many sources and relate not only to traffic state but also to road and network conditions, pedestrian movements and weather conditions. The fusion of data of different kinds and from different sources can help to address problems of consistency and reliability. Applications will benefit if they have a reliable supply of data that is coherent and of known accuracy.

Research Required In order to use the data effectively, research will be required into ways of reliably fusing data from different sources into a coherent whole.

- For tracking pedestrian movements ways must be developed so that information obtained from motion sensors and image processing can be reconciled with data from smart phones.
- Identification of the fraction of vehicles supplying real-time data such as location. This will be needed to estimate traffic state and travel time reliably and with quantified accuracy. Understanding how this may differ for different types of network and different applications.
- The accuracy and timeliness requirements of different applications need to be investigated and means found of meeting these requirements. The role of fusing data from different sources to meet differing requirements will also require research. For example, can a combination of fixed and mobile sensors provide better information for monitoring and control? If so, what information is needed from each?
- There is a need to develop algorithms and software that will allow applications to fuse relevant data from different sources. In this case, the application finally determines which data sources are needed as input into which fusion algorithm, and with what quality.

3.2.3. Data Processing

Motivation In order for data to be useful it needs to be supplied to applications and systems in useful and consistent forms. The previous sections 3.1.1, 3.2.1 and 3.2.2 have already addressed issues related to ensuring data is fit for its intended use. The research discussed in these sections will need to be supported by effective data processing tools. Furthermore, applications will be needed to extract useful information from the data. Abundant data from multiple sources will present both opportunities for exploitation and challenges to assure adequate quality.

Premises Appropriate data processing will be required for many applications and investigations. Having a common understanding of ways in which data can be processed for different purposes will be beneficial. Statistical methodology for processing and analysis is available that has been developed for large amounts of data, and this will become increasingly relevant.

Research Required To ensure that tools, applications and models have the resources they need to process and use data.

- The development of statistical methods that are able to estimate from collected data the indicators commonly used to describe traffic (density, speed, flow). Traffic and travel models can also be developed to use these estimates as the basis for prediction. Tools such as probabilistic graphical models, mixture models and hidden Markov fields can be used for the development of this kind of traffic model. Fusion of information from probe vehicles and loop detectors is also a promising line of investigation. Belief function theory can also be considered in this context.
- Because of the heterogeneity of the data sources and interests of the end users, a good understanding will be needed of their different objectives, interests, and willingness to pay. These will differ among users of the transport system.
- Collection of data from cooperative traffic management system to generate additional information such as better estimates of travel demand. These are needed in order to improve the planning models that will be used in the future to support traffic management. These data will reflect the demand pattern of the group that provided the raw data, and this might require adjustment for general travel patterns.
- Appropriate user interfaces and data mining methods need to be developed so as to make effective use of data for different applications. This includes the definition of generic protocols and interfaces to facilitate exchange of information between tools, applications and management systems.
- Means of processing traffic data collected in real-time to provide usable information to models and tools need development.
- New databases to store and organise the large quantities of data, including classical measurements (loop detectors) and individual user data (GPS) need investigation and devel-

opment. What kind of fast merging data algorithms can be applied (*e.g.* data fusion, imputation, missing and false data detection)?

- How to identify and exploit opportunities to use newly available kinds of data. Sample in a uniform manner, especially when penetration rates are low. Almost all well-established traffic control and traffic management applications use flows rather than either speeds or travel times. These kinds of newly available data therefore provide opportunities for use in extended and novel methods with algorithms developed to exploit the additional information that they provide. Examples of this have already been identified, including for example a method for single intersection control based on these data as a supplement to traffic flows and headways.

3.2.4. Expected Outcomes

The increased availability of data resulting from use of novel measurement systems and techniques will enrich and enhance traffic management and control. Measurement of traditional quantities can be improved in accuracy, can be enhanced by fusion with other data, and can be expanded in scope and scale. Use of this improved data will result in more accurately calculated control measures and so will enhance system operation and efficiency. Quantities will also become available that have not been measured in the past. These will include some that reveal travellers' intentions in a way that informs beyond the current state of traffic on the network. Use of information of this kind will enable systems to anticipate future developments in traffic more accurately and hence to calculate more appropriate control and management measures.

3.3. Improved Modelling at all Scales

Accurate estimation of future traffic states and of the effects of management measures is essential for effective traffic management strategies and decisions. This will require the use of good models, appropriate for the problem at hand. The use of cooperative traffic systems offers both opportunities and challenges for modellers. The increased availability of data at finer levels of detail supports the development of more accurate and sophisticated models of traffic and travel behaviour. At the same time the increased interactions and flow of data between different components of the traffic system will affect the behaviour of traffic both locally and over wide areas. Adequate models will be needed to explore the consequences of these interactions and to achieve a good understanding of the enhanced systems.

3.3.1. Real-Time Estimation of Traffic Conditions

Motivation Prompt and reliable estimation of traffic conditions is prerequisite for real-time traffic management. There are three main purposes of traffic estimation:

- to estimate promptly the state of the transport system, including operators and users, and also to assess their plans and intentions
- to produce short-term prediction for real-time traffic control
- to estimate likely responses of the transport system as a whole to implementation of control policies

Premises There is an increasing availability of traffic data from different sources, which should allow us to produce more accurate estimates of traffic conditions. Many relevant traffic models are already available in both academia and industry. Several of these can produce good estimates of traffic conditions and the ways in which they are likely to evolve.

There should be more research on modelling the interaction between travel demand and supply. In particular, the effect of variations in supply on travel demand and choices is important in estimating the likely consequences of a proposed intervention. The traditional Wardrop equilibrium assignment principle is a steady state assumption, which may not represent users' collective responses in a real-time context. There are efficient, tractable and reliable data processing algorithms that can be developed for these applications (*e.g.* imputation algorithms for missing data, and fusion algorithms for data from different sources).

Research Required The research proposed here will ensure that reliable estimates of traffic conditions can promptly be made available to traffic management applications.

- Various models are available for traffic estimation with different granularity. A finer (*e.g.* microscopic) model can represent operation and behaviour in more detail than can an aggregate (*e.g.* macroscopic) one. Cooperative traffic management will use communicating models of different levels of granularity. These models require different degrees of accuracy in supplied data and consequently output results of varying degrees of accuracy and detail. The degrees of accuracy required for effective integration and combination of models requires careful investigation.
- Current models will need to be adapted and new models created to use the increased data and take into account the consequences of cooperative traffic measures and of the feedback loops that arise with increased communication.
- As floating vehicle data are increasingly available (*e.g.* due to the popularity of smart phones, and in-car navigation and positioning systems), there should be more research on

using these kinds of data for traffic estimation purposes. For example, what will be the required proportion of GPS equipped vehicles for an accurate estimate of traffic conditions? Some previous studies have suggested that a relatively low proportion (10%) will be enough to produce a reasonable estimate of instantaneous traffic patterns.

3.3.2. Improving Estimation of Travel Time and Other Performance Measures

Motivation Reliable and efficient estimation of travel times and other performance measures is still not a widespread accomplishment on arterial roads because it requires extensive sensor infrastructure normally found only on motorways (fixed sensors located about every kilometre in most motorway systems). The increased availability of both real-time and historic data support the development of efficient estimation of travel time reliability measures, allowing for these measures to increase in accuracy and robustness as new sources of current and recent data become available.

Premises Richer more varied data sources and traffic models that use this data can result in better estimates of traffic states. This will require that:

- The data gathered can be stored, processed and verified on a short time-scale.
- Adequate models have been created to implement research results and to estimate performance measures.

Research Required Among other things, the research proposed here will build upon and influence the research of section 3.3.1.

- The development of reliable real-time estimation of travel times for routes where data is available, including motorways, arterial roads and urban networks. Imputing travel times for routes where data may not be fully available for specific times of a day. In particular, the use of data from cooperative traffic management systems for travel time prediction algorithms.
- Research will be required to understand the effect on traffic behaviour of the widespread availability of reliable travel time estimates.

3.3.3. Dynamic Modelling of Travel Behaviour

Motivation Because congestion is a transient phenomenon, dynamic models of travel choices and behaviour are required to achieve reliable estimates of travel conditions. Principal amongst models of this kind are dynamic traffic assignment (DTA) and departure time choice. These methods offer many potential benefits for a wide range of traffic management applications, such as network optimisation and control, dynamic route guidance, trip planning and environmental sustainability. The topic has been the subject of extensive research throughout the last three decades, but methodologies have been largely based on simplifying assumptions without models that are adequate for practical application emerging. In addition, while substantial theoretical research has been undertaken, the topic has been affected by the scarcity of the required data, which has inhibited its real-world implementation. As such, dynamic transport modelling remains a topic of research and has yet to realise its full potential. Nevertheless, advances in the field of cooperative ICT offer promising prospects for the incorporation of DTA models in traffic management through the provision of more sophisticated user interfaces and the ability to collect large quantities of relevant data.

Collection of Origin-Destination (O-D) matrices is prerequisite input for the modelling and the solution of traffic assignment (either static or dynamic) for large or medium-sized traffic networks. Today the collection of the OD matrix requires a large traffic flow measurement campaign at each origin and destination of the considered network, which is expensive. Consequently, in order to update the existing O-D matrix, the traffic management authority (most usually the national transport ministry) organises such campaign with a varying time interval (from 5 to 10 years). This time interval is too long to have an accurate O-D matrix for current travel. On the other hand, several paths are usually used between each origin-destination pair in the network and direct measurement of the fraction of flow on each such path is very limited. All these limitations will affect the accuracy of DTA estimates.

Premises The implementation of cooperative traffic management systems will increase the availability of individual vehicle data and so will lead to the improved timeliness, availability and accuracy of the O-D matrix and travel time estimates.

Research Required Dynamic modelling of travel behaviour requires knowledge and research over a wide spectrum, including:

- There is a need to develop self-consistent and convincing dynamic models of traffic and travel that can be used to represent and so to evaluate cooperative ICT measures.
- There is a need to devise efficient and practical DTA models for use in developing and analysing dynamic and responsive traffic management applications.
- Dynamic transport planning models require proper integration to represent the various dimensions of choice that are available to travellers in a mutually consistent way. A key element of this is the issue of multi-modal and mixed-modal modelling, as research so far has focused on single transport modes. Research should also focus on quantifying the environmental impacts of the transport system through DTA so that they can be managed and reduced. This will allow for the realisation of co-modal sustainable traffic management applications.

- The development of dynamic models of travel for a whole city. This will be supported by drawing on emerging concepts such as agent-based demand model, so that a more detailed approach can be adopted to investigate the response of users to dynamic management measures and to changing traffic conditions that are far from equilibrium.

3.3.4. Developing microscopic traffic flow models to address safety issues

Motivation: Most microscopic traffic flow models are constructed explicitly to be crash-free, and exceptions from this are most usually due to programming or modelling errors. These models therefore implicitly exclude an important element of real traffic flow, which is collisions. To construct a model that allows for accidents in a rigorous and satisfactorily manner is a major challenge, partly because of the lack of useful data on pre-crash conditions, near misses, and crashes that could be used to reconstruct the last few seconds before a crash. Fortunately, this will change with new approaches and new data-sets becoming available that will support a fresh approach to research on this.

Premises New approaches and new data-sets becoming available that will support the development traffic models that are more complex and more realistic. Models that allow for the possibility of vehicle collisions will enhance the assessment of traffic management measures so that traffic performance can be improved without compromising safety. Furthermore, use of these models, once developed, will help in the investigation and prevention of crashes. Ultimately it will enhance the assessment of traffic management measures so that traffic performance can be improved without compromising safety.

Research required The research proposed here will support development of an understanding of conditions that contribute to the occurrence of crashes.

- The development of indicators that can be derived from practical measurements that could provide useful safety indicators. The extension of simulation models to incorporate these indicators and investigate how well they perform as crash frequency estimators.
- Better understanding the limitations of current driving behaviour models in representing crash or near crash events is needed. Also investigation of extensions to current models that could be useful for improving models. Examples of this include representing reaction time explicitly, having distributions of reaction times across the population of road users, and suitable representation of distraction, fatigue and other factors that are detrimental to driving safety.
- Investigation of the use of data from real-world observations, and data from controlled experiments using driving simulators and other sources to provide rigorous estimates of the parameters of the safety-extended models.

- Investigation of the interplay between distinct elements of complex human behaviour such as anticipation, reaction and relaxation and their representation in models. The human ability to anticipate the kinematics of multiple leading and following vehicle masks the influence of reaction-time, which might provide an explanation of why simple direct measurement of reaction-time is unreliable.

3.3.5. Expected Outcomes

Improved modelling of traffic and operation of transport systems will lead to more accurate calculation of control measures for the prevailing and likely future conditions. Combined use of observed data with anticipative models can be used within filtering frameworks to improve the quality of estimates of traffic conditions and system state in real time. This in turn will support monitoring and control functions for management of the network, including the estimation of measures of performance. Dynamic transport models, which are required for congested conditions because they are necessarily transient, will become more practical and more applicable as more and better sources of timely data become available through enhanced ICT. This will lead to better management of networks in congested conditions. Improvements to microscopic traffic models in respect of their representation of safety-critical behaviour will improve understanding of circumstances that contribute to crashes, and hence will lead to improvements in design and operation for safety.

3.4. The Need for Communication Between Autonomous Systems

Cooperation of all kinds requires communication of appropriate information. For cooperation to be effective, this will entail timely communication of factual, intentional and attitudinal information. This will include traffic and other data that describe the state of the transport system and its usage, which will inform decision making. Further communication of plans and intentions will provide opportunities for cooperative joint decision making to the benefit of travellers and system operators. Research will be required to identify appropriate information to transmit and to develop standards for its communication. This will be particularly important in cases where autonomous systems are to cooperate with each other effectively: there must be agreement about the information to be communicated and means for the receiving system to evaluate the significance of the information. There will also be a need to ensure that systems can issue a request for up to date information when this is required. Systems of this kind will be able to specify the information they can supply and the information that they require.

Several means will be available in the near future for communication of this kind. These include direct bi-directional use of dedicated short-range communication (DSRC) among vehicles, potentially up to a range of about 1km according to specific requirements. Communication among vehicles in the fleet can be facilitated by channels through infrastructure, including DSRC links from vehicles to infrastructure for uplink and infrastructure to vehicles for downlink. In cases where the communication is between one or more individual users and elements of the transport system, this can be provided by DSRC and can also be provided by asymmetric communications using satellite-based systems. The advantages of satellite include high broadcast bandwidth and wide area coverage for the downlink; the limitations include that broadcast communications *via* the downlink are undifferentiated, that uplink bandwidth is limited, and that connectivity depends on clear-sky views or provision of a proxy.

3.4.1. Cooperative Strategies for Fleet Management

Motivation It is normal now for administrations of urban areas to promote sustainable multi-modal transport systems. These are intended to reduce energy consumption, pollution and vehicle emissions whilst maintaining transport safety, economy, efficiency and accessibility.

Current organisation of the distribution of goods in urban areas is inefficient, with impacts on the environment (through sub-optimal route and tour planning, and through the almost exclusive use of motorised vehicles), on safety (through violation of restrictions, *e.g.* in the transport of hazardous materials and through interactions with other motorised and non-motorised road users) and on monetary costs. One of the main causes is the lack of cooperation between hauliers and shippers, and the retailers that they supply, and also among hauliers themselves. Namely, while most trucking companies make use of advanced technologies and systems to monitor and optimise the performance of their own fleets, they do not share data with other hauliers, thus contributing to the global inefficiency. The development of new system-optimal methodologies and the creation of a platform for sharing information based on cooperative ICT can achieve substantial benefits to the field of city logistics.

Buses are a key form of public transport in most urban areas, being managed increasingly within control centres that incorporate Automatic Vehicle (Bus) Location (AVL) systems. Urban Traffic Control (UTC) centres are also in widespread use for control of general traffic, and are being extended in scope to incorporate traffic management more generally as urban traffic management and control (UTMC) centres. However, these two systems are often operated separately so there is clearly scope for co-operation, co-ordination and even full integration. This is becoming increasingly practical technically and directly matches transport policy aspirations at the European, national and local levels.

Premises Vehicle fleets of various kinds form an important part of urban and interurban traffic. Cooperative use of information available from AVL data in these fleets will bring wide benefits.

- There exists a vast amount of data, collected by individual hauliers, as well as background research for scheduling and optimising the delivery of goods in urban environments.
- Technological advances in the fields of positioning and communications (crowd sourcing, vehicle-to-infrastructure communication *etc*), but also in terms of environmental sensors

and programmes such as the London Low Emissions Zone, can be useful tools for improving the operation of city logistics.

- Bus management centres are being implemented widely across Europe, supported by Intelligent Transport Systems (ITS). These are often bespoke, using specific architectures and often not exploiting the capabilities of ITS technologies to the full.
- UTC systems are evolving to UTMC, which has a broader range of management functions and more heterogeneous architecture.

Research Required In order to facilitate effective cooperative fleet management, several organisational and technical issues must be addressed. These include:

- Fleet operators may be reluctant to share information that they consider to be commercially sensitive. What are the organisational and institutional barriers to cooperation and how can they be overcome? This requires investigation of ways to enable competing companies to share data without compromising their business interests but nevertheless facilitating traffic management?
- Given new ITS technologies, how can these centres cooperate to best effect, with flexibility to adapt according to developments in transport policy.
- There is a need for developing advanced and applicable system-optimal (rather than haulier-optimal) tour planning, routing and scheduling algorithms for efficient, safe, sustainable and cost-effective city logistics. The algorithms will be required to solve a wide range of problems, such as the booking and allocation of loading bays, the routing of hazardous materials, and the reduction of the environmental impacts.
- It is important to incorporate inter-modal solutions to city logistics, by making use of modes such as rail and canals, and include them in the planning and operations processes.
- The current situation of data sharing calls for the creation of a pan-European community system for sharing tools and information on a voluntary basis, such that logistics providers can benefit from a greater range of experience and lessons learnt in the field.
- Data can be shared among heterogeneous and non-competing systems, such as between AVL-based bus management systems and UTMC centres.

3.4.2. Expected Outcomes

Communications between autonomous systems is an essential component of cooperation. This will include sharing of current data and information on system states, which will be available to each system component in the course of its normal operation. Sharing information of this kind will ensure that best use can be made of data that have been measured throughout the transport system. Beyond this, mutual information control and management actions will be beneficial for coordination and cooperation even with autonomous systems. In cases where decisions can be made jointly by distinct system components, this will provide opportunities to enhance performance beyond what can be achieved by autonomous action. Communication of objectives and intentions of different systems will enable others to anticipate likely responses and so to adjust control actions accordingly in order to enhance performance.

3.5. Understanding Interactions at Various Levels

Cooperative interactions can take place at many levels. Because the communicating systems are autonomous, the interaction of their independent decision making processes can result in combined behaviour that is complex, suboptimal and at times unstable. Understanding the mechanisms of interaction, their consequences and the potential benefits that arise from cooperation will be essential for reliable operation. Autonomous systems that respond to the effects of decisions made by other such systems can exhibit feedback loops that give unstable behaviour. For these reasons, mechanisms of cooperation are required that lead to coherent and desirable combined behaviour.

3.5.1. Intelligent Vehicles

Motivation Vehicles are becoming increasingly intelligent with the incorporation of systems that provide support variously for safer driving, efficient use of resources and reduction in pollution. At the individual level this may lead to safer travel for example by guaranteeing lateral position management within lanes and speed-dependent minimal spacing from the preceding vehicle. But at a macroscopic level the collective behaviour of traffic will be influenced by these new support capabilities. This will depend on the kind of support that is implemented in the vehicles, the penetration of equipped vehicles in the fleet and the spatial density of traffic in the stream.

Road vehicle fleets in Europe are still overwhelmingly powered by fossil fuels (petrol and diesel). However, with increasing shortages of these fuels, tighter legislation on vehicle emissions and a range of incentives, the vehicle fleet will have increasing proportions of hybrid and electrically powered units in the coming years, and will behave differently as a consequence. In addition, vehicles are being equipped increasingly with new technologies for driver support, such as adaptive cruise control (ACC), dynamic route guidance, and hazard warning systems. The combination of these changes in vehicles and technologies could make a significant difference to traffic operations and performance. This will have to be represented in new traffic modelling systems and exploited in new traffic management systems if further efficiencies are to be achieved, even if cooperative systems evolve more slowly than currently seems likely.

Premises Research on the integration of intelligent vehicles into a system with cooperative management is based on several assumptions.

- ACC and other approaches to driver assistance appear to offer the driver and the passengers improved safety. The use of these approaches will affect local traffic behaviour and characteristics.
- Changing vehicle fleets, from fossil fuel based to hybrid and electric vehicles and new in-vehicle ITS technologies will affect vehicle operations and performance.
- The equipment of the vehicle fleet will not be uniform leading to transition periods with traffic of mixed vehicle types.
- Traffic flow research has proved that heterogeneity within the populations of vehicles and their drivers can lead in some circumstances to increased congestion.
- Current lane changing modelling have been found to be weak and of limited accuracy, particularly in their limited capability to take into account the unsafe distances chosen by some drivers in constrained road geometry or traffic conditions.
- Vehicles will be able to notify neighbouring vehicles of their plans and intentions.

Research Required The impact of intelligent vehicles on traffic management systems requires research on a wide range of issues.

- Investigation of changes in car-following behaviour within a fleet that includes intelligent vehicles. These changes may be influenced by the abilities, types and penetration. This research can capitalise on field experiments performed with equipped vehicles. The changes in behaviour will impact on link capacity as a consequence of changes in speeds inter-vehicular spacing. Intelligent vehicles will also have an effect on lane changing and weaving behaviour, which will also affect capacity.
- The consequences of the presence of intelligent vehicles on macroscopic traffic behaviour requires investigation. For example, in congested states of traffic does the presence of equipped communicating vehicles affect the formation, prevalence and intensity of stop and go waves? Changes in macroscopic behaviour will have consequence for dynamic traffic management measures such as traffic flow control, access control, variable speed limits and dynamic lane management on traffic with varying mixtures of intelligent vehicles. This has relevance and is contributory to the research identified in sections 3.3 and 3.5.2.
- The safety implications of mixtures of vehicles with different capabilities need careful study, including the development of simulations to estimate the safety effects. This is relevant to section 3.3.4.
- The development of urban traffic-oriented driver assistance to improve the safety of all users of the urban road network.

- The evolution of the vehicle fleet and in particular in-vehicle ITS systems over the coming years: the effect of this should be investigated. How it will this affect driver choices and behaviour, and traffic operations. Understanding these changes can be reflected in evaluation tools, particularly microscopic traffic simulation. Research to ensure that traffic management systems adapt to these changes will be need. (See section 3.5.2)

3.5.2. Multi-scale Traffic Control

Motivation Traffic control is exercised locally by measures such as signals, ramp metering, access control and variable speed limits. The decisions taken within each of these measures are influenced by expectations of the local traffic performance as influenced by that measure, and this is estimated according to the modelled macroscopic behaviour of the traffic. Increased communication between vehicles, and between vehicles and infrastructure will change this behaviour (section 3.5.1). Because of this, control systems will require adaptation to take account of these changes and so to exploit the new communication opportunities in their control of traffic.

Controls are usually decided according to their expected effects on local traffic conditions. Increased cooperation offers the possibility of taking into account some of the wider effects of a control measure on the network. The control models could use the information made available by means of ICT in order to perform real-time optimisation of the traffic on network scales.

Premises Traffic control systems will communicate with each other exchanging information about traffic states, control decisions, objectives, plans and intentions. Control decisions and directives will be communicated directly to vehicles. Software and models used to determine traffic control measures will be developed to facilitate and make use of this information exchange. At the level of individual vehicles, communication and cooperation among vehicles will modify the traffic dynamics in some important ways, and this is likely to influence optimal decisions.

Research Required Multi-scale traffic control is one of the key products of cooperative traffic management. Much research remains to explore this and to establish practical approaches to it.

- Develop understanding of how expected changes in macroscopic traffic dynamics will affect local control objectives.
- Developing local control strategies that will take into account changes in macroscopic traffic dynamics.
- Develop systems to make use of information from vehicles about driver intentions and decisions such as turning movements.
- Develop an understanding of how and when control decisions may be communicated directly to vehicles. (See section 3.1.2).

- Identification of information about local conditions and control decisions that should be communicated to peer systems to improve traffic system performance.
- Investigate the management of interactions among local systems, urban network controllers and regional controllers. When is peer to peer interaction beneficial and when should it be mediated by wider network controllers?
- Develop an understanding of ways in which travellers other persons and other system elements are likely to respond to management and control measures so that this can be anticipated when deciding on actions.

3.5.3. Understanding interactions

Motivation Traffic flows nearing or in a congested state are inherently unstable as the flow evolves through both space and time in a way that depends strongly on the decisions of individual vehicle operators. As cooperative systems become more prevalent, we obtain a view of the state of the system that is both more detailed and more comprehensive, and can also exert a greater level of control over the system. With this favourable combination of information and control, we will become able to achieve finer and more responsive levels of strategic and technical management. As improved control enables us to operate systems closer to the limits of their theoretical capacity, the consequences of these instabilities will become increasingly critical so we must ensure that management actions are calculated to achieve increasing stability as well as capacity and efficiency.

Premises Systems are usually most responsive to changes in parameters and conditions when operating close to their region of instability. To operate in this way requires a precise understanding of the characteristics of the system and its responses to changes.

Research Required The complexities of interactions between cooperating system working at different levels will require substantial research to ensure that potential sources of undesirable feedback and instability can be managed, and where possible controlled.

- Development of protocols and tools to enable the different levels of control made possible by cooperative systems to interact effectively.
- Development of models and protocols so the response of different systems can be anticipated in a constructive way when devising controls.
- Develop tools that can quickly identify the effects of control decisions in the general noise within the network. (See section 3.3.1)
- Design controls to minimise the propagation of instabilities through space and time.

3.5.4. Expected Outcomes

Understanding interactions between distinct active sub-systems is important in achieving stable and acceptable operation. In systems with multiple actors, the data for one can correspond to the decision variables of another. If this is not managed, the possible consequences include poor operation, poor performance and poor stability, to the disadvantage of users and managers. On the other hand, if the kind and nature of interactions among system components are understood adequately, then the collective system can be managed effectively and performance enhanced. This will entail decisions that are modified in light of an understanding of the effects that they will have indirectly though interaction with other system components.

3.6. Achieving effective large-scale transport systems and their efficient usage

This theme is at the heart of much of the anticipated benefits of cooperative transport management. Rather than acting locally to anticipate problems and deal with local traffic and transport issues, management systems will be better able to consider the wider effects of local decisions and make their own decisions on the basis of better information about future anticipated traffic conditions

The research identified here can contribute synergetically to the achievement of effective cooperative transport management. In order to do this the challenges of large-scale management must be addressed, the tools needed to make this effective identified, and the issues of integration addressed.

3.6.1. Incident Management

Motivation Traffic incidents of all kinds are a major source of delay and disruption for road traffic. They also have safety implications. As a consequence of this, accidents, break downs and other disruptions are a major concern to main road and motorway managers. Management of non-recurrent congestion phenomena caused by incidents is a fundamental task of road network managers. Prompt detection, fast response and up to date information can all help to minimise the disruption caused and reduce the associated safety risks. This will have considerable benefits for safety and traffic efficiency. Incident management (IM) policies require a number of actions, starting from the time of occurrence of the incident and continuing to the time of queue dissipation, with the aim to restore normal service as quickly and effectively as possible. The actions include detection and verification, initiating a response including involvement of the emergency services, on-site processing and traffic control measures. Improving the effectiveness and speed of any of these actions is important, because any such improvement may lead to substantial gains in safety and traffic efficiency.

Incident detection and verification is the first element and essential stage. New technologies and systems make it possible to consider innovative approaches in automatic incident detection, increasing reliability and detection rates, and reducing response time and false alarm rate.

Premises Considerable progress in traffic measurement technologies, including cameras, inductive loops, microwave sensors, mobile communications, probe vehicles, *etc*, have been achieved in recent years. All these factors have led to increased data availability in terms of quality, type, and spatial and temporal resolution. This new data abundance could be used to support improvements to automatic incident detection systems, but new analysis and algorithms will be required for this.

The widespread use of mobile communications including eCall and personal mobile telephones improves the verification and sometimes the detection of incidents. A rapid confirmation of the event reduces the time required for detection and verification. Probe vehicles acting as sensors also enhance the surveillance of the road network. Fleet vehicles equipped with automatic vehicle location (AVL) are used increasingly widely, which will also improve management of incident response vehicles.

Research Required The aim of this research is to explore the possibilities offered by innovative technologies in the field of automatic incident detection, improved response and better user information. Examples of these possibilities are new algorithms, and use of mobile communication and probe vehicles.

- Development of algorithms making use of data on traffic states to detect unusual patterns of traffic behaviour, including integration of data from probe vehicles. Possible techniques include artificial neural networks, filtering techniques, state vector machines, data fusion and statistical models. (See sections 3.2.2, 3.2.3 and 3.3.1).
- The investigation of pathways for using reports from mobile phones to help with early detection and validation. In particular, the development of image processing and other techniques to make use of the ability of mobile phones to transmit still and video images to determine the severity of incidents.
- Development of software making use of AVL to assist in the dispatch of appropriate response vehicles for an incident.
- The development of traffic management tools that can easily and quickly adjust to abrupt changes in network conditions to assist in determining effective traffic control measures to minimise the impact of an incident. (See section 3.3.4) These measures should include the generation of diversion routes for affected traffic. (See section 3.3.3).
- The development of cooperative systems to use all available information media to for drivers and others affected by an incident.

3.6.2. *Pedestrians in the Multi-modal Environment*

Motivation Walking is an important constituent of mobility, especially in dense urban networks, as nearly every trip carried out includes at least one segment covered on foot including walking between a parking space or public transport stop and final destination. The "walkability" of transport networks is therefore a priority for transport management. It falls into two main categories: the street environment, where pedestrians share the network infrastructure with other transport modes and walking is a mode in its own right; and public transport hubs, where pedestrians use dedicated or shared infrastructure to transfer between public transport modes.

Parts of the urban road network are increasingly being redesigned to make them more attractive and efficient for pedestrians. In many cases this means removing or reducing the separation between pedestrian and vehicular traffic (see section 3.7.1) ITS and cooperative technologies have the potential to play a prominent role within the new approach to pedestrian environments. These technologies can be used to monitoring the behaviour of road users and assist their efficient and safe movement. For example, ITS could support drivers by using on-board devices and intelligent street signs to inform them about close proximity to pedestrians and warn about excessive speed. On the other hand, cooperative ITS could assist blind and partially-sighted pedestrians to navigate around a space.

There is continuing effort to improve pedestrian movement in mobility hubs. The improvements need to be supported by good models of pedestrian movement behaviour. While some of these aspects are considered in new designs, there is still considerable existing infrastructure designed based on old concepts.

Premises New types of pedestrian detection systems, such as volumetric, upstream and passive detection, have been developed or will be available in the next future. These will allow detection of waiting and approaching pedestrians.

- There is an increasing range of advanced communications technologies available, which can provide valuable data in terms of positioning and detection (*e.g.* of approaching or waiting pedestrians); examples are Dedicated Short Range Communications (DSRC), radar technology and mobile phones tracking. Advances in image processing are a further asset facilitating the research in question.
- As walking is the primary means connecting different modes in mobility hubs, it is important to be able to model passenger walking behaviour, both at the microscopic (individual passenger) and the macroscopic (aggregate passenger flow) levels in these environments.
- Significant advances in traffic flow theory and modelling allow for the better monitoring and investigation of the behaviour of road users in shared space environments.
- Social and behavioural modelling of pedestrian behaviour will play an important rôle in developing new models of pedestrian movements.

Research Required The new communications technologies and methodological advances leave room for further research in the field of the efficient operation of complex multi-modal networks, in which walking plays a significant part.

It will be important to investigate how to make best use of advanced tools such as cooperative technologies of different types and behavioural models in the context of supporting and promoting the walkability of street environments and public transport networks. A principal example of behavioural models that is relevant to pedestrian activity and flow is the social force model, in which pedestrians' movement is influenced by their proximity to others, represented by social forces between them. Understanding the mechanisms of pedestrian interaction and their effects on pedestrian movement will support more effective planning and provision for this, and management of pedestrian traffic. This will result in improving the quality and attractiveness of walking through features such as increased safety and better information provision. For example, cooperative technology could assist pedestrians and drivers in their manoeuvres in shared space environments, and could provide public transport passengers with accurate walking and waiting time information at public transport interchanges through journey planning software.

- The requirements and capabilities, such as positioning accuracy, of the new detection technologies need to be studied to ensure they can be effectively used.
- Further models and methodologies need to be developed to make use of the new data. These would include traffic flow theory for shared space and pedestrian-oriented signal control strategies. These will support not only immediate control and information systems but also support better design of shared space and mobility hubs. (see section 3.7.1)
- Also, there should be more research into the two-way relationship of cooperative ITS and infrastructure design, as the implementation of new technologies and methodologies will not only support users, but will also provide qualitative and quantitative feedback to design.
- Research will be required into the use of the social force models to develop advanced theoretical tools for both street environments and for public transport networks.
- The development of new and refinement of existing behavioural models such as next-step, route-choice, and destination-choice models to account for the behaviour of pedestrians and passengers.

3.6.3. Active Management of Motorway Traffic

Motivation Urban and interurban motorways were originally conceived to provide virtually unlimited mobility to road users. However, the continuous increase of car ownership and the steady expansion of land use in metropolitan areas have led to the daily appearance of extended and ever-growing recurrent and non-recurrent motorway congestion. This is a serious burden for economic and social life in metropolitan areas.

Over the years, a number of traffic-responsive control strategies, involving ramp metering, variable speed limits, dynamic lane allocation, *etc*, have been developed and have been deployed in the field. Fewer studies have tried to integrate and coordinate different strategies.

The effect of motorway traffic control on the arterial streets is still an open question. Given the high variability in demand and level of congestion, there is also a need to develop integrated strategies that use both motorway and urban road networks to achieve best network performance, treating users in an equitable manner.

Premises Despite the accelerated deployment of ramp metering in Europe and beyond during the last decade, ramp metering is applied in Europe only to few hundred motorway entry ramps in few countries. Indeed, there is no motorway ring-road in Europe that has ramp metering installed on the majority of its on-ramps. Moreover, motorway-to-motorway metering is also non-existent in Europe. Finally, virtually all installations employ only local algorithms. In view of this state of affairs, there is great potential for improvements in motorway traffic flow efficiency that could be achieved if available state-of-practice ramp metering strategies were enhanced and applied in a coordinated way, including on merging motorway ramps.

The innovative and unconventional concept of mainstream traffic flow control (MTFC) has recently been proposed as a promising approach for efficient motorway traffic management. This aims at influencing the motorway traffic flow directly *via* an appropriate actuator (such as variable speed limits (VSL) or specially operated traffic lights or the emerging vehicle infrastructure integration (VII) systems) in order to avoid the detrimental effects of congestion forming at an active bottleneck. The idea that underlies MTFC may be traced back to research reported in the 1980s and 1990s which, however, did not develop this concept in full technical detail; some operational systems, such as the toll plaza of the Oakland–San Francisco Freeway, are essentially MTFC systems based on traffic lights, albeit for a special case. Mainstream traffic flow control has been considered to some extent (mainly using VSL as an actuator) in some recent scientific articles under different traffic application settings.

The number of VSL installations is increasing rapidly in Europe and beyond. This approach to motorway control is valuable for traffic safety, but its potential for throughput increase, reduction of journey times and possibly capacity increase have not yet been exploited fully.

Research Required Active traffic management has been used at a local level for many years. The research identified here aims to integrate active traffic management into larger-scale cooperative systems for network-wide management.

- The development of appropriately modified coordinated ramp metering algorithms based on experience from other continents.
- Development and deployment of metering systems for motorway-to-motorway interconnections or merging motorways.
- Large-scale deployment of developed systems on a European motorway ring-road.

- Integration of control strategies that may be implemented in the field for maximum exploitation of the potential benefits offered by various control measures (traffic signals at the adjacent urban intersections; variable speed limits; and further link control measures on the motorway mainstream such as lane assignment).
- Research activities aiming to exploit cooperative systems for ramp metering are sparse. Possible directions for this include algorithms that dynamically determine and apply speed limits on the motorway within a ramp merging area, lane changing advisory algorithms and algorithms that time the release on-ramp vehicles when sufficient gaps are expected for them to merge into the mainline traffic.
- The development and deployment of practical locally determined MTFC concepts addressing known active bottlenecks, using VSL as an actuator. Consideration of control architecture, and practical and safety requirements are crucial elements for this research into MTFC.
- Related research using other MTFC actuators such as signal control and VII is also necessary.
- Research is also needed for the integration of MTFC with ramp metering control strategies at the local and global levels, along with a single coordinated MTFC strategy for large-scale networks.
- Development and deployment of innovative VSL control algorithms, capable of improving the traffic capacity and flow efficiency on motorway sections and networks.

3.6.4. Urban Traffic Control

Motivation Congestion in urban road networks around the world continues to increase in space and time during the peak periods, leading to excess delays, fuel consumption and environmental impact. All major actors (authorities, industry, researchers) agree that there is no practicable signal control strategy available to efficiently address saturated traffic conditions.

The typical operating mode of traffic signals around the world is based on limited levels of knowledge (vehicles often detected some distance upstream and then behaviour predicted) and non-optimum levels of control. With cooperative systems the potential exists for continual monitoring of vehicle positions, giving additional information about vehicle positions and intentions to be known by the signal control algorithms. In addition, there is potential for advanced signal control information to be transferred directly to vehicles.

Premises Improvements to urban traffic management and control through adoption of cooperative measures will bring many benefits by building on recent insights.

- Urban network congestion is persisting or increasing and presents a genuine threat for economic and social life, as well as for citizens' health in cities around the world.

- Deployed UTC strategies are known to be less efficient in the saturated traffic conditions that are encountered daily during peak periods.
- Recent insights (*e.g.* the notion of network fundamental diagram) indicate significant network degradation (due to queue spill-back and consequent gridlock) for high network density. These insights, along with other recent methodological advances, offer opportunities for efficient traffic management in saturated traffic conditions.
- Emerging cooperative systems may offer additional opportunities for improved UTC under all possible traffic conditions.

Research required Research required to use cooperative measures to develop urban traffic management and control includes:

- Parts of urban road networks that suffer from link blocking-back and consequent gridlock during the peak periods need to be protected from over saturation that leads to this degradation. There are various possible ways to address this need, depending on the network characteristics and the available real-time information from detectors. The adequacy of these potential approaches needs to be evaluated and compared under realistic conditions and through trial field deployment to identify the most appropriate methods for specific application conditions.
- The impact of control strategy decentralisation in saturated traffic conditions is not well understood. Targeted analytical and empirical investigations are needed to understand the relative merits of centralised control algorithms against decentralised ones, along with an understanding of the reasons for possible differences in performance. The result of this will guide the development of novel UTC systems.
- The role of the signal cycle time in congested traffic conditions needs to be re-visited, because long cycles (that are deemed to increase network capacity) will under some circumstances prove counter-productive by leading to increased risk of link blocking-back and gridlock. Related insights should lead to novel ways of adjusting cycle times in real time, as compared to traditional approaches.
- Traffic signal offsets between adjacent junctions are usually calculated with the objective of managing queues. Because straightforward applications of this approach are not possible in congested traffic conditions, new insights and methodological tools are needed to achieve optimal adjustment of offsets in real time during peak periods.
- Emerging cooperative systems (V2V, V2I) may offer additional opportunities for more efficient UTC in both saturated and under-saturated traffic conditions in the near future. Research is required for the timely development of corresponding methods that would exploit emerging functionalities as they become available (*e.g.* advanced knowledge of the location and turning intentions of approaching vehicles). Related developments must take into account the progressive deployment of cooperative systems, which calls for appropriate consideration of penetration rates of new technologies and further issues.

- Traditional signal control has focused on minimising vehicle delays. Research is needed into control strategies that can be used to include a wider range of policy requirements and desired outcomes, including impacts on priority vehicles, non-motorised users, energy consumption, the environment and road safety.
- Network-optimum traffic management requires a modelling approach in which signal control and timings are optimised taking into consideration relevant elements of traveller response in an integrated process. This needs new research to develop such models, particularly those which could be applied in real-time and take account of driver behaviour, re-routing, incidents, *etc*.

3.6.5. Responsive and Adaptive Optimisation

Motivation The ultimate performance of a designed or operational traffic control system (*e.g.* urban signal control or ramp metering or VSL control) depends on two main factors: the exogenous influences such as demand, weather conditions, incidents, and the values of some design parameters included in the control strategy. When a new control algorithm is implemented (or an operational but ”aged” control algorithm needs to be updated), there is a period of, sometimes tedious, fine-tuning activity that is needed in order to elevate the control algorithm to its best achievable performance. Fine-tuning concerns the selection of appropriate (or even optimal) values for a number of parameters of the control strategy.

Premises Control algorithms are typically fine-tuned using a manually conducted procedure, following a trial-and-error approach that depends on expertise and human judgement. If the control algorithm was designed in a transparent way regarding the targeted objectives and sub-objectives of individual modules, then manual fine-tuning of this kind could lead to acceptable results with moderate effort. In contrast, if the control strategy that is employed does not address the objectives pursued in a sufficiently specific and direct way, or if the control strategy is complex, the manual fine-tuning can be cumbersome and, most importantly, have an uncertain outcome regarding the control performance achieved. To address this, a research activity will be required to develop algorithms that could undertake fine-tuning of control systems automatically so that they adapt to their operating environment and quality remit. Algorithms of this kind can be based on rigorous but straightforward adaptive optimisation and stochastic approximation principles.

Research Required Responsive and adaptive optimisation will play a central role in practical cooperative systems. It is therefore crucial to understand the nature and limitations of the algorithms used in these methods.

- Investigate where these algorithms can fully or partially replace the conventional manual fine-tuning in real traffic control field implementations. What is the range of applicability?
- Investigate the safety and performance efficiency of operational traffic control systems.

- The simplicity of adaptive optimisation algorithms is also an issue. Traffic operators are the actual users of these tools in the traffic control centre and they should be able to understand them. Researchers that develop adaptive fine-tuning algorithms should take this into account when considering the complexity of algorithms.
- Investigate and identify any special characteristics of traffic control systems.

3.6.6. Safety on Rural Roads

Motivation Improving road safety has been one of the main objectives of traffic management during recent years. Among three distinct road types (motorways, urban non-motorway roads, and rural non-motorway roads), about half of all fatalities and a quarter of all casualties occur on rural non-motorway roads. These roads are not generally well equipped in terms of signage and traffic control, so there can be a lack of information for road users. With the introduction of vehicle-to-vehicle communication, several possibilities arise to improve traffic safety on rural roads.

Premises The timely provision of appropriate information to road users will help them to adjust their usage beneficially to enhance safety. This could include relevant information on road design and condition, traffic state and conditions, environmental conditions including meteorology, and the presence of any objects or incidents that will affect driving. By using vehicle-vehicle and vehicle-infrastructure-vehicle communication pathways, information of this kind can be propagated quickly beyond the line of sight.

Research Required This will explore possibilities supported by innovative technologies in the field of real-time crash risk identification on rural roads. This will address the following research questions:

- Investigation of contributory factors to accidents in rural environments.
- Identification of special risks on rural roads.
- Determination of accident types that mobile communications can help to reduce.
- Decision on information that could beneficially be shared among vehicles on rural roads.
- Collection and analysis of detailed data on conflicts, close encounters and near-misses on rural roads to expand the information base for safety studies.

3.6.7. Differential Road Pricing

Motivation Road pricing as a demand management measure is widely recognised as a way in which congestion can be alleviated or reduced. The mechanism for this is to promote the choice to use of less-congested routes or travel at less busy times. Road pricing may be more effective and acceptable when clearly related to road traffic conditions. This can be achieved by developing more fine-grained charging in space and time according to conditions that prevail at and immediately after the time of use.

Premises Implementation of differential road pricing will encounter several technical and social challenges. Conditions that must be met include that:

- Real-time vehicle position information is available.
- Reliable and acceptable charge collection methods are required.
- Charging information must be available to drivers in sufficient time to allow them to make informed choices.

Research Required Two distinct aspects of road pricing need to be addressed. There is a purely technical side as to what is possible in principle and under what conditions. Once this has been established the social issues need to be understood.

- Investigate how fine-grained the differential road pricing can be made both in space and time. The technical constraints that must be met must be identified. What is technically achievable?
- Understand knowledge of the current traffic state that will be required to ensure that road pricing based on this is applied consistently.
- Identification of means by which charging can be accomplished.
- Identify acceptable ways in which information about charges can to be made available to drivers.
- Understand and investigate the social obstacles to and implications of road pricing.

3.6.8. Expected Outcomes

The benefits of achieving more effective transport systems will be that a greater provision of transport will be possible with a given practical level of resource input. This will promote the more economic provision of transport to achieve greater mobility and reduced impact without increasing resource costs. The benefits of achieving more efficient usage of the transport system include that users will be able to satisfy their own travel requirements at reduced resource costs and impact on others. These improvements will be achieved by matching provision of transport systems to users' needs for transport and managing their operation better through use of better and more timely information.

3.7. Support for policy developers, decision makers, managers and operators

Realisation of the potential benefits of cooperative traffic management will require appropriate and relevant legislation and policies to be implemented. For this to happen, policy developers and decision makers will need to be properly informed and advised. This support must provide an awareness of opportunities for application, the scope of technological development and capability, and the specific nature of benefits that are likely to arise from implementation. Policy developers will need tools to facilitate evaluation of possibilities, identification of the range of possible benefits, and ultimately quantification of them.

3.7.1. Designing shared spaces for pedestrians

Motivation Pedestrian mobility is an important means of transport, especially in dense urban networks. In this context, pedestrians share use of the network with other users such as private vehicles, public transport and cyclists. Pedestrian use of street environments has often been neglected by traditional urban street design and traffic engineering concepts, in favour of designing for vehicle traffic as a priority. Examples include segregation of pedestrians from vehicular traffic by use of guardrails and other measures, and orientation of signal control strategies towards vehicular traffic. These approaches often result in systems that are inconvenient for pedestrians.

Premises Recent trends, however, have induced a shift towards designing more to the pedestrian scale, mainly through exclusion of segregating features from street design and introduction of a greater degree of vehicle-pedestrian interaction (a concept commonly referred to as *shared space*), and through implementing more pedestrian-friendly control strategies (*e.g.* all-pedestrian phases and countdown signals). ITS and cooperative technologies have the potential to play a prominent role within the new approach to walkable environments, by monitoring the behaviour of road users and assisting their efficient and safe movement (see section 3.6.2). Beyond this, cooperative ITS could also assist blind and partially-sighted pedestrians to navigate around urban space through use of intelligent street signs and infrastructure.

Pedestrian movements are important in so-called “mobility hubs” that connect various transport modes such as buses, metros, and regional trains. The design of efficient hubs needs to ensure that the requirements for movement of transferring passengers are addressed properly. While some of these aspects are considered in new designs, a considerable amount of existing infrastructure remains that was designed based on old concepts. As walking is the primary means connecting different modes in mobility hubs, it is important to be able to model passenger walking behaviour, both at the microscopic (individual passenger) and the macroscopic (aggregate passenger flow) levels.

Particular focus should be given to the special requirements of disabled users.

Research Required Designing and implementing effective shared space environments will require technical developments, design tools and assessment tools.

- Developing tools based on models and ideas (for example section 3.6.2) that will help policy makers to understand better the benefits and consequences of using new technologies in shared space environments.
- Development of planning tools that integrate the new possibilities for pedestrian detection, new pedestrian flow models and new information distribution methods to help improve the planning process.
- Investigate how better pedestrian flow models and new technologies can be used to improve the use of existing infrastructure.

3.7.2. Urban Traffic Control (UTC) and Urban Traffic Management

Motivation Urban Traffic Control (UTC) and Urban Traffic Management centres play an increasingly important role in the management of traffic in urban environments. Their effectiveness will have a significant impact on both urban travellers and on the environment. It is therefore important to ensure that measures that are implemented have the desired effects and are used properly. As new tools and understanding emerge from research they need to be made available to practice as quickly as possible.

Premises Urban Traffic Control (UTC) and Urban Traffic Management centres are often staffed by people with a range of abilities and understanding of working with contemporary UTC approaches. This heterogeneous community needs to be supported and educated on the job to use newly developed approaches based on cooperative systems. There is also a challenge of bridging the gap between the sometimes more theoretical approaches of researchers and the practitioners in these centres. Also there needs to be communication of knowledge about circumstances that have been found to be appropriate for the success of each of the measures that are available.

Research Required Projects that help to bridge the gap between researchers and practitioners need to be developed to promote evaluation, understanding and application of novel management approaches.

- Develop projects that make use of ITS test-beds where researchers and practitioners can work together.
- Ensure that there are mechanisms for reporting and disseminating the outcomes of these projects.
- Developing means and channels of communication to inform policy makers, planners and operators about the possibilities of emerging cICT approaches to ITS to garner insti-

tutional support for testing mature instruments developed and for implementation in the field.

3.7.3. *Expected Outcomes*

By providing support for policy developers, decision makers, managers and operators, cooperative ICT systems can enhance transport provision on timescales ranging from short-term operational ones to long-term planning ones that influence future choices of location and hence demands for travel. Support of this kind will include identification of the range of measures that are appropriate for certain specified circumstances, through descriptions of the outcomes of their use in the past to estimates of likely performance in the present case. Support that is based on evidence and reasoned analysis can be used to generate a critical analysis of proposals and hence to support current professional choices.

4. Conclusions

4.1. Introduction

Rapid developments in information and communications technology give rise to many opportunities for applications in traffic management and control. In particular, the emergence of systems that provide high capacity and widely available communication within the vehicle fleet and between vehicles and infrastructure will provide scope for revolutionary developments. A crucial opportunity that arises in this is that of cooperation among elements of the transport system as a whole that will depend on communication of traffic data, decisions, intentions and objectives in ways that hitherto have not been practical. These will incorporate various kinds of cooperation within vehicles, among vehicles, between vehicles and traffic management systems, and among different traffic management systems. The broad effect of these developments will be to achieve better management of traffic networks as a whole through coordination of efforts and interventions, and cooperation among the elements.

The potential for benefit that arises from these opportunities can be achieved best by pursuing a considered and structured approach to their development. In the presented document, we propose and explore an appropriate structure for this based on a novel 5-dimensional framework for analysis of cooperative ICT measures. This framework, which was developed specifically for the present purpose, includes each of the dimensions of

- Objectives of Cooperative ICT
- Research Themes
- Areas of Expertise
- Traffic Management Applications
- Opportunities for innovative contribution

The approach presented here explores each of these dimensions in turn. This is achieved first by populating the dimension with relevant items and then by considering the relevance of cooperative ICT to each of them in turn. Through this approach, we present a systematic analysis of the scope and opportunities for development in traffic management and control that could benefit from application of cooperative ICT. The framework provides multiple views on this activity that help to identify ways in which contributions can be made to each topic, and ways in which each topic will promote the objectives of traffic management and control in general, and cooperative ICT in particular. This leads to formulation of an agenda for research that will be required to develop and exploit the opportunities for advances in traffic management that are furnished by ICT. By taking this analytical approach, we are able to achieve some perspective on future opportunities and identify the actions that will be required to realise them.

4.2. *The harmonised research agenda*

The agenda for research presented here to progress the application of cooperative ICT to traffic management and control was developed by exploring the 7 broad themes that had been identified for future challenges to be addressed in this area. This fundamental classification of opportunities leads to a thematic view of the research that will be required. These research themes are as follows.

1. Increased availability of mobile communication
2. Increasing data availability
3. Improved modelling at all scales
4. The need for communication between autonomous systems
5. An understanding of these interactions at various levels
6. Achieving effective large-scale management of transport systems and their efficient usage
7. Support for policy developers and decision makers.

Considering each of these in turn led to the formulation of a thematic programme of research across a broad agenda. By considering the agenda as a whole, it could be harmonised in the sense that interrelationships among these themes could be recognised and explored. This will support the research effort by identifying commonalities and opportunities for cross-linkage. It also supports the research effort by identifying the complementarities that will enhance the value of each contribution.

4.3. *Contributions to research*

We envisage that research to address the agenda identified in this document will be undertaken following an open call to invite bids. Whilst those who have contributed to the formulation of this agenda have interest in this and expertise, no claim is made either to an exclusive ability to undertake the research or that the agenda as formulated here is complete in all respects. However, the broad base of expertise within the NEARCTIS consortium leads us to suppose that many of the main topics and issues are identified in it.

Each research project and activity that addresses the programme will, in our view, address one or more of the many combinations of descriptions within the 5-dimensional framework. We do not expect that research coverage will be uniform across all these possible combinations. Some combinations that are central to the endeavour seem likely to appear in several projects, possibly with distinct treatments according to their linkage with others. By contrast, other combinations by their nature might rightly not be addressed in any project.

4.4. Next steps

The present deliverable D14 (Specification of the harmonised research programme) represents one of the major contributions of the NEARCTIS network of excellence. It does not, however, exist in isolation from other activities and contributions from the network of excellence. Two other deliverables are closely related to the present one. Deliverable D15 (Specifications and evaluation approaches for possible case studies) will specify and evaluate possible case studies that will help to inform, strengthen and progress the research identified here. The deliverable D18 (Evaluation and assessment of likely benefits of the harmonised research programme) will identify the likely benefits that the research based on and motivated by the present research programme is expected to deliver. These will accrue to the many people using, managing and affected by the transport system.

Because of their relevant expertise and established research interest in this field, we expect that partners of the NEARCTIS consortium will join in bids for research following any call of the kind proposed here. This response will be based on areas where partners' established strengths and interests can contribute to the research effort. Joint research activity of this kind will have the effect of perpetuating the NEARCTIS network through continued collaborative research contributions.