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Key Performance Indicators for traffic management and Intelligent Transport Systems

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Executive summary

Cities today face many common transport problems and implement similar urban traffic management solutions, with Intelligent Transport Systems (ITS) playing a prominent role. However, in the absence of a set of widely accepted performance measures and transferable methodologies, it is very difficult for a city to objectively assess the effects of specific applications (policies and technologies) and to make use of lessons learnt from other cities. The aim of this report is to define a common evaluation framework for the performance of traffic management and ITS in the form of a set of Key Performance Indicators (KPIs), and to present guidelines as to its application.

The report initially identifies the needs from a performance evaluation framework, as these have been set out by a number of European city transport authorities through a focus group, and describes the development methodology, discussing the issues of goals and objectives, dimensions, selection criteria, data requirements and measurement tools. Then, the new framework is defined and considerations of its scope and applicability are made. Four strategic themes of urban traffic management and ITS are tackled: traffic efficiency; traffic safety; pollution reduction; and social inclusion and land use. A series of potential measures are identified and listed, before being refined for the formulation of KPIs for each of the four themes. Operative definitions are given for the new KPIs.

For the theme of traffic efficiency, three KPIs are defined for mobility, reliability, and system condition, respectively. The mobility KPI mainly takes into account the travel times on the road and public transport networks and expresses the ease of access between certain representative origin-destination pairs. The reliability KPI, on the other hand, expresses the ease of mobility and deals with congestion occurrence and duration on both the road and the public transport network. The index for system condition complements the other two by accounting for the fact that the condition of the network itself (i.e. road pavement, rail tracks, etc.) has a significant effect on traffic efficiency.

With respect to traffic safety, a performance evaluation based on the direct quantification of accidents is proposed on one hand (with a respective KPI), and on the general quantification of the impact of various traffic management measures and ITS on safety on the other. As concerns the latter, a disambiguation of applications with direct and indirect safety impacts is made, for urban and motorway environments, with three KPIs being defined. An additional KPI is further presented for the effects of car-to-infrastructure (C2I) systems, though it is recognised that its importance will become more relevant in future, when C2I systems will achieve higher penetration rates.

Given the scarcity of data on emissions originating from traffic, it is suggested that the evaluation of the performance of urban traffic management and ITS with respect to pollution reduction be done by using well-established and widely-used emissions models. Accordingly, KPIs for pollution reduction are defined, making a disambiguation between motorised vehicle fleets and fleets with significant numbers of electric vehicles. A total emissions index is also defined.

As concerns the evaluation of the performance of urban traffic management and ITS with respect to social inclusion and land use, finally, four KPIs are defined. These cover the aspects of accessibility to activities, social mobility of special groups, public transport usage of special groups, and total covered area as a function of transport growth.

1 Introduction

As part of the earlier stages of the CONDUITS project it was identified that, while cities have different characteristics and individualities, they share common transport problems and objectives with respect to traffic management, and put great focus on Intelligent Transport Systems (ITS). However, despite the fact that similar policies and technologies may be implemented in different cities, each city tends to be autonomous and act in response to its own political pressures, which may be different even within the same country.

In the absence of a set of widely accepted performance measures and transferable methodologies, it is very difficult to globally assess the effectiveness of urban transport policies and ITS. Indeed, cities have often developed their own performance indices with the aim of evaluating the effectiveness and success of individual traffic management policies and ITS implementations. However, these have been mostly used independently in each city, and as a result, refer only to the city in question and are not able to provide objective conclusions about whether a specific policy or technology that had certain effects in one city could have similar or different effects in other ones.

As identified by a focus group consisting of representatives of 16 European cities during the 1st CONDUITS Technical Workshop in Rome in May 2010, the development of a common evaluation framework (a set of Key Performance Indicators/Indices (KPIs)) can assist in overcoming the issue of the assessment of traffic management and ITS. Cities believe that such a framework would be a very useful tool for cities, not only to assess their own strategies, actions and investments, but also to compare themselves with other cities in what could be an innovative benchmarking process. Nevertheless, the development and use of such a framework also raises a number of collateral implications, mainly relating to problems in data availability and to political matters (e.g. negative publicity in the media as a result of worse performance than another city).

As part of CONDUITS, three research teams from Imperial College London, Technion – Israel Institute of Technology and Technische Universität München have worked on the task of the definition of an evaluation framework for urban traffic management and ITS. Four strategic themes of urban traffic management have been tackled: traffic efficiency; traffic safety; pollution reduction; and social integration and land use. The aim of this report is to present the defined KPIs for each of the four themes and to provide guidelines for their application, leading to their validation in the cities of Paris, Rome and Barcelona in Deliverable D3.6. It is expected that the report will act as a long-term reference and manual for performance measurement of urban traffic management and ITS.

The report is structured as follows. Chapter 2 sets the context of the work documented, which includes the concept of performance measurement in the transport field and the steps involved in the definition of the new evaluation framework. Chapter 3 then goes on to identify specific areas of implementation in each of the four strategic themes of urban traffic management and ITS, and to list potential performance measures. Chapter 4 presents the operative definitions of the new KPIs and reports on the methodology of their application. Finally, Chapter 5 draws the main conclusions of this work in order to build the foundation of the application of the KPIs to specific case studies.

2 Context of performance measurement

This chapter sets the context of performance measurement in the field of urban traffic management and ITS. At first, the concept of performance measurement is defined, outlining the principles of performance measurement and relating them to the cities' needs from an evaluation framework. Then, the steps involved in the development of new performance measures are presented, which include the definition of goals and objectives, the selection of appropriate dimensions, the identification of the selection criteria, and the description of data requirements.

2.1 Performance measurement concept

Defining the concept of performance measurement, the principles of performance measures are outlined first, making the disambiguation between a performance measure and a performance index. Then, the needs from performance measurement in urban traffic management and ITS are identified.

2.1.1 Principles of performance measurement

Performance measurement and monitoring significantly impact the development, implementation and management of existing transport plans and programmes, and largely contribute to the identification and assessment of successful alternative programmes and projects. Moreover, performance measurement and monitoring enable obtaining the data necessary to compare the performance of different projects and programmes in future scenarios and to evaluate the performance of the same project and system at different time points. Accordingly, data obtained from performance measures are elaborated in order to construct composite indices for these comparison and evaluation purposes. It should be noted, however, that a measure may also be an index by itself; for example, travel time is a measure, but can also be the sole part of a mobility index, which may consist only of the travel time element.

Transport plans and projects have goals and objectives that motivate the definition of performance measures. Data requirements should be defined and analytical methods should be chosen with the intention of generating performance measures and applying them in a process of alternatives evaluation, decision-making support and ongoing monitoring.

According to this vision, transport planning and project design should be performance-based in order to achieve the desired goals and objectives, and consequently improve transport systems. The following components constitute a strategic performance-based plan:

- Definition of general goals and objectives of the transport plan or project
- Identification of specific performance objectives expressed in an objective, quantifiable and measurable form
- Identification of specific performance measures to be used in measuring or assessing the relevant outputs, service levels and outcomes of each component of the plan or project
- Recognition of the factors that can be modified to positively affect the transport system performance
- Description of the resources required to achieve the performance goals

Goals and objectives should be clear, concise, and achievable, in order to allow the integration of performance criteria and project evaluation in the decision-making process. Also, goals should be operational, namely a goal should be unambiguously compared with an existing situation, in order to improve tracking between plans and implementation decisions. Common practice has too often abandoned goals and objectives once the implementation of specific transport projects started, also because of the lack of data or analytical tools to reliably measure progress towards a goal or an objective.

Performance measures should objectively relate to the goals and the objectives identified. The risk is that the selection of a single measure of system performance would affect the types of projects selected and would introduce inherent biases, which should be reduced through the adoption of several measures to evaluate system performance and possibly combine them within a composite synthetic index. Also, performance measures should relate to outcomes of system investments and project decisions, not only to the output. Outcomes provide a better indication of the effectiveness of an activity proposed by the planner, while outputs usually measure only the level of activity and not its actual result.

Performance measures should be classified according to dimensions or market segments. Measures are related to broad goal categories such as traffic efficiency, traffic safety, pollution reduction and social inclusion. These many dimensions make performance-based planning more challenging in the transport field than in more narrowly focused sectors. Also, performance measures can be classified according to whether they are multimodal or mode-specific, to whether they apply to freight or passenger transport, the system level or the planning jurisdiction for which they are most relevant. Lastly, performance measures can be classified by performance from the user's perspective or from the planner's perspective.

Performance indices, on the other hand, should combine various measures into a single indicator, potentially covering multiple dimensions or goal categories. Performance indices are relevant to planners and decision makers that intend to reduce the complexity and volume of performance-related data that must be regularly monitored or factored into a specific decision. An example is the Consumer Price Index in Microeconomics, which reflects through a single number the cost of a broad "market basket" of goods and services regularly purchased by the typical consumer. Especially for goal categories such as safety the interest in defining a common performance index could be strong, as a synthetic index can add great value to individual descriptors. This, however, may be difficult to do in other areas, as the nature of some measures may make their combination meaningless (adding "apples and oranges").

2.1.2 Needs from performance measurement

Performance measurement should not be arbitrary but should be driven from and cater for the needs that the users of the measures and the indices have. In the case of urban traffic management and ITS, these users are the planning authorities of cities. To understand their needs, 16 European city representatives participated in a focus group at the 1st CONDUITS Technical Workshop in Rome in May 2010, where they were prompted to express how they perceive performance measurement and what they would need from the new evaluation framework. This led to the production of a city "wish-list", which is described here.

The most important requirement from performance measurement, as expressed by the cities, is that it should assess benefits. This assessment of the benefits does not necessarily indicate the direct comparison of the effectiveness of a city's policies with another, but signifies mainly the evaluation of the benefit of a specific investment against its cost. Also, it relates to the assessment of the usefulness of ITS, not with respect to specific applications, but rather as a whole, which enables the identification of the limits of ITS in offering traffic management solutions.

Another important requirement from performance measurement expressed by the cities is the ability to assist traffic managers in their decision-making procedures. This is closely tied to the previous requirement, as the assessment of the costs and benefits of existing policies and technologies offers invaluable assistance to decision-makers in the form of “lessons learnt”. However, it is frequently the case that no previous case studies exist and that decisions have to be made based on projections. In that case, it is important to ensure that the projections are supported by a priori performance measurement.

Other desired functionalities stated by the cities are that performance measurement should assist contract monitoring, and that it should promote cities’ interests. Most importantly, the new performance measurement framework should make use of existing data, as collected by cities already, and should not necessitate the collection of any new data. Performance measures should also consider the individuality of cities rather than adopting a one-for-all approach, and should be of value to the cities without causing problems.

Last but not least, performance measurement should be easy to apply and simple to convey to the public. It is important that indices are customer-oriented and the planning process should make concerted efforts to assess customer satisfaction and perception of the transport system performance.

In relation to the above, several considerations emerge for the development of a performance-based approach:

- Performance measurement should reflect the satisfaction of the transport service user, in addition to the concerns of the system operator or owner.
- Performance measurement before, during and after the delivery of a transport service can affect the ability to diagnose problems and develop solutions of the planning organisation.
- Performance measurement can benefit from the opportunity of collecting real time feedback from system users, as the transport service is often consumed at the same time is produced.
- Transport organisations should not neglect soft measures, such as customer perception of safety, in favour of hard measures, such as number of highway accidents, because of the difficulties in interpretation.
- Performance measurement should balance short- and long-term system needs and should recognise the need to balance short term results and long term benefits.

In summary, the performance measurement process should start with the definition of the services that the planning organisation intends to provide. Accordingly, goals and objectives that can be made operational are defined, monitored performance measures are linked to the objective implemented and the measurement process informs transport decision-makers how well services are being provided.

2.2 Development of performance measures

The development of performance measures involves the definition of goals and objectives, the specification of the dimensions of performance measures, the identification of the selection criteria for performance measures, and the description of the data requirements and analytical tools for monitoring performance. Detailed discussions of performance measures can be found in the literature [*1-4*]. Moreover, the development of performance measures assumes relevance as composite indices are constructed for the purpose of comparing different projects under different future scenarios and evaluating projects at different time points.

2.2.1 Development of goals and objectives

Even though sometimes mistakenly considered synonyms, goals and objectives represent different concepts. A goal is a general statement of a desired state or ideal function of a transport system, for example "to improve safety in the city centre". An objective is a concrete step towards achieving a goal that is stated in measurable terms, e.g. "to reduce the number of alcohol-related traffic fatalities". Objectives may have specific performance standards which set out in numerical terms a desired or required degree of achievement, e.g. "the number of traffic fatalities in the EU should be reduced by half in the period 2001-2010".

Some practitioners believe that a performance standard should be established for every objective and measure, but some planning organisations do not use performance standards because of limited experience in handling the measure in question, defining the data requirements and mastering the analytical tools. Experience is fundamental for planning organisations to "set the bar" in terms of desired future performance.

The breadth and depth of issues identified by transport planners produce challenges for decision-makers, who face trade-off decisions to avoid excessive complexity as the volume of issues and information required increases. Examples of goals and objectives for different categories of transport management can be found in the literature. The following examples illustrate the difference between more specific and quantifiable measures of the objectives with respect to the goals:

- Accessibility: a goal can be to provide accessibility to the main activity area using various transport modes, and an objective to provide cycling lanes and routes [*5*].
- Mobility: a goal could be to work with public agencies and private organisations to ensure basic mobility for an entire region [*6*], and an objective could be to cooperate with large companies for initiatives to abandon private traffic [*5*].
- Quality of life: a goal could be to ensure that transport investments are cost-effective, protect the environment, promote energy efficiency and enhance quality of life [*7*], and an objective could be to provide opportunities for safe, enjoyable and low environmental impact water recreation a specific area [*8*].
- Operational efficiency: a goal could be to develop strategies that improve the transport of people and goods by reducing delays and minimising inconveniences [*9*], and an objective could be to utilise economies of scale by providing for the joint use of ports by several tenants [*10*]
- System condition and performance: a goal could be to preserve the highway infrastructure's cost-efficiency so as to protect the public investment [*11*], and an objective could be to improve construction techniques and materials to minimise construction delays [*12*]

Decisions about the areas in which the performance measurement is done significantly affect the types of projects that are eventually implemented. For example, using level of service (LOS) as the only mandated measure of system performance (as done for the California Congestion Management Program) could result in choosing only projects that enhance roadway LOS by virtue of this measure definition. For this reason, most transport planning organisations avoid this bias by defining several measures and accounting for several desired outcomes in order to evaluate and select projects with broader effects.

2.2.2 Dimensions of performance measures

Performance measures can be classified according to their multimodal or mode-specific nature, to their application to freight or passenger transport, to the system level to which they apply or to the planning jurisdiction to which they are most relevant. Also, performance measures can be classified according to the user's or the planner's perspective. Performance indices can be classified according to the nature of the measures that compose them.

The comprehension of the dimensions involved is vital for the development, selection and implementation of a set of applicable performance measures that address all relevant issues. Accordingly, the following common dimensions of performance measures are envisioned with options in each dimension:

- Sector: freight and passenger.
- Mode: highway (car, truck, public transport), rail, water, cycle, walk and other non-motorised modes.
- Perspective: user versus supplier and performance versus condition.
- Concern: traffic efficiency, traffic safety, environmental conservation, social inclusion.
- Spatial concern: metropolitan (urban versus suburban), rural, interurban, international.
- Level of responsibility: national, regional and local.
- Use of information: management decision-making, diagnostic tool, tracking and monitoring, resource allocation, signalling systems and information systems.
- Timeframe: present or short-term, future or long-term, point in time versus trend.
- Time impact – at what timeframe the project implemented has an impact on the index.
- Level of refinement: primary versus secondary indicator and primary versus composite measure.

These categories are obviously flexible and several planning organisations further divide or unite alternative options according to their goals and objectives. All ITS plans take in a combination of the aforementioned categories.

2.2.3 Selection criteria for performance measures

Performance measures are required to be operational with respect to the objectives and dimensions listed. Accordingly, they are required to satisfy some of the properties that by definition constitute their selection criteria. The following properties or requisites characterise performance measures:

- Measurability: performance measures should be measurable with tools and resources available, costs should be reasonable with respect to budget, accuracy levels should be comparable with respect to requirements, data should be retrievable through field measurement.
- Predictability: performance measures should allow to compare future alternative projects or strategies, and also to use existing forecasting tools for its definition.
- Clarity: performance measures should be understandable to policy makers, professionals and also the general public.
- Usefulness: performance measures should be a direct measure of the issue of

concern, either to cause further study or action to occur, or to diagnose transport deficiencies and their causes.

- Multimodality: performance measures should encompass every relevant transport mode, even when modes are combined.
- Temporality: performance measures should be comparable across time, namely should be able to express the temporal extent of congestion or other conditions, and should fit the timeframe of analysis and action.
- Geographical scale: performance measures should be applicable to the appropriate geographical level (national, regional or local) and should be useful at that same level.
- Multiple indications of goals: performance measures should be suitable to address every goal of the system that applies to different dimensions.
- Control: performance measures should allow the planning organisation to control and correct the measured characteristic.
- Relevance: performance measures should be relevant to planning and project design processes, and their reporting should provide decision-makers with relevant information for their decision making processes.

These characteristics are obviously flexible, and several planning organisations use different criteria depending on needs, resources and capabilities. Knowledge of the particular situation in which performance measurement is carried out facilitates an understanding of which combination of properties is important to monitor the existing transport system. Also, it should be noted that most problems are related to the costs of data collection and processing.

2.2.4 Construction of performance indices

A composite performance index can be an efficient means to compare multimodal alternatives or different dimensions among the ones described above. For example, the composite mobility index of the Southern California Governments Association accounts for the value of vehicle-miles of travel (VMT), operating speeds, free-flow speeds, average vehicle occupancy and population [*7*].

There are advantages and disadvantages in having an index measure that represents system performances through a single number without dimensions, by establishing a uniform unit of measurement and relying on available data to make the measure operational. The main advantage is that for certain audiences (i.e., non-technical) it is much easier to understand and grasp a single number rather than a large collection of individual measures whose meaning requires trained insight and careful analysis, and it may be less likely to provoke large numbers of questions on individual measures' values and how or why each one of them contributes. The main disadvantage is that an aggregate number does not provide immediate insight into which aspects of performance are changing or why. Since the individual components and relative weights are not identified in general reporting, it can be difficult to determine quickly the sensitivity of an index to changes in its component measures.

However, this obscurity or ambiguity may lead to some other advantages. The index increases the opportunity for all modes and markets to be included, conveys the idea that each service is important and elevates the discussion about how best to measure and report system performance. This dialog between modes and sectors enhances awareness, broadens perspectives and leads to more comprehensive solutions, even though the index concept is still under discussion and is not fully evolving into wide practice.

2.2.5 Data requirements for performance measurement

Performance measures are selected also according to data needs and costs. In theory, it is preferable to have the goals determine the performance measures and the data requirements, in order to have a sound foundation for the evaluation of system performance. In practice, it is difficult to answer all the needs and face all the costs for the collection of the necessary data and the implementation of the necessary analytical tools.

Operations-oriented measures rely to some extent on traditional data collection programmes and techniques, but more broadly defined outcome measures are likely to require additional types or quantities of data. For example, traffic efficiency measures frequently necessitate sample data on travel time or speed, while social inclusion measures require spatially allocated travel and socioeconomic information.

Answers to the data needs are retrievable from the following sources:

- Surveys, accounting for household travel surveys, workplace surveys, stated-preference surveys, longitudinal and panel surveys, public transport on-board surveys, commercial vehicle surveys, external station surveys and parking surveys.
- Traffic monitoring, including traditional traffic volume counts, vehicle classification recording and weigh-in-motion.
- Highway performance monitoring system, containing yearly summary data about system length and daily travel, environmental impacts, fatal and injury motor vehicle accidents, travel activity, divided by road type.
- ITS data, exploiting traffic surveillance technologies, automatic vehicle classification,

short range communication, automatic vehicle identification, smart cards and vehicle navigation systems.
- Consumers' satisfaction and perception data, consisting of extensions of surveys focused about the customer evaluation of the transport system.

The approach most used in practice consists of identifying the ideal measures that relate to a specific goal, then working backwards to surrogate measures that are developed using more readily available data. The intent is to migrate towards ideal measures over time, according to the availability of resources, the success with the surrogate measures and the priorities of the planning organisation.

Data requirements vary according to the spatial concern and the level of responsibility. Surveys may be easily adapted to the requirements of municipalities, regional councils and governments to answer the necessities in terms of spatial concern, and moreover may be easily prepared to answer the goals and the level of depth required. Traffic monitoring is also performed at different levels according to the spatial concern of the project, as municipalities might be interested in arterials and governments be focused on motorways and highways. ITS data are usually provided at different levels of detail according to the geographical scope of the project, as local information might be provided with a certain level of detail for municipal applications and extensive information might be provided with a different level of detail for national applications. Also, the extent of the time span for the information depends on the spatial concern of the project, as information at the local level requires frequent updates related to the fast modification of the traffic conditions, while at the national level necessitates less frequent updates connected to the slower modification of the traffic conditions. Evaluations at the customer level of the projects are interesting mainly at the local level and for specific interventions, such as interventions at the level of single intersections or public transport planning. Moreover, national and local authorities are interested in identifying and analysing trends that are not necessarily interesting to the customer level.

Data requirements vary according to the timeframe of the evaluation, namely according to the fact that performance indices are used either to compare different projects related to different future scenarios or to evaluate the same project at different time points. The former requires data that are suitable for an analysis on the long period, for example data from surveys and about consumers' perceptions and attitudes that may be collected about long-term scenarios. The latter requires data that are specific to certain conditions (i.e., period of the day, period of the week), for example data from traffic monitoring and ITS applications that may be collected regularly and in similar conditions for creating a solid basis for comparison. It should be noted that data analysis techniques are also different, since the comparison of different projects requires cross-sectional analysis and the evaluation of the same project at different time points necessitates time-series analysis. It should also be noted that time series analysis necessitates accounting for trend tendency and seasonality of the data through dedicated statistical models that are able to correct for this characteristic of the traffic data.

Data requirements are different in terms of the reliability of the collected data. Information from surveys and queries from consumers' perceptions and attitudes are reliable as long as the preparation of the survey allows collecting meaningful and useful information that the analyst can use for predicting and anticipating travellers' decisions. Data from traffic monitoring and ITS sources is reliable as long as the technology for data collection is reliable. Local in-roadway sensors that are either embedded in the pavement, implanted in the sub-grade or taped to the surface of the roadway (e.g., inductive loop detectors, magnetometers, pneumatic tubes) collect direct information about vehicle passage and presence, while other traffic flow parameters such as density and speed are inferred through algorithms that interpret and analyse the measured data. The reliability of these measures depends on the device installation and maintenance, given that their mounting usually disrupts traffic flow and their functioning frequently suffers from pavement deterioration, improper installation, weather-related effects and street maintenance. Local over-roadway sensors that are mounted either above or alongside the roadway with some offset distance from the nearest traffic lane (e.g., video image processors, microwave radar, active and passive infrared sensors, ultrasonic and passive acoustic sensors, laser radar sensors) measure traffic flow parameters and provide an advantage over in-roadway devices in terms of installation and maintenance. The reliability of these measures depends on the mounting location, given that their functioning sometimes suffers from tall vehicles obstructing the view of distant lanes or projecting their image into adjacent lanes. Alternative sources of traffic flow data utilise spatial information from mobile phone companies and non-stationary airborne platforms: mobile phone companies monitor the transmitting status of phones during conversations, and the location of the phones is potentially available to traffic management agencies to track vehicles and estimate congestion and travel time over wide areas, while protecting the anonymity of the phone subscriber; satellite, aircrafts and unmanned aerial vehicles may also be used to estimate arterial and motorway traffic characteristics over long timescales and large geographic areas, expanding the data availability to scales not previously available. The reliability of these measures depends on the network density, given that in urban areas mobile phone data cannot differ between arterials served by the same antennas and that satellite data cover large areas with low details.

Lastly, data requirements concern simplicity of collection and elaboration. Performance measures and indices must be easy to grasp for two reasons: (i) national and local authorities should be able to apply them without great difficulty and with resources readily available when commercial software and devices are used, and (ii) municipalities should be able to market the results to the general public who is supposed to understand them easily in simple terms. Composing simple indices helps transferring them across areas that are different in terms of both geographical location and network characterisation, simplifying the work of the engineers of the national and local authorities without requiring general knowledge of the subject, and marketing the results to the public opinion (especially crucial for example to generate consensus about policy implementations).

2.2.6 Analytical tools for performance measurement

The analytical methods required to make operational each performance measure reflect the underlying goals being addressed and the type of data available for input. For example, goals and objectives focused on improving the flow of vehicles, people or goods require system or corridor-level operations measures, and the analytical methods relevant to this strategy might include traffic simulation models, capacity and delay modelling packages and network models.

The following analytical tools used to elaborate the data collected are identified:

- Urban travel demand forecasting models, used for example in the preparation of regional and local plans and air quality conformity analyses; allow to estimate data that would be difficult to measure in the field.
- State-wide travel models, moving from trend-line models to network-based models with distribution, mode choice and assignment capabilities; allow forecasting data with particular accuracy in the short-term.
- Travel survey manuals, describing current practices and improved techniques to implement the surveys required for travel model system development; help to improve traditional data collection with the surveys mentioned in the previous section.
- Cost-benefit analyses, evaluating alternative transport projects or investment scenarios; allow accounting for user benefits, such as travel time savings, and for externalities, such as vehicle emissions, energy costs and benefit-cost ratios.

Incident-related effects and management strategies, consisting of accident detection, service patrols, computer-aided dispatch, and infrastructure intervention, such as hard shoulder widening, allows estimating the impacts on non-recurring congestion and the effectiveness of strategies to mitigate that congestion.

3 Performance measurement framework

This chapter gives definitions and identifies the relevant application areas for performance measurement in each of the four strategic themes of urban traffic management and ITS, tackled in this report (traffic efficiency, traffic safety, pollution reduction, and social inclusion and land use), in line with the European Commission's strategy on the future of transport, as presented in the 2001 and 2011 white papers [*13,14*]. The chapter also specifies example performance measures that could form the basis of the performance indices described in Chapter 4. An overview of the developed performance measurement framework is shown in Figure 1.

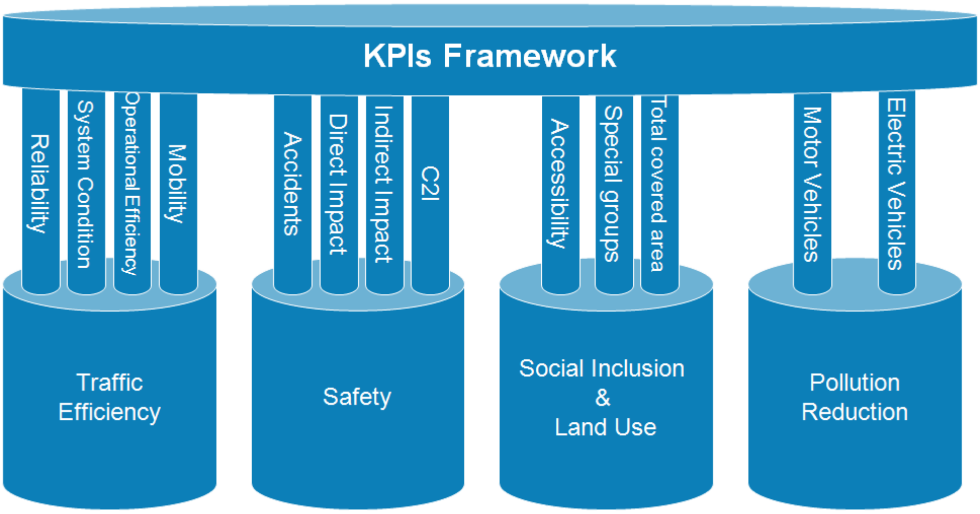

Figure 1: Overview of the performance measurement framework

3.1 Traffic efficiency

The vast majority of urban traffic management policies and solutions, including those involving ITS, have the improvement of traffic efficiency as their objective. While the implementation of a specific policy or technology may have several objectives across the spectrum of urban traffic management, traffic efficiency usually figures high among them. This makes the quantification of the performance in terms of traffic efficiency very important.

3.1.1 Scope and applicability of traffic efficiency

The term traffic efficiency may cover a variety of aspects. For the purposes of the present study, traffic efficiency is constituted by the following four sub-categories: mobility; reliability; operational efficiency; and system condition and performance.

Mobility is defined as the ability of a transport system to provide access to jobs, recreation, shopping, intermodal transfer points, and other land uses, which is one of its primary purposes. Measuring the performance of mobility is hence an important part of quantifying the performance of the system in terms of traffic efficiency as a whole. Mobility measures should reflect the ability of people and goods to reach different destinations using different modes. Moreover, measures of mobility should capture the density of transport service within a given area and express the user's perspective. Mobility is mainly concerned with the travel time on the road and public transport networks.

Reliability is another important function of transport systems, which expresses the ease of mobility. Reliability is an essential component of traffic efficiency and should thus also be measured. Reliability measures should reflect the ease or difficulty of people and goods to perform their trips. Since reliability is concerned with travel time variability, speed, system usage and system capacity, many reliability measures will come from the perspective of the suppliers of the modes and the infrastructure.

Operational efficiency refers to the good organisation of resources to produce an acceptable level of transport output and is, as such, an important constituent of traffic efficiency. The quantification of the performance of operational efficiency is of particular interest to the suppliers of transport services, and measures evaluate the competency of systems from a financial, operational, time and user's perspective. The most frequently used measures are trip time, congestion-related attributes, mode shares, transfer times at connecting facilities and public transport cost performance. As specified with regard to reliability measures, congestion-related attributes and trip times are typically estimated with travel models, mode shares are collected through surveys, and connecting times and distances at transfer facilities can be collected with field data or user surveys.

Finally, system condition and performance refers to the physical condition of the transport infrastructure and equipment, which is seen as a vital directive by most practitioners. System condition and performance measures can focus on the condition of the system itself (e.g. roadways with deficient ride quality) or on the efficiency of transport programmes (e.g. cost to maintain roadways). The most common measures relate to roadway and bridge conditions and age, as well as maintenance by their management organisations.

3.1.2 Potential performance measures of traffic efficiency

A large number of performance measures can be adopted for the evaluation of traffic efficiency. Keeping in line with the goals and objectives specified in the previous chapter, but also with the categories of traffic efficiency introduced in the previous sub-section, a library of potential performance measures is presented. It should be noted that some of the measures appear in more than one of the categories, as they are relevant to more than one goal.

Mobility

The following is a mobility measures library, with consideration for actual calculation requirements according to basic, intermediate and advanced levels of complexity.

- Average travel time to relevant points of interest (e.g. hospitals, local government offices, key highway intersections) on the road network, calculated at a basic level with probe vehicles, at an intermediate level with travel demand models providing information on travel time for origin-destination (OD) pairs, and at an advanced level with GIS (Geographical Information System) data platforms containing information on average travel times on the road network links. Spatial related information may be collected with advanced technology systems, such as Floating Car Data (FCD) or Automatic Number Plate Recognition (ANPR) data about the speed of links that might provide average travel times on crossed links. The same measure may be calculated for different times of the day and different levels of congestion (relating to reliability).
- Average travel time to relevant points of interest on the public transport network, calculated at a basic level with field data collection, at an intermediate level either by means of a survey among public transport users or approximations from maps of the area and public transport lines, and at an advanced level with historical real-time databases containing information on average travel times on the network links and each public transport line.
- Public transport supply in route-kilometres (or seat-kilometres, or passenger-kilometres), calculated at an intermediate level with the collaboration of public transport companies providing information about the number of seats/passengers and distance covered by public transport lines, and at an advanced level with GIS data platforms containing information about routes, average occupancies and average travel times of public transport lines on the network links.
- Connection times at transport facilities, calculated at a basic level with field data collection, at an intermediate level by means of surveys conducted among public

transport users, and at an advanced level with real-time information about connections and transfers provided by the facility's control centre.

- Average distance and duration of transfers between modes, calculated at an intermediate level by means of surveys conducted among public transport users, and at an advanced level with either GIS data platforms containing information about connection links among facilities or with real-time information about connections and transfers provided by the facility's control centre.
- Access times to public transport facilities, calculated at a basic level with field data collection, and at an intermediate level by means of surveys conducted among public transport users.
- Average parking search time at public transport facilities, calculated at a basic level by field measurements and at an intermediate level through passenger surveys. The same measure may be calculated for different times of the day and for different periods of the year (relating to reliability).
- Average commuting time by public and private transport, calculated at an intermediate level with either approximations from maps of the area and of public transport lines or by means of surveys conducted in workplaces or among public transport users, and at an advanced level with GIS data platforms containing information about travel times on links served by public transport lines that connect houses (origins) with workplaces (destinations).
- Average commuting distance, calculated at an intermediate level with the elaboration of household travel surveys describing the distance covered from home to work daily, and at an advanced level with GIS data platforms containing information about travel times on links that connect houses (origins) with workplaces (destinations). The same measure may be calculated for different modes.
- Total motorway lane-kilometres, calculated at an intermediate level with approximations from maps of the area integrated with the description of the road hierarchy, and at an advanced level with GIS data platforms containing information about lanes, lengths and hierarchy of the road network.
- Number of kilometres with ITS, calculated at an intermediate level with approximations from maps of the area integrated with expert knowledge about the implementation of ITS, and on an advanced level with GIS data platforms containing additional information about the availability of ITS on the network links.
- Modal split, calculated at an intermediate level by means of surveys among travellers, and at an advanced level with transport demand models providing information about the ratio between trips of different modes. The same measure may be calculated for different trip purposes and different destinations (e.g., public services).
- Percentage of non-motorised trips for commuting, calculated at an intermediate

level with an elaboration of data from household travel surveys. The same measure may be calculated for different non-motorised modes.

- Number of kilometres of non-motorised facilities, calculated at a basic level with approximations from maps of the area integrated with the description of the road hierarchy, and at an advanced level with GIS data platforms containing information about the dedicated use of each network link.

Reliability

The following is a reliability measures library, with consideration for actual calculation requirements according to basic, intermediate and advanced levels of complexity.

- Origin-destination (OD) route travel time and total travel time, calculated at an advanced level with a transport demand model providing information about travel times between nodes in the network. The same measure may be calculated for different modes and for different times of the day.
- Average/total travel times, calculated at a basic level with probe vehicles (FCD), or video detection using ANPR, and at an intermediate level with positioning systems (Galileo, GPS) to enrich the data fusion of cellular phone probes and FCD. The average/total travel times can be calculated for links within the urban network or routes of OD pairs. Routes of OD pairs can also be calculated through video detection using ANPR. Calculating travel times using direct positioning systems or ANPR might present delays in data relevance for real-time traffic management goals. Composing the travel time index from travel time calculations of short segments supports travel time relevance for real-time traffic management decision making.
- Average/total speeds can be calculated directly through local point detection means (such as loop detectors) for links, or calculated based on a time-space transformation for links and routes.
- Vehicle-kilometres-travelled, calculated at an intermediate level with rough information from household travel surveys, and at an advanced level with the elaborate results of a transport demand model providing information about all link traffic volumes and all the trips in the network. The same measure may be calculated for different congestion levels and for different modes, as well as per capita, per employee and per day.
- Trips, calculated at an intermediate level with rough information from household travel surveys, and at an advanced level with the elaborate results of a transport demand model providing information about all the trips in the network. The same measure may be calculated for different purposes and for different modes, as well as per capita, per household and per day. Some novice works of estimating OD matrices using cellular data might also support this measure [*15,16*].

- Delay, calculated at an intermediate level with elaborate results of a transport demand model providing information about travel times on the network links and their comparison with respect to travel time in free flow conditions, and at an advanced level with traffic controllers' information calculated at signalised intersections. The same measure may be calculated for different congestion levels and different times of the day.
- Modal split, calculated at an intermediate level by means of surveys among travellers, and at an advanced level with transport demand models providing information about the ratio between different trip modes. The same measure may be calculated for different trip purposes and different destinations (e.g., public services).
- Percentage of non-motorised trips for commuting, calculated at an intermediate level with elaborate data from household travel surveys. The same measure may be calculated for different non-motorised modes.
- Transfer times, calculated at a basic level with field data collection, at an intermediate level by means of surveys conducted among public transport users, and at an advanced level with real-time information about connections and transfers provided by the facility's control centre.
- Percent of transfers between modes to be under "X" metres and "N" minutes, calculated at an intermediate level by means of surveys conducted among public transport users, and at an advanced level with either GIS data platforms containing information about connection links among facilities or with real-time information about connections and transfers provided by the facility's control centre.
- Frequency of public transport, calculated at a basic level from timetables provided by public transport operators, and at an advanced level with either GIS data platforms containing information about frequency of public transport lines on the links of the network or with real-time information about the current position of public transport vehicles on the network.
- Number of public transport trips, calculated at a basic level from public transport operators. The same measure may be calculated for different origin-destination pairs.
- On-time performance of public transport, calculated at an intermediate level from either field data collection or surveys among public transport vendors and users, and at an advanced level with real-time information on the arrival time of public transport vehicles to their stations.
- Variance of the time headway between consecutive vehicles of the same public transport line.
- Average delay of public transport at intersections, calculated at an intermediate level with elaborate results of a transport demand model providing information about

travel times in the network links and their comparison with respect to travel time in free flow conditions.

- Number of stops of public transport at intersections, calculated from field data collection such as loop detectors and Automatic Vehicle Location (AVL) system.
- Number of missed connections at transfer points, calculated from field data collection, surveys among public transport vendors and users, and at an advanced level with real-time information on the number of missing connections at transfer point.
- Public transport rides per capita, calculated based on surveys among public transport users.
- Pedestrian/cyclists red times in signalised junctions, calculated from field data collection.

Operational efficiency

The following is an operational efficiency measures library, with consideration for actual calculation requirements according to basic, intermediate and advanced levels of complexity.

- Public cost for transport, calculated at an intermediate level with data from governmental offices and private transport companies.
- Private cost for transport, calculated at an intermediate level with data from governmental offices and private transport companies.
- Cost-benefit of existing facility versus new construction, calculated at an advanced level with data from governmental offices and consultancy firms.
- Average cost per constructed lane-mile, calculated at an intermediate level with data from governmental offices. The same measure may be calculated per mile and per trip.
- Value of fuel savings, calculated at an advanced level from the results of a travel demand model providing information on the total amount of travel and an evaluation of the average fuel consumption per unit of travel and type of vehicle defined by literature or expert opinion, combined with information about travel time saved. The same measure may be calculated for different modes, different trips and different purposes.
- OD travel times, calculated at an advanced level with a transport demand model providing information about travel times between network nodes. The same measure may be calculated for different modes and for different times of the day.
- Total travel time, calculated at an advanced level with a transport demand model providing information about travel times on all the links and all the trips of the network. The same measure may be calculated for different modes and for different

times of the day.

- Average speed, calculated at a basic level with probe vehicles, and at an intermediate level with FCD or ANPR data collecting information on local speed for each link in the network.
- Vehicle-kilometres-travelled, calculated at an intermediate level with the approximation of information from household travel surveys, and at an advanced level with the elaborate results of a transport demand model providing information on all the link traffic volumes and trips in the network. The same measure may be calculated for different congestion levels and for different modes, as well as per capita, per employee and per day.
- Travel time, calculated at a basic level with local sensors and at an advanced level with FCD or ANPR data providing information on speed and allowing the calculation of travel times on road segments under consideration.
- Delay, calculated at an intermediate level with the elaborate results of a transport demand model providing information about travel times on the network links and their comparison with respect to the travel time in free flow conditions, and at an advanced level with traffic controllers' information calculated at signalised intersections. The same measure may be calculated for different congestion levels and different times of the day.
- Modal split, calculated at an intermediate level by means of surveys among travellers, and at an advanced level with transport demand models providing information on the ratio between trips of different modes. The same measure may be calculated for different trip purposes and destinations (e.g., public services).
- Average travel time to relevant points of interest (e.g. hospitals, local government offices, key highway intersections) on the road network, calculated at a basic level with probe vehicles, at an intermediate level with travel demand models providing information on travel time for origin-destination (OD) pairs, and at an advanced level with GIS (Geographical Information System) data platforms containing information on average travel times on the road network links. Spatial related information may be collected with advanced technology systems, such as Floating Car Data (FCD) or Automatic Number Plate Recognition (ANPR) data about the speed of links that might provide average travel times on crossed links. The same measure may be calculated for different times of the day and different levels of congestion (relating to reliability).
- Average travel time to relevant points of interest on the public transport network, calculated at a basic level with field data collection, at an intermediate level either by means of a survey among public transport users or approximations from maps of the area and public transport lines, and at an advanced level with historical real-time databases containing information on average travel times on the network links and

each public transport line.

- Customer satisfaction with completed projects, calculated at an intermediate level by means of a survey among travellers.
- Customer perception of "kept promises" on project completion, calculated at an intermediate level by means of a survey among travellers.
- Access times to transport facilities, calculated at a basic level with field data collection, and at an intermediate level by means of surveys conducted among public transport users.
- Transfer times, calculated at a basic level with field data collection, at an intermediate level by means of surveys conducted among public transport users, and at an advanced level with real-time information about connections and transfers provided by the facility's control centre.
- Percent of transfers between modes to be under "X" metres and "N" minutes, calculated at an intermediate level by means of surveys conducted among public transport users, and at an advanced level with either GIS data platforms containing information on connection links among facilities or with real-time information about connections and transfers provided by the facility's control centre.
- Cost per passenger for urban public transport systems, calculated at an intermediate level with data from governmental offices and public transport companies. The same measure may be calculated per vehicle-kilometres-travelled.
- Cost per vehicle miles of travel (VMT), or person miles of travel (PMT) for urban transit systems, calculated at an intermediate level with data from governmental offices and public transport vendors.
- Frequency of public transport, calculated at a basic level from timetables provided by public transport companies, and at an advanced level with either GIS data platforms containing information about frequency of public transport lines on the network links or with real-time information on the current position of public transport vehicles in the network.
- Number of public transport trips, calculated at a basic level from public transport operators. The same measure may be calculated for different origin-destination pairs.
- On-time performance of public transport, calculated at an intermediate level from either field data collection or surveys among public transport operators and users, and at an advanced level with real-time information on the arrival time of public transport vehicles at destinations.
- Level of service of walking and cycling facilities, calculated at an intermediate level from field data collection, and at an advanced level from GIS data platforms containing information on non-motorised mode facilities.

System condition and performance

The following is a system condition and performance measures library, with consideration for actual calculation requirements according to basic, intermediate and advanced levels of complexity.

- Percent of highway mainline pavement rated good or better, calculated at an intermediate level with data from governmental agencies combined with expert opinion. The same measure may also be calculated for pavement roughness/distress/friction indices.
- Percentage of highway mainline bridges rated good or better, calculated at an intermediate level with data from governmental agencies combined with expert opinion.
- Kilometres of highway rated “good” or “fair” for bicycle travel, calculated at an intermediate level with data from governmental agencies combined with expert opinion.
- Age distribution of public transport vehicles, calculated at a basic level with data from public transport vendors.
- Remaining useful life of public transport vehicles, calculated at a basic level with data from public transport vendors.
- Kilometres between road calls for public transport vehicles calculated at a basic level with data from public transport vendors.
- Customer perception of the steps taken to improve the system, calculated at an intermediate level by means of a survey among travellers.
- Number of lane kilometres designated for capacity upgrade contracts, calculated at an intermediate level with data from governmental agencies.
- Number of lane kilometres designated for resurfacing contracts, calculated at an intermediate level with data from governmental agencies.
- Construction grants issued, calculated at an intermediate level with data from governmental agencies.
- Number of projects funded, calculated at an intermediate level with data from governmental agencies. The same measure may be calculated for different modes and various facility types.

3.2 Traffic safety

Despite considerable improvements in recent years, safety is still a key issue within transport planning, as many people are involved in road accidents every day, often suffering injury or death. A variety of measures aiming at reducing traffic accidents have been introduced throughout the last decades; these include in-vehicle fixtures and fitments (seatbelts, airbag, headrests, etc.), as well as on-road traffic engineering features (pedestrian crossings, traffic calming, etc.), with ITS playing a prominent role in both categories (e.g. collision control, variable speed warning signs, etc.). As is expected, the improvement of traffic safety is a priority for city authorities, and the quantification of a city's performance in that aspect is essential.

3.2.1 Scope and applicability of traffic safety

The safety level of transport infrastructure (road or track section, intersection, railway station) is defined by the number of accidents on one hand, and by the impact of the accidents on the other. Accident numbers are fairly straightforward to obtain and analyse; however, the quantification of the impact is more complex and is mostly measured as the number of people injured or killed [*17*].

The main factors influencing road injuries are: exposure (the amount of travel), accident rate (the risk of accident per unit of exposure), and accident severity (the outcome of accidents concerning injuries). Given these factors, there are four different ways to reduce the amount of injuries and fatalities in road accidents:

- reducing exposure to the risk of accident by reducing the amount of travel,
- shifting travel to means of transport with a lower level of risk,
- reducing the accident rate for a given amount of travel, and
- reducing accident severity by improving the protection of road users.

Most policies and ITS applications aimed at improving traffic safety satisfy one or more of these four requirements. As such, and for the purposes of the present study, the measurement of the performance of policies and systems is analysed, aside from the direct quantification in terms of accident numbers, in terms of two categories: policies and applications with a direct safety impact, and policies and applications with an indirect safety impact.

The former category mostly includes policies and ITS applications which are put in place specifically for the avoidance of accidents and the improvement of safety. These include active safety systems, such as the Anti-lock Braking System (ABS) or the Brake Assist System (BAS) implemented in vehicles, and their effectiveness is demonstrated through standardised tests and scenario-assessments during their development. The latter category, on the other hand, includes policies and technologies mostly implemented on the transport infrastructure focussing on influencing factors of safety, and as such imply a major fiscal investment. A transparent information policy towards the taxpayers is thus important for the acceptability of these policies and applications, and an objective evaluation methodology allowing cities and infrastructure operators to monitor the success of safety-related applications is required. This is a particularly challenging task, as a connection between changes in safety levels and the impact of a policy or system on certain influencing factors of safety needs to be made.

3.2.2 Potential performance measures of traffic safety

To evaluate the impact of a specific traffic management or ITS application and select the appropriate performance measure, a classification is first made, where the application is placed under one of the following four groups:

- Infrastructure-based application with direct safety impact (application installed only to avoid accidents and to improve safety);
- Infrastructure-based application with indirect safety impact in urban environments (application in inner-city areas with a primary goal other than safety);
- Infrastructure-based application with indirect safety impact on urban motorways (application on motorway to influence traffic flow); and
- Car-to-infrastructure-related application.

Prior to selecting performance measures, the following obstacles have to be taken into account:

- Traffic management and ITS applications are often implemented in larger bundles of synergetic measures;
- influencing factors can evolve even after short periods of time and thus bias the results of the evaluation;
- a single application has influence on several safety-relevant aspects of the transport system, and this influence is sometimes contradictory; and
- the influencing mechanism of the application can be so indirect, that a connection between the application and the safety impact cannot be quantified.

In order to address the first problem, there has to be a solid situation analysis of the targeted object, of the predominant conditions and of all the transport-related measures already implemented or due for implementation during the evaluation period. The second problem requires a comparison of the relevant data at different levels. In addition to the obligatory before- and after-comparison, a reference object with similar original characteristics has to be chosen. This reference object has to maintain its original characteristics for the duration of the evaluation process. Changes in safety levels of the reference object have to be investigated in depth and eventually subtracted from the performance of the evaluated object.

Requirements resulting from the third and fourth problems can only be met to some extent using a set of different indicators that are directly influenced by the application. They can provide a better picture of the implementation's impact in different fields and also deliver a basis for qualitative description of the application's outcome, in case the mechanisms of action do not allow a direct quantitative connection between direct impact and safety level.

The most commonly-used performance indicators of traffic safety are: accident rate; number of fatalities; number of injured; and economical damage. With the help of some examples of specific applications of traffic management and ITS, a library of performance measures is assembled next for each of the four application groups mentioned.

Infrastructure-based applications with direct safety impact
Three applications are considered: feedback sign; train control system; and guideway intrusion detection system.

Application: Feedback sign
Description: Using feedback signs authorities have the opportunity to influence the driver's behaviour by reducing the speed as a result of the current traffic conditions and by adapting the spacing behaviour according to the current speed. The effects of feedback signs and their given information can be measured by comparing the traffic situation just in front of and behind the location of the feedback sign.
Impact: Raising awareness to the traffic environment
Indicators: speed, spacing
Measurement techniques: inductive loop detectors, radar

Application: Train control system
Description: Train operation is subject to very different conditions than private car transport. The infrastructure is equipped with intelligence preventing conflicts. The degree of freedom for the trains is therefore restrained by the interlocking system. Thus train accidents are extremely rare compared with car accidents. Nevertheless there is still a certain probability for human errors, for which additional systems have been implemented. Since train accidents are rare the conventional accident statistics are not sufficient for the evaluation of safety improvements through these systems. The assessment has to be based on the analysis of the theoretical safety level before and after the implementation. The

safety level can be defined by the number of critical situations that occur frequently without necessarily leading to an accident, e.g. exceeding speed limits, late reaction to signalling. These potentially dangerous situations can be reflected on the actual action taken by the train control system.
Impact: Prevention of human errors
Indicators: number of speed limit violations, number of signal violations
Measurement techniques: analysis of interlock-system-data and trip recorder information

Application: Guideway intrusion detection system
Description: A guideway intrusion detection system prevents accidents between passengers and trains, and can to some extent be effective in the prevention of suicides. The impact can therefore be assessed through the accident rates. Apart from the direct prevention of incidents, the system recognises potential conflicts, not necessarily leading to an accident and therefore improves the safety potential of stations. The increase in the number of detected conflicts, either critical or non-critical, can quantify this improvement of safety potential.
Impact: Improvement of safety potential
Indicators: number of detected critical and non-critical conflicts
Measurement techniques: records of the operation centre

Infrastructure-based applications with indirect safety impact in urban environments
Two applications are considered: adaptive signal control; and dynamic route and parking guidance.

Application: Adaptive signal control
Description: Adaptive traffic signal control aims to improve the traffic flow as a whole. Specific objectives include the harmonisation of traffic flow and the reduction of journey time by traffic concentration at primary roads, and the reduction or avoidance of congestion occurrences. Adaptive traffic signal control systems directly influence the traffic flow according to the current traffic conditions. The effects for the whole road network can only be covered by using an adequate fleet of vehicles sending their speed and position in the network, or with periodical driving inspections at routes with a high risk of congestion. By reducing congestion occurrences, indirectly, the risk of rear-end accidents decreases.
Impact: Harmonisation – concentration on primary roads, reduction of congestion occurrences
Indicators: number of stops, number of congestion occurrences, queue lengths
Measurement techniques: FCD, driving inspections, traffic models

Application: Dynamic route and parking guidance
Description: As an effect of dynamic route and parking guidance systems the whole road network should be more or less equally loaded. This means that shares of traffic will be distributed to alternative routes and this will lead on the one hand to reduced traffic volumes on primary roads and on the other hand to additional traffic volumes on alternative routes. As a result, the probability of congestion will decrease on the main routes but may increase on the alternative routes. In this way the amount of congestion occurrences will reduce the risk of rear-end-accidents.
Impact: equal degree of saturation throughout the network, reduction of congestion occurrences
Indicators: traffic volume, number of congestion occurrences, queue lengths
Measurement techniques: inductive loop detectors, traffic models

Infrastructure-based applications with indirect safety impact on urban motorways
The application of motorway section control is considered.

Application: Motorway section control
Description: The safety effects of section control systems result primarily from influencing the driver's behaviour. Aims include the harmonisation of the speed (and spacing) according to the current traffic volume, the reduction of the speed due to current weather conditions, and the issuing of warning messages for congestion, works and other dangerous situations. The direct effect of the assignments and information given by the section control can easily be measured. The operation of such systems requires a widespread sensor infrastructure collecting traffic data, providing the necessary basis for the assessment. Section control has yet another effect that influences traffic safety to a longer extent, as it reduces the number of congestion occurrences, as well as their intensity. Since congestion is a major reason for rear-end-collisions, the system has a secondary effect on traffic safety. The influence is though so indirect, that a reliable quantitative assessment is very difficult.
Impact: Harmonisation – adaptation to weather conditions, issuing of warning messages
Indicators: speed, spacing, number of congestion occurrences
Measurement techniques: inductive loop detectors, radar

Car-to-infrastructure-related applications
Applications of car-to-infrastructure communication may include different systems, such as turning assistance, red-light assistance and collision warning. Nevertheless, they are considered as one application here, as they rely on the same technology.

Application: Car-to-infrastructure communication
Description: The main effect of car-to-infrastructure communication is to influence the

driver's behaviour in specific situations. To validate these effects a comparison of driver behaviour with and without system support is necessary. In most cases this comparison is only possible by the use of additional data from the vehicles. Another aim of car-to-infrastructure-communication systems is warning the driver of critical traffic situations. To measure the effects of such warnings in a direct way a pool of test drivers is needed. The reductions of critical situations indirectly decrease the number of accidents.

Impact: reduction of red light violations, reduction of critical conflict situations

Indicators: number of red light violations and warnings, speed, brake pedal activations, number of conflict situations

Measurement techniques: inductive loop detectors, red light cameras, vehicle data, pool of test drivers

3.3 Pollution reduction

Globally, the transport sector was responsible for about 61% of world oil consumption and about 28% of the total final energy consumption in 2007 [*18*]. The significance of transport's contribution to air pollution is well-acknowledged and discussed worldwide [*19*]. Modern cities face numerous challenges associated with the use of urban transport, such as road congestion, energy expenditure, and noise and air pollution, all of which degrade the quality of urban life. These, in turn, by diminishing the attractiveness of living and working at city centres, contribute to the development of unsustainable suburbs. Nevertheless, there is an increasing awareness that technology can contribute to the sustainable development of cities, with ITS potentially playing a key role. It is thus clear that quantifying required improvements in traffic management and ITS with respect to their impact on the environment is an important step towards the improvement of a city's quality and its degree of attractiveness.

3.3.1 Scope and applicability of pollution reduction

While the environmental impact of a traffic management policy or ITS application usually consists of several elements (e.g. noise, visual intrusion, impact on flora and fauna, etc.), this study focuses on the emission of pollutants from traffic, which has the highest effect on urban city life. Most large cities today carry out air quality monitoring, which makes a vast amount of data available. However, not all pollutants' emissions originate from traffic, and distinguishing the various pollution sources (industrial, vehicular, etc.) can be a very challenging task, often making the assessment of traffic-induced urban air pollution using measured air pollution difficult. On the other hand, there are reliable models, based on extensive and rigorous measurements (e.g. ARTEMIS and COPERT), which allow the assessment of vehicle fleet emissions as function of fleet composition, traffic activity, road data, fuel type etc. It is hence suggested here that available transport emission models be used for quantifying pollution reductions through specific urban traffic management and ITS applications.

The influence of traffic management and ITS on vehicle fleet emissions is reflected usually in their effect on vehicle traffic activity and demand. The former is mainly influenced by changes in traffic conditions, and possibly driving routes. Traffic conditions can be explained by the so-called typical driving cycle, presenting the typical speed of a vehicle as a function of driving time. The main parameters describing a vehicle's driving cycle are: average speed; maximum speed; number of stops; and maximum acceleration/deceleration. The parameters of driving routes, on the other hand, are length and topography (road gradients).

It is often the case that detailed data on a vehicle's traffic activity, and especially its driving cycle, are not available. As a contingency, emissions prediction models (e.g. ARTEMIS) enable a broader forecast of pollutant emissions based on limited available input data, such as vehicle average speed only and traffic general classification (stop-and-go, free flow, etc.), together with detailed data approach. Route data, however, is still required.

It should be noted that special conditions apply if a vehicle fleet includes a significant number of electric vehicles (EVs), as their influence on the total vehicle fleet emissions need to be assessed by different models, such as TEVeS. It is clear that EVs have zero tailpipe emissions, but they may affect urban air quality through an increase in emissions by electric utilities, due to the growth of electricity production. Sometimes a study about the potential of extensive introduction of EVs and its environmental and energy impact may be requested by cities. If the number of EVs in the vehicle fleet under consideration is very low, however, their influence on pollutants emissions is negligible and may be ignored.

3.3.2 Potential performance measures of pollution reduction

The driving cycle and route parameters, together with vehicle fleet data, are performance indicators that should be known and serve as inputs of the emissions prediction models. Therefore, their change as a result of a traffic management or ITS application will be reflected in an appropriate change in the vehicle fleet emissions. Of course, an assessment of the typical driving cycle (or vehicle average speed) before and after implementation of the application is required to ensure consistency.

The following is a list of the main performance measures that should be available in order to allow for an assessment of pollution reduction:

- Fleet data: The fleet composition by vehicle category and fuel type is required, along with the age distribution for each vehicle category. For each category, the total travelled distance within a specific timeframe is a crucial factor in emissions and needs to be known.
- Traffic conditions: The traffic volume by time of a day and by vehicle category is necessary to quantify pollution reduction, along with the number of stops and the average speed for each of the vehicle categories. It is also important to know the maximum allowed speed on each of the network's links concerned. Additionally, data on traffic conditions should also include the average passenger load and the average parking time by vehicle category.
- Route data: It is important to have knowledge of the average gradient and of the number of signalised junctions, as these play an important part in the emissions of pollutants from vehicles.

For the case where the urban vehicle fleet under consideration contains a significant number of EVs and their influence on emissions cannot be ignored, the following performance indicators should be available, in addition to the above, to enable an assessment of the impact of an application in terms of pollution reduction:

- Vehicle data: The weight, dimensions (height and width), passenger capacity, battery type, battery weight and maximum power of the electric motor of each EV in the fleet are required.
- Data on electricity production: The total amount of electricity generated and the total emissions due to electricity production are needed.

As concerns the fleet data, this is published by the National Statistics Office of each country. If public or goods transport is taken under consideration, the appropriate fleet data may be available from transport companies and public transport providers. The main potential sources of data on traffic conditions are: field data collection, carried out periodically; transport demand models; positioning systems; surveys; and enforcement cameras. Route data, on the other hand, may be provided by field data collection, positioning systems, and the city's traffic control centre. Of course, other data sources may be used as well.

As concerns data on EVs, this can be made available by local transport companies and/or vehicle manufacturers. Data on electricity production is published by the National or Regional Statistics Office or/and other responsible Governmental organisation in each country.

If a change in air pollution level at the considered area of interest is to be assessed, appropriate complicate atmospheric dispersion models must be used in addition to the emissions models. Atmospheric dispersion modelling is the mathematical simulation of how air pollutants disperse in the ambient atmosphere. It is performed with computer programs that solve the mathematical equations and algorithms which simulate the pollutant dispersion. The dispersion models are used to estimate or to predict the downwind concentration of air pollutants or toxins emitted from sources such as industrial plants, vehicular traffic or accidental chemical releases. The dispersion models vary depending on the mathematics used to develop the model, but all require the input of data that may include:

- Meteorological conditions such as: wind speed and direction, the amount of atmospheric turbulence, the ambient air temperature, cloud cover, solar radiation etc.
- Source term (the concentration or quantity of toxins in an emission or accidental release source term) and temperature of the material.
- Emissions or release parameters such as source location and height, type of source (i.e., fire, pool or vent stack) and exit velocity, exit temperature and mass flow rate or release rate.
- Terrain elevations at the source location and at the receptor location(s), such as nearby homes, schools, businesses and hospitals.
- The location, height and width of any obstructions (such as buildings or other structures) in the path of the emitted gaseous plume, surface roughness or the use of a more generic parameter “rural” or “city” terrain.

The atmospheric dispersion models are also known as atmospheric diffusion models, air dispersion models, air quality models or air pollution dispersion models. There is a wide variety of such models available, such as OSPM [*20*] and AERMOD [*21*].

3.4 Social inclusion and land use

Social inclusion is a field in which transport plays an important role as a supporting means for extending the action radius of individuals and helping then to undertake vital activities. Specific targeted traffic management policies and ITS applications have been developed for that purpose. Their individual effectiveness is measurable with the help of performance indicators that can be obtained by the operation of the systems themselves. Apart from this direct systems' output there is also a necessity to evaluate the systems' outcome on a more global level.

Land use, on the other hand, is a field that is not directly targeted by urban traffic management and ITS. Nevertheless, transport systems and land use patterns have a strong mutual influence on the each other's development, and it is an interesting task to investigate how urban traffic management and ITS can contribute to this interaction.

3.4.1 Scope and applicability of social inclusion and land use

The terms "social inclusion" and "land use" cover a variety of aspects and can be interpreted by different disciplines in different ways, according to their respective focus. This has direct implications as to the quantification of their impacts.

Social inclusion

Most sources defining social inclusion usually begin from the opposite, i.e. the definition of social exclusion. In the 2004 Joint Report by the European Commission and the Council on Social Inclusion, social exclusion is defined as "a process whereby certain individuals are pushed to the edge of society and prevented from participating fully by virtue of their poverty, or lack of basic competencies and lifelong learning opportunities, or as a result of discrimination" [*22*]. As such, the report defines social inclusion as the process which ensures that social exclusion is dealt with appropriately. For the purposes of this study, social inclusion through traffic management and ITS involves the facilitation of the participation of individuals in economic, social and cultural life.

Social inclusion is a complex issue which is influenced by numerous factors. The nature of these factors can be personal, geographical, institutional, economical, cultural, or political. In this context, transport is not an independent activity but rather a supporting action, which becomes necessary if the undertaking of vital activities is not possible within the individual's environment. It is with respect to these influencing factors that urban traffic management and ITS aim at improving social inclusion.

Land use

In general the term "land use" describes the nature, intensity and spatial distribution of different functions or human activities in a certain area of consideration. For the purposes of this study, the term "land use" additionally reflects the quantity of land consumption for the function of transport. There is a strong bi-directional interdependency between transport and land use patterns: changes in land use alter the spatial distribution and intensity of transport demand by rearranging travel routes, while changes in the transport supply enhance the accessibility of certain locations making them more attractive, which can lead to the decline of other locations. As concerns land consumption, the provision of transport infrastructure decreases the attractiveness of a location for a number of activities and makes the area used unavailable for other uses. Both processes develop over longer periods of time, and therefore combined strategies for land use and transport can only be planned and evaluated in the long-term.

The major influencing factors of the relationship of transport and land use are: access options (variety of modes with which the activity can be reached, availability of the modes in the desired time of the activity); travel time; reliability of the transport service (timetables and transfers in public transport, delays due to congestion and parking search); access time between transport and activity (walking distances from stations or parking spaces); access quality between transport and activity (user friendliness of access routes safety for road users, access barriers); capacity of the transport system (saturation of public transport vehicles, saturation of road infrastructure, availability of parking spaces); and other externalities. The role of urban traffic management and ITS in this context is complex, having a direct measurable impact in some cases but mostly contributing indirectly as part of an overall strategy to the sustainable development of land use.

3.4.2 Potential performance measures of social inclusion and land use

Social inclusion

There are several performance indicators for measuring the impacts of ITS on social inclusion. The data set should be chosen according to the goals of the respective application and availability of the data sources. Social inclusion is a personal issue and as such it is not possible to personally evaluate its impacts for each individual citizen. Moreover measuring social inclusion is a matter of approximation in terms of a spatial unit (i.e. a reference zone that can represent a house, a house-block or a borough), a target group (i.e. deprived, elderly, etc) or a specific activity. The results are average values showing a general trend rather than the exact situation of all individuals. For the calculation GIS can be a very useful and cost-efficient tool.

Indicators proposed for measuring social inclusion are:

- Average travel time to basic everyday activities (working, education, shopping, public services (e.g., hospitals, local government offices), leisure): this can be calculated by a spatial approach using a GIS database with population and other structural data. It can be also calculated through origin-destination models and calibrated by surveys including all modes of transport.

- Average cost for the transport to basic everyday activities: this can be calculated as an average value for local zones through GIS.
- Average access time to public transport: this can be calculated through a GIS database using data of the transport system (lines, stops, timetables) or by a survey of public transport users.
- Percent of population within “X” kilometres of basic everyday activities: this can be calculated by a spatial approach using a GIS database with population and other structural data. It can be also calculated through origin-destination models and calibrated by surveys including all modes of transport.
- Percent of population within “N” minutes from basic everyday activities: this can be calculated by a spatial approach using a GIS database with population and other structural data. It can be also calculated through origin-destination models and calibrated by surveys including all modes of transport.
- Percent of mobility-impaired population with access to public transport: this can be calculated by a spatial approach using a GIS database with population and other structural data. Since the exact locations of mobility impaired persons are not available to planning authorities, with the exception of very specific types of applications, average values for different types of impairment among the population can be used.
- Usage of public transport by mobility impaired road users: this can be calculated through representative surveys among public transport users. In some cases ITS applications aiming at assisting sensitive passenger groups can provide the necessary data.
- Number of trips per day for specific population groups: this can be calculated through representative surveys among the population. It can also be differentiated by different modes.

Land use

Due to the slow development rate of land use patterns, it is more appropriate to survey the land-use-related impacts of traffic management and ITS over long periods of time rather than to measure their performance with respect to it. Surveying the nature, quantity and distribution of human activities and other land functions is not only a basic means for monitoring the general economic and social (and ecological) development, but also a way of obtaining basic data for the evaluation of accessibility and social inclusion.

The basic indicators proposed are:

- Type and location of businesses, number of employees: these can be obtained by the local chamber of commerce, fiscal authorities or direct surveying of businesses. The number of employees may be available from social insurance authorities.

- Type and location of education facilities: this data is mostly already available at municipalities, but can also be surveyed at school authorities or the facilities themselves.
- Type and location of public services: these can be obtained from the responsible authorities or the facilities themselves.
- Location and access procedure of parking facilities, number of parking spaces: on-street parking can be measured directly via site inspections or be approximated by analysing topographical maps. Special parking facilities can be surveyed as all other businesses.
- Transport network, number and width of tracks/ lanes: the data is commonly available at planning authorities, but can also be either surveyed via site inspections or acquired from commercial digital network providers.

Data acquisition can be costly since the area that needs to be covered is large and the required detail very high. The update-cycles of the data, though, are fairly long, ranging from one to several years. In addition, this data is also required for a wide range of other planning and assessment procedures. The amortisation of the original cost needs thus to be put to perspective.

4 Key Performance Indicators

The specific performance measures described in the previous chapter usually refer to single applications and are addressed to experts. The political stakeholders, though, require a quantification of the added value generated by applications, which is described by a single indicator and is scalable, starting with a specific application at a single location and ranging up to the city-level, containing several applications. The quantification process introduced in this chapter includes the operative definition of KPIs for each of the four strategic themes of traffic management and ITS, as defined earlier, the means to control their parameters and the way to encompass several elements of each theme into single composite indices.

4.1 Indices for traffic efficiency

Each traffic efficiency performance measure presented in the previous chapter necessitates an operative definition from the perspective of the unit of measurement and levels of implementation. The following sections summarise the measures from these perspectives and create the basis for the definition of KPIs related to each category.

4.1.1 Index for mobility

A mobility KPI can be composed of different elements but essentially consists of the average travel time to different destinations in the highway and public transport networks expressed in time units, normalised by the distance to the destinations, and weighted by importance according to the goals and objectives of the application under consideration. The mobility index, I_{MOB}, may be formulated as follows:

$$I_{MOB} = w_{PV} \cdot \frac{1}{|R_{PV}|} \sum_{r \in R_{PV}}^{|R_{PV}|} \frac{ATT_{PV}^{r}}{D_r} + w_{PT} \cdot \frac{1}{|R_{PT}|} \sum_{r \in R_{PT}}^{|R_{PT}|} \frac{ATT_{PT}^{r}}{D_r} \qquad (1)$$

where:

r a route (specific OD pair) among a set of selected R_{PV} and R_{PT} on the road

	and public transport network respectively
ATT^{r}_{PV}	average travel time for route *r* on the road network
ATT^{r}_{PT}	average travel time route *r* on the public transport network
D_r	length of route *r*
w_{PV}	represents the weight of the travel time on the road network
w_{PT}	denotes the weight of the travel time in public transport

Within the average travel time assessment the above weights have to be assessed with values from 0 to 1, with the target sum set to 1. The spatial concern of the analysis influences this selection of routes (origins and destinations), as national and regional authorities are likely to have different needs than local authorities. In general, locations of public services relevant to the examined spatial concern, the main road network junctions according to the road hierarchy of the examined area, and the public transport terminals at the desired level of depth, should all be considered.

Moreover, the I_{MOB} KPI depends on the selection of the actual paths connecting the OD pairs. The paths selected influence travel time and accordingly the index, but logical considerations of the minimal travel time path in congested conditions across different projects or different time points allows a fair comparison of mobility conditions. The minimum travel time path guarantees the evaluation of mobility as a necessity, since travellers who do not choose the shortest path probably do not regard mobility as a necessity. The congested conditions ensure the “worst case scenario” condition of major interest, as free-flow conditions imply good mobility regardless of the implemented project or plan.

It should be noted that the units of I_{MOB} KPI are “travel time per km”, and that the dimensionless weights w_{PV} and w_{PT} have to be determined. This is documented in Section 4.5.

4.1.2 Index for reliability

A reliability index may be composed of different elements related to different modes of transport (e.g. public and private transport). Reliability deals mostly with system efficiency from the perspective of the suppliers who invest most of their efforts in reducing congestion hence providing better mobility.

Congestion may be defined as an increase in travel time (or reduction of speed) above a threshold or could be calculated based on available algorithms in the literature (such as [*23*]) based on data gathered from detectors, signal program information and static topological layout.

The congestion index which represents reliability could be calculated in different ways according to the acceptable methods of each transport agency. In order to allow a normalised benchmarking the congestion or reliability KPI is to be normalised so that he result remains within pre-defined limits, i.e. 0-1.

The reliability index, I_{REL}, calculated for links and for modes, may be defined as follows:

$$I_{REL} = 1 - \sum_{l \in L}^{|L|} \left(w_{PT} \cdot \sum_{pt \in PT}^{|PT|} w_l \frac{CT_{pt}^l}{T_{w_l}} + w_{PV} \cdot \sum_{pv \in PV}^{|PV|} w_l \frac{CT_{pv}^l}{T_{w_l}} \right) \quad (2)$$

where:

CT^l_x	total congestion duration on link l in the "x" network, where $x=pt \in PT$ for public transport and $x=pv \in PV$ for the road network
w_l	the relative importance of link l
w_{PT}	represents the weight of public transport
w_{PV}	represents the weight of private transport
T_{w_l}	represents the examined period in which congestion is monitored and to which w_l is attributed to

The reliability index is computed over all the monitored links as the total congestion ratio on public and private transport.

The weights w_{PT} and w_{PV} have to be defined with a continuous value between 0 and 1 and they are required to add up to 1; their value should reflect the importance of the mode, and as a result, they are usually city-wide weights.

The weight w_l should be defined according to the following points:

- The length of the link.
- Inner links relative importance – the weight of a link should reflect its general importance compared to other links (arterials are often more important than the local roads)
- Seasonal importance – the weight of a link should reflect its changing importance during the year (links near recreation areas are to be assigned with higher weights during holidays and weekends rather than on weekdays).

- Time importance – the weight of a link should reflect its changing importance during the day (a link that leads to the city is more important during the morning peak and of less importance during the evening peak).

4.1.3 Index for operational efficiency

An operational efficiency index may be composed of different elements that are already reported in the other indices, so its definition is not considered.

4.1.4 Index for system condition and performance

A system condition and performance KPI, I_{SC}, may be composed of different elements:

$$I_{SC} = w_{HW} \cdot SC_{HW} + w_{BT} \cdot SC_{BT} + w_{PTV} \cdot SC_{PTV} + w_{HWR} \cdot SC_{HWR} + w_{HWF} \cdot SC_{HWF} \quad (3)$$

where:

SC_{HW}	percentage of highway kilometres rated "good"
SC_{BT}	ratio of cycling infrastructure kilometres rated "good"
SC_{PTV}	percentage of public transport vehicles under a certain age threshold
SC_{HWR}	percentage of highway kilometres contracted for resurfacing
SC_{HWF}	percentage of highway kilometres funded for new projects
w_{HW}	weight of having a highway rated "good"
w_{BT}	weight of having cycle routes rated "good"
w_{PTV}	weight of the availability of public transport vehicles under a certain age
w_{HWR}	weight of contracting highway kilometres for resurfacing
w_{HWF}	weight of funding projects for new highway kilometres

4.2 Indices for traffic safety

Based on the safety-related performance measures introduced in the previous chapter, the operative definitions of KPIs are given here. Due to the nature of the subject of traffic safety, a global synthetic traffic safety KPI is also defined.

4.2.1 Index for traffic accidents

Traffic accidents are the most suitable form of evaluating the safety level of a transport network. The KPI for road traffic accidents takes into account the fact that each city has its own traffic and accident characteristics. As such, the importance of decreasing a specific type of accidents can be adjusted by using a higher weight w.

Because of different impact areas of traffic management and ITS applications, however, a differentiation between accidents at links and junctions is necessary. For links, the accidents index, $I_{ACD\text{-}L}$, is formulated as:

$$I_{ACD-L} = \sum_{l \in L}^{|L|} \left\{ w_l \cdot \sum_{se \in SE}^{|SE|} \left[w_{se} \cdot \sum_{m \in M}^{|M|} \left(w_m \cdot \frac{ACD_{l,se,m}}{DTV_l} \right) \right] \right\} \tag{4}$$

whereas for junctions, the respective index, $I_{ACD\text{-}J}$, is:

$$I_{ACD-J} = \sum_{j \in J}^{|J|} \left\{ w_j \cdot \sum_{se \in SE}^{|SE|} \left[w_{se} \cdot \sum_{m \in M}^{|M|} \left(w_m \cdot \frac{ACD_{j,se,m}}{DTV_j} \right) \right] \right\} \tag{5}$$

where:

w_{se}	weight representing the importance of reducing the number of casualties in accidents with a specific severity se from the set of possible severity levels SE (uninjured, slightly injured, seriously injured or killed)
w_m	weight representing the importance of reducing the number of casualties in accidents involving a specific traffic mode m from the set of possible traffic modes M (car, truck, bus, motorcycle, bicycle, pedestrian)
w_l	weight representing the importance of link l, among the set of links L of the network, in terms of safety
w_j	weight representing the importance of junction j, among the set of junctions J of the network, in terms of safety
$ACD_{l,se,m}$	number of casualties of severity se involving users of mode m on link l on an average day
$ACD_{j,se,m}$	number of casualties of severity se involving users of mode m at junction j on an average day
DTV_l	daily traffic volume on link l
DTV_j	daily traffic volume through junction j

The values of w_{se}, w_m, w_l and w_j can be varied between 0 and 1, but it should be ensured that the values of each importance item have to sum up to 1. The procedure for setting the weight values is given in Section 4.5.

4.2.2 Index for applications with a direct safety impact

The key feature of applications with direct safety impact is the number of system interventions. A large number of system interventions indicate a lower safety level due to the higher frequency of interactions between road users, leading to a critical situation or to an accident.

The traffic safety KPI for applications with direct safety impact, I_{DS}, is formulated as follows:

$$I_{DS} = \sum_{l \in L}^{|L|} w_l \cdot \frac{INTERV_l}{DTV_l} \qquad (6)$$

where:

$INTERV_l$ number of system interventions on link l on an average day
w_l weight representing the importance of link l in the network

The reference area of I_{DS} is a scalable part of the network as a sum of links. It can refer to areas ranging from a single network branch to a whole metropolitan area. The KPI can be calculated separately for different transport modes according to the goals of the applied measure. Interventions at junctions can either be separately calculated to a second index, or rather be distributed to the links attached to the respective junction. The dimension of the index is "actions/vehicle" and is summable and comparable with the other indices in this section.

The use of the number of interventions requires the implementation of an ITS solution that can provide such data. Systems concerning public transport regularly keep a record of interventions which is used by transport operators for their internal safety management. In the case of private transport applications, however, which often lack an appropriate data collection means, enforcement systems such as red light violation cameras can provide reliable data.

The weight w_l has a value ranging from 0 to 1 and represents the importance of link l in terms of safety. It can depend on sensitive activities surrounding the link, high accident rates on specific parts of the network etc.

4.2.3 Index for applications with an indirect safety impact in urban environments

This category of applications targets the reduction or avoidance of situations with various negative impacts including safety. Due to the very complex interaction of road users in urban environments it is difficult to assign safety impacts solely to traffic management and ITS applications. The validity of the results improves, though, if other major influences are taken into account.

The KPI accounting for such applications, $I_{IS\text{-}U}$, is defined as follows:

$$I_{IS-U} = \sum_{l \in L}^{|L|} w_l \cdot \frac{CS_l}{DTV_l} \tag{7}$$

where:

CS_l number of detected critical situation on link l on an average day
w_l weight representing the importance of link l in the network

The reference area of $I_{IS\text{-}U}$ is, as before, a scalable part of the network as a sum of links. Issues concerning junctions and different modes can be handled as described previously. The dimension of the index is “actions/vehicle”.

The use of the number of critical situations can be derived from the data provided by ITS applications and their sensors. Such situations can be the congestion or oversaturation of parking facilities, the cycle failure of traffic signals etc. The main challenge in this case is the comparability of the results due to different definitions of terms such as “congestion” and the different thresholds used in cities to identify a situation as “critical”. Apart of this consistency issue the data clarification has a significant role, especially in complex urban environments. Datasets of periods with major public works, extreme weather conditions and other unpredicted events should not be taken into consideration. The weight w_l has, as before, a value from 0 to 1.

4.2.4 Index for applications with an indirect safety impact on urban motorways

Urban-motorway-related traffic management and ITS applications with an indirect impact on safety aim at harmonising traffic and preventing congestion. Their main goal is the enhancement of the system’s performance. Their safety impact is mostly positive since unstable traffic conditions are a major cause of accidents. In some cases, though, a decrease of safety levels can occur, as technology-based enhancements come into conflict with fixed parts of the system, e.g. use of the hard shoulder at motorway intersections. Therefore the monitoring of safety levels in such cases is necessary.

The KPI accounting for such applications, $I_{IS\text{-}M}$, is defined as follows:

$$I_{IS-M} = \sum_{l \in L}^{|L|} w_l \cdot \frac{LOScrit_l}{DTV_l} \qquad (8)$$

where:

$LOScrit_l$	number of detected critical levels-of-service on link l on an average day; this can be substituted by the number of detected unstable traffic situations
w_l	weight representing the importance of link l in the network

The reference area of $I_{IS\text{-}M}$ is, as before, a scalable part of the network as a sum of links. Issues concerning junctions and different modes in this environment are negligible since the systems are applied along motorway sections. The dimension of the KPI is, again, "actions/vehicle".

The use of the number of critical levels-of-service can be derived from the data provided by ITS applications and their sensors. Such situations are unstable traffic conditions and congested situations. In spite of the less complex conditions on motorways compared to the urban road network, other boundary conditions should be taken to account during the data clarification. The installation of ITS often requires extensive work, and safety levels and critical situations in the time directly before the system's launch are influenced by this instance and should not be taken into consideration. As before, the weight w_l takes values from 0 to 1.

4.2.5 Index for car-to-infrastructure-communication-related applications

Car-to-infrastructure communication systems aim at the direct warning of dangerous situations and conflicts for drivers. Since such systems are still the subject of research and development and therefore not yet available as wide-area applications, the calculation of an index for their safety impact is theoretical with the present means of infrastructure operators.

For car-to-infrastructure communication systems the number of sent-out warning messages can be used as a significant figure for evaluating their safety impact. The proposed index, I_{C2I}, is defined as follows:

$$I_{C2I} = \sum_{l \in L}^{|L|} w_l \cdot \frac{WARN_l}{DTV_l} + \sum_{j \in J}^{|J|} w_j \cdot \frac{WARN_j}{DTV_j} \tag{9}$$

where:

$WARN_l$	number of sent-out driver warnings on link l on an average day, referring to a critical situation
$WARN_j$	number of sent-out driver warnings on junction j on an average day, referring to a critical situation
w_l	weight representing the importance of link l in the network
w_j	weight representing the importance of junction j in the network

The reference area of I_{C2I} is, as before, a scalable part of the network as a sum of links, a sum of junctions, or a combination of both, depending o the type of application in use. Therefore the index consists of two terms: one referring to links and one referring to junctions. The dimension of I_{C2I} is, again, “actions/vehicle”.

The number of warnings is provided by the infrastructure operator. These systems are either link-based warning of congestion, accidents or local weather conditions, or junction-based warning of possible conflicts or possible red light violations. The data availability is still a subject for further investigation in research projects, as issues of privacy and data security, as well as the sheer problem of handling such large amounts of data, must be taken into account. As before, the weights w_l and w_j take values from 0 to 1.

4.2.6 Total index of traffic safety

The KPIs described above refer mostly to the safety-related performance of a respective category of applications. This level of differentiation is important for experts and specialised political entities, because it provides an easy but still targeted assessment of the systems. Non-specialised political entities, on the other hand, need more general indicators, giving an overview of all systems in a larger area. Therefore a synthetic traffic safety KPI, I_{TS}, can be introduced summarising the specific indices.

$$I_{TS} = w_{ACD} \cdot \left(I_{ACD-L} + I_{ACD-J} \right) + w_{DS} \cdot I_{DS} + w_{IS-U} \cdot I_{IS-U} + w_{IS-M} \cdot I_{IS-M} + w_{C2I} \cdot I_{C2I} \tag{10}$$

where:

w_{ACD}	weight of the accident situation related to the evaluation of traffic safety
w_{DS}	weight of the importance of the group of applications with direct safety impact
$w_{IS\text{-}U}$	weight of the importance of the group of applications with indirect safety impact in urban environments
$w_{IS\text{-}M}$	weight of the importance of the group of applications with indirect safety impact on urban motorways
w_{C2I}	weight of the importance of the group of car-to-infrastructure-related applications

The reference area of I_{TS} is scalable to the extent that the indices it consists of are. At this level though, the resolution of the results is not very high. Especially the involvement of the accident indices includes a variety of influencing factors that may not be related to the application considered, e.g. the strictness of enforcement. A suitable spatial reference area is therefore wide and covers larger city sectors or network parts. Changes in the indicator's value over the years have always to be seen as considering all possible influences on safety.

4.3 Indices for pollution reduction

In order to quantify improvements resulting from the implementation of an urban traffic management or ITS solution in terms of their impact on the environment, an assessment of emissions levels by appropriate vehicle fleets before and after the application is required. Such an assessment is suggested to be carried out with the aid of available emissions simulation models, suited for different types of vehicle fleets under consideration.

4.3.1 Index for emissions from motor vehicles

A direct calculation of the energy demand can be carried out to assess transport energy and environmental impacts, including greenhouse gas (GHG) emissions. The energy demand in the road transport sector for a year y, ED_y, is calculated according to [*24*] as a product of several important driving factors, as shown by the following expression:

$$ED_y = \sum_{t \in T}^{|T|} \sum_{f \in F}^{|F|} VP_{t,f,y} \cdot FAVDT_{t,f,y} \cdot FAFE_{t,f,y}^{-1} \tag{11}$$

where

ED	the direct energy demand in MJ
y	the calendar year
t	vehicle type from the set of all vehicle types T
f	fuel type from the set of all fuel types F
$VP_{t,f,y}$	population of vehicle type *t* of fuel type *f* in year *y*
$FAVDT_{t,f,y}$	fleet average annual vehicle distance (in km) travelled of vehicle type *t* of fuel type *f* in year *y*
$FAFE_{t,f,y}$	fleet average on-road fuel economy (in km/MJ) of vehicle type *t* of fuel type *f* in year *y*. The term "fuel economy", which is introduced here, means distance in km that the vehicle can be driven per unit of energy consumed

$VP_{t,f,y}$ is calculated by the following expression:

$$VP_{t,f,y} = \sum_{v \in V}^{|V|} VRS_{t,f,y,v} = \sum_{v \in V}^{|V|} \left(Sales_{t,v} \cdot Surv_{t,y-v} \cdot FShare_{t,f,v} \right) \qquad (12)$$

where

v	vintage, i.e. the year when a vehicle is put into use, among the set of all vintage years V
$VRS_{t,f,y,v}$	remaining stock in the year *y* for vehicles of type *t* with fuel type *f* and vintage *v*
$Sales_{t,v}$	the number of new vehicles added for the vehicle type *t* in year *v*
$FShare_{t,f,v}$	share of fuel type *f* within the Sales for vehicle type *t* in the year *v*
$Surv_{t,y-v}$	the fraction of vehicles surviving after *y–v* years for vehicle type *t*.

For example, the remaining stock of petrol passenger cars sold in 2005 in the calendar year 2015 will be the Sales of passenger cars in 2005, the share of petrol vehicles within that sale and the fraction that survive 10 years (2015–2005).

$FAVDT_{t,f,y}$ is calculated by the following expression:

$$FAVDT_{t,f,y} = \sum_{v \in V}^{|V|} \frac{VP_{t,f,y,v} \cdot VDT_{t,f,v}}{VP_{t,f,y}} \qquad (13)$$

where $VDT_{t,f,v}$ (km) is the average annual vehicle distance travelled during the lifetime of vehicles of type *t*, fuel type *f* and vintage *v*.

$FAFE_{t,f,y}$ is calculated by the following expression:

$$FAFE_{t,f,y} = \sum_{v \in V}^{|V|} \frac{VP_{t,f,y,v} \cdot FE_{t,f,v}}{VP_{t,f,y}} \tag{14}$$

where $FE_{t,f,v}$ (km/MJ) is the average on-road fuel economy during the lifetime of vehicles of type *t* with fuel type *f* and vintage *v*. A vehicle's fuel economy is usually defined as the vehicle distance travelled per unit of energy (or fuel amount) consumed.

The parameters used in the above expressions can be borrowed from the corresponding literature. Fuel economy data, for example, can be mainly determined by using available data on fuel economy research, including [*25-27*]. The fuel economy of vehicles is improved gradually due to technology advances and the implementation of mandatory fuel economy regulations [*28*]. It has been assumed that the fuel economy for commercial vehicle types using petrol, diesel, compressed natural gas (CNG) or liquefied petroleum gas (LPG) will have an average annual improvement rate of 0.3% from 2007 to 2030. For other alternative vehicles and fuels, fuel economy data are set based on their advantages over conventional petrol and diesel vehicles [*29,30*]. The fuel economy of vehicles using bio-fuel and coal-based fuel is assumed to be the same as that of their substituted fuel during the scenario period. Demand for bio-diesel and coal-derived oil fuels must be estimated according to the governments' target and scenario settings. Petrol and diesel demand are calculated by assuming that all of the petrol and diesel vehicles used only pure petrol and diesel and then subtracting the amount substituted by the alternative fuels, respectively.

If the motor vehicles fleet under consideration is a property of any transport company, average fuel economy data are usually measured and available for single vehicles, selected fleet segments and the vehicle fleet as a whole. If a fleet of private passenger cars is considered, the appropriate average data on fuel economy may be gathered, in addition to the available information on fuel economy research, from the publications of national statistics offices.

The analysis given above is input in elaborated complex road emissions models, such as ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) [*31*]. Such models usually contain a fleet module that allows the user to setup the necessary fleet composition with an appropriate segmentation for a particular region or country, for one or several years. ARTEMIS, for example, the following fleet segmentation: firstly, the fleet is divided in various vehicle categories (passenger cars, two- or three-wheeled vehicles, heavy goods vehicles, etc.); each vehicle category is further divided to subcategories subdivided in "segments", which are vehicle groups of equal size and fuel types. These segments are further split into sub-segments according to different emissions concepts, etc.

An emissions factor module allows the access to the emissions factors database and calculates weighted emissions factors for particular traffic situations using the user specified fleet composition resulting from the fleet module. Finally, road emissions models contain an emissions module that calculates the overall emissions either on an aggregate basis for the particular country or region, or for a specific network. The emissions module refers to the user-specified description of the traffic activity and the emissions factors incorporated in the fleet and emissions factor modules respectively.

Scenario analysis on road transport vehicles enables to turn to the analysis of fuels and emissions including, GHG. The GHG emissions during the vehicle's operation stage are assumed to include CO_2 only (CO_2 is the dominant tailpipe GHG, though it is acknowledged that emissions of other GHG also occur). The GHG emissions rate E_{GHG} (g CO_2/MJ) for a certain fuel type may be derived using a carbon balance method, as follows. The heating value Q_{HV} for each specific fuel is known and usually measured in MJ/kg. So, the mass of fuel required to produce 1 MJ of energy can be easily calculated. The carbon content by mass C_{mass} for this fuel (%) may be assessed based on the known fuel type. Assuming that all of the carbon introduced with a fuel to the engine is fully oxidised to CO_2 an appropriate GHG emissions rate can be calculated as follows:

$$E_{GHG} = \frac{1000}{Q_{HV}} \cdot C_{mass} \cdot \frac{M_{CO2}}{M_C} \tag{15}$$

where M_{CO_2} = 44 g/mol is the molar weight of CO_2 and M_C = 12 g/mol is the molar weight of carbon. The GHG emissions rates for each fuel type are listed in Table 1 [*18*].

It should be noted that a speed limit of 80 km/h leads to a reduction of emissions of the order of 5–30% for NO_x and 5–25% for PM10 [*32*]. The limit with "strict enforcement" has been introduced in 2005 in zones of urban motorways in the Netherlands with an aim to reduce air pollution by NO_2 and PM10 along these motorways. Traffic data measured in Rotterdam and Amsterdam at the zones without and with speed management showed that traffic dynamics have been significantly reduced as a result of speed management with strict enforcement. Reduction of traffic dynamics results in more free-flowing traffic with relatively less NO_x and PM10 emissions compared to congested traffic, i.e., stop-and-go traffic.

Table 1: Carbon content by weight and GHG emission rate for each fuel type [*18*]

Fuel type	Heating value	Carbon content by mass	GHG emission rate
	MJ/kg	%	g CO_2/MJ
Petrol	42.5	84.6	73.2
Diesel	42.7	86.5	74.3
LPG	47.3	82	63.6
CNG	43.0	75	64.0
Bio-ethanol	27.0	52.2	70.9
Bio-diesel	38.0	77.3	74.6
Coal-derived methanol	19.7	37.5	69.8
Coal-derived oil	42.7	86.5	74.3

Requirements for fuel quality and after-treatment technology, while taking into consideration the reduction of emissions, have become more rigorous with time. For example, sulfur content in diesel fuels has been reduced from 1300 ppm for Euro 1 vehicles to 10 ppm only for Euro 5 modern vehicles. For an assessment of particular fuel effects on harmful emissions the corresponding regression equations are normally used. Such equations for the emissions calculation depending on fuel parameters were suggested in the ARTEMIS project [*33*], but their inclusion is omitted here, as they extend beyond the scope of this study.

4.3.2 Index for emissions from electric vehicles

Currently pure battery EVs have significantly higher energy efficiency than conventional petrol and diesel vehicles, while hybrid electric vehicle (HEV) technologies can improve fuel efficiency by 15%, 30% and 50% in the form of mild-, full- and plug in-form, respectively. As an essential assumption, the share of the distance travelled in electricity mode may be set to a potential of 40% for future plug-in capable vehicles. The drawback of present-day EV designs is a relatively low battery energy capacity and, correspondingly, a low driving range.

Table 2 presents the parameters data for the simplified classification of electric vehicles. It is important to evaluate the electric power consumed by the vehicle fleet, as this will make possible, in addition to the assessment of the energy impact of EVs, the estimation of their environmental influence. However this information varies from model to model and depends heavily on the driving conditions.

Table 2: Simplified classification for electric vehicles [*34*]

Size	Capacity (kWh)	Range (km)	Consumption (kWh/100 km)
Cars			
Small	10	100	10.00
Mid-size	20	130	15.38
Large	35	180	19.44
Light duty vehicles	20	100	20.00

In the cases where a vehicle fleet is based on EVs and the vehicle driving behaviour at different traffic conditions is known or may be assessed, some available simulation tools, such as the TEVeS model developed within the framework of the CYBERCAR, CYBERMOVE and CITYMOBIL European-Commission-funded projects, can be used to assess the energy and environmental impacts of traffic management and ITS.

In the TEVeS model, The performance of electric vehicles can be evaluated with a theoretical model based on the relations between the electrical motor efficiency and load factor $P = P_{mot}/P_{mot.max}$ (here: P_{mot} – motor power, $P_{mot.max}$ – maximal motor power), and between the battery/ies efficiency/ies and the depth of discharge (DOD) for driving and regenerative braking (RB) operation modes; this can be seen in Figure 2 and Figure 3 [*35*]. These analytical relations have been derived in previous research, and their form and set of required input parameters are based on published literature. Known mechanical equations and expressions for the heat losses in the electrical circuit have been used too. The latter relation involves the load factor as an independent variable and is obtained based on the known electro-dynamic relations. The model does not presuppose using large data files for the efficiencies of the vehicle motor η_{mot}, of the transmission η_{tr}, of the inverter η_i, of the battery η_{bat}, and for driving and RB operational conditions of the engine. The model uses empirical equations for the vehicle motor and battery efficiencies.

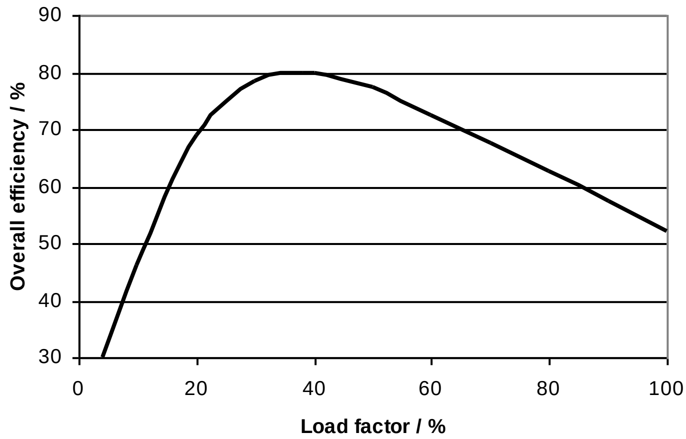

Figure 2: Load factor effect on the overall electrical motor efficiency

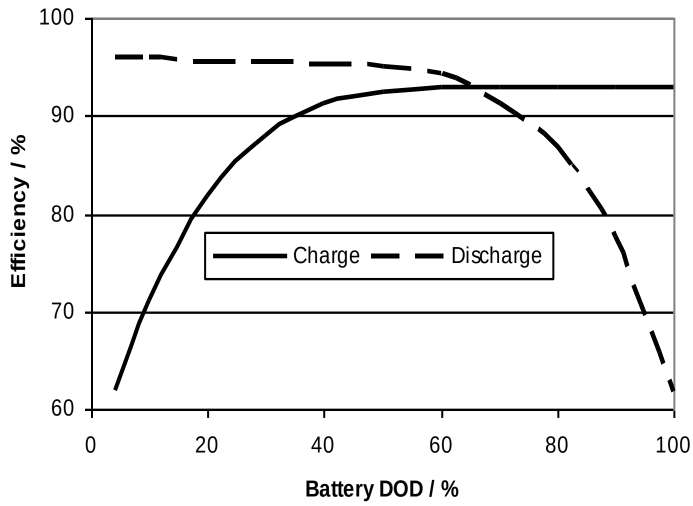

Figure 3: Battery efficiency dependence on the DOD

A number of assumptions are adopted. It is supposed that the motor efficiency dependence on the load factor P (for driving and regenerating modes) has a form similar to that shown in Figure 2. This assumption is justified, since in the discussed case the electric motor is only part of the propulsion system and its efficiency does not reflect heat losses (which cause a slope of the $\eta(P)$ curve at high loads). These heat losses occur mainly in batteries. Transmission efficiencies $\eta_{tr.dr}$ and $\eta_{tr.reg}$, under driving and RB operation conditions respectively, and those of the inverter $\eta_{i.dr}$ and $\eta_{i.reg}$, are constant. An effective Ohm load resistance is used in the calculations of heat losses in the electrical circuit of the vehicle. The mechanical equations are taken from [*36,37*], and the approach suggested in [*37*] is used to account for the effect of the wind direction and speed on the aerodynamic drag coefficient. The vehicle's total efficiency at loads close to a maximal motor power is assumed to be constant (near 0.5). The vehicle's route is divided into segments, and on each segment the vehicle's speed and/or acceleration and the road gradient are constant.

The environmental impact of vehicle fleets based on EVs may be assessed by using the following algorithm:

- Derivation of data on total emissions EM_{tot} released in the considered region/country in the process of electricity production;
- Derivation of data on total electrical energy EE supply in the considered region/country;
- Calculation of specific emission SEM values per unit of electrical energy consumed:

$$SEM = \frac{EM_{tot}}{EE} \tag{16}$$

- Calculation of emissions per pass-km released due to EVs activity:

$$EM_i = E_{sp} \cdot SEM_i \tag{17}$$

where i is a pollutant type, such as CO, NO_x, PM, etc.

4.3.3 Total index of pollution reduction

The results of emissions values produced by a vehicle fleet before or after implementation of traffic management or ITS measures may be further processed in order to provide a so called total emissions indicator, which will act as a synthetic index of pollution reduction. This can be used as a tool for an integral assessment of environmental impact resulting from the implementation of various solutions.

It is suggested to define the pollution reduction KPI, I_{PR}, as a sum of normalised emissions values of different pollutants. It can be calculated by using the following formula:

$$I_{PR} = c_{cor} \sum \frac{EM_i}{TLV_i} \tag{18}$$

where

EM_i emission value of pollutant i, [g/km] or [g/pass-km];

TLV_i threshold limit value for pollutant i, [mg/m^3];

c_{cor} correction coefficient aimed at providing dimensionless value of I_{PR}.

The values of TLV_i can be taken, for example, from appropriate sources in the literature, such as the ones shown in Table 3.

Table 3: TLVs for selected pollutants [*38*]

Pollutant i	TLV_i [mg/m^3]
Nitrogen dioxide NO_2 (for normalisation of NO_x emissions)	5.6
Carbon monoxide CO	28.5
Hexane C_6H_{14} (for normalisation of HC emissions)	176
Particulates matter PM	0.05

4.4 Indices for social inclusion and land use

Following the identification of potential measures in the previous chapter, performance indices for social inclusion and land use are defined here.

4.4.1 Index for accessibility

The basic contribution of traffic management and ITS to social inclusion is the provision of access to basic activities of everyday life. The accessibility of activities can be considered solely at a spatial level calculating the opportunities for a specific activity that can be reached from a certain zone by the means of certain transport mode. This method uses only predefined spatial zones, their respective structural data and the quality of the transport system. The population of the zones and their actual travel demand matrix are not necessary for this calculation.

The accessibility from location/zone z_1 to activity act in each zone $z_2 \in Z$, where Z is the set of all other zones, $ACC_{z_1,act}$, is defined as:

$$ACC_{z_1,act} = \sum_{z_2 \in Z}^{|Z|} B_{z_2} \cdot a_{z_2,act} \qquad (19)$$

where:

$a_{z_2,act}$ Opportunities for activity act in zone z_2

B_{z_2} A binary value, equalling 1 if zone z_2 is within a predetermined threshold (e.g. a certain distance) and 0 otherwise

Accessibility represents the sum of opportunities for an activity act in all zones that are located at a certain distance from the zone of origin z_1. The reference area is thus the location or zone of origin. The necessary data are mostly provided by GIS of the planning authorities since they usually already possess detailed information on land use structures and the transport system. The calculation of the social accessibility can be done as an additional task in the GIS application.

The dimension of $ACC_{z_1,act}$ is "number of activities", and for specific case studies it may also be used as a performance index. However, for the complete assessment of social accessibility the various $ACC_{z_1,act}$ values for different origin zones and activities are cumulated into a combined KPI, representing the average accessibility to all activities (set ACT) from all zones of origin (set Z). The resulting average accessibility KPI, I_{ACC}, is defined as follows:

$$I_{ACC} = \sum_{z_1 \in Z}^{|Z|} \sum_{act \in ACT}^{|ACT|} \frac{w_{act} \cdot ACC_{z_1,act}}{|Z|} \tag{20}$$

where:

w_{act} weight representing the importance of activity act

$|Z|$ number of elements in the set of zones Z, i.e. number of zones

The dimension of I_{ACC} is "number of activities". The weight w_{act} represents the weight of activity act among the set of all considered activities ACT, and takes values between 0 and 1, with the sum of all weights under consideration being 1.

4.4.2 Index for social mobility of special groups

If special population groups are targeted, e.g. people with disabilities, elderly and deprived, then an important objective of traffic management and ITS applications with respect to social inclusion is to enhance their mobility by providing enough options. The objective is termed "social mobility" (so as to be distinguished from the mobility term of traffic efficiency).

A system of ideal inclusion would enable all citizens to have the same mobility patterns on average. Consequently, the average daily trips of a special population group g would equal the average of the whole population. The mobility ratios of different population groups can hence express the extent to which this is happening. The social mobility of special group g for all activities (set ACT), $SMOB_g$, is defined as:

$$SMOB_g = \sum_{act \in ACT}^{|ACT|} w_{act} \cdot \frac{ADT_{g,act}}{ADT_{tot,act}} \qquad (21)$$

where:

$ADT_{g,act}$	average number of trips of special population group g for activity act
$ADT_{tot,act}$	average number of trips of the whole population for activity act
w_{act}	weight representing the importance of activity act

The social mobility represents the comparison of the mobility patterns of the targeted population group to those of the total population. The results are reliable for target groups containing a wide range of age categories that could or should have the same activity structure as a representative cross-section of the population. If, however, a very narrow segment of the population, such as a single age category, is chosen, the comparison is not possible since the activity patterns differ from the average.

The reference area of $SMOB_g$ is a geographical space, in which social inclusion is to be assessed. Acquiring the necessary data for the calculation requires surveys of the mobility behaviour. Such surveys are frequently undertaken in some countries; nevertheless, data availability is insufficient in many cases. ITS applications targeting inclusion can provide the necessary data about the mobility of their target groups.

$SMOB_g$ is dimensionless taking values from 0 to 1 with 1 as the “ideal” result, and for specific case studies it may also be used as a performance index. However, for the complete assessment of social mobility the various $SMOB_g$ values for different population groups are cumulated into a combined KPI, representing the average social mobility of all special population groups (set G). The resulting average social mobility KPI, I_{SMOB}, is defined as follows:

$$I_{SMOB} = \sum_{g \in G}^{|G|} w_g \cdot SMOB_g \tag{22}$$

where

w_g weight representing the importance of special group g

In the same way as $SMOB_g$, I_{SMOB} is dimensionless taking values from 0 to 1 with 1 as the "ideal" result. The weights w_{act} and w_g represent the relative importance of activity act among all considered activities (set ACT), and of special population group g among all considered special population groups (set G), respectively. They take values between 0 and 1, with the sum of all weights under consideration being 1.

4.4.3 Index for public transport usage of special groups

Several traffic management and ITS applications target the empowerment of special population groups, and particularly the mobility-impaired, to use public transport. A similar benchmark as in the previous section, comparing the usage of public transport by special groups with the average of the population is not applicable in this case due to the different modal choice patterns of people with mobility impairments. A practical way to assess this modal choice behaviour is the comparison of the potential public transport demand to the realised demand.

The public transport usage of special group g, PTU_g, is defined as follows:

$$PTU_g = \frac{PTT_{g,real}}{PTT_{g,pot}} \tag{23}$$

where

$PTT_{g,real}$ number of public transport users of special group g
$PTT_{g,pot}$ number of people of special group g with access to public transport

PTU_g represents the percentage of people of special population group g, that actually use public transport, to the total of group g that has access to public transport services. The reference area of the indicator is, as in the social mobility, a geographical space, which can contain the whole city territory but can also be narrowed down to the area in which the targeted applications are deployed.

$PTT_{g,real}$ can be obtained by two methods. If the user group of the application is distinct, then the application delivers the necessary data. This is the case mostly for personalised ITS systems, such as personal mobility assistants. If the actual circle of users is unknown, however, the necessary data can be acquired by extensive passenger surveys. The value of $PTT_{g,pot}$ can be approximated through GIS databases. Since it is impossible to know the exact location and demand pattern of all people of group g, their percentage in the population can be used to calculate their theoretical distribution in the area concerned.

In the special case of mobility-impaired users, if the data concerning the public transport system are attributed with barrier information, then the number of potential passengers with access to a barrier-free public transport system can be elaborated and used as the value of $PTT_{g,pot}$. While there is uncertainty within this approach, since the OD-matrix of the potential passengers is not known and a non-use of public transport can be the result of lacking suitable connections rather than barriers, it can still be used in the absence of a more exact approach given the means of public authorities.

PTU_g is dimensionless taking values from 0 to 1, and for specific case studies it may also be used as a performance index. However, for the complete assessment of public transport usage by special groups, the various PTU_g values for different population groups can be cumulated into a combined KPI, representing the average public transport usage of all special population groups (set G). The resulting average public transport usage KPI, I_{PTU}, is defined as follows:

$$I_{PTU} = \sum_{g \in G}^{|G|} w_g \cdot PTU_g \qquad (24)$$

where

w_g weight representing the importance of special group g

It should be noted that even though I_{PTU} (and PTU_g) is dimensionless, it cannot be combined with the social mobility KPI, as they refer to different sizes of total population.

4.4.4 Index for land use

The main difficulty in assessing the additional value generated by traffic management and

ITS with respect to land use is the large difference in the reaction times of both elements. Traffic management and ITS aim at short term improvements of their targeted aspects, whereas the land has long-term adaptation times to its boundary conditions. Some applications, though, have the aim to enhance existing infrastructure and so to prevent the building up of new infrastructure. These effects can have a mid-term impact on land consumption by the transport system. The index of the proportionality of the covered area is used to demonstrate these effects at a macroscopic level.

Despite the unclear data availability situation, a direct calculation of land consumption is feasible through GIS. Namely, defining the relative growth in vehicle-kilometres over five years, ΔVKM_5, as

$$\Delta VKM_5 = \frac{VKM_i - VKM_{i-5}}{VKM_{i-5}} \tag{25}$$

where VKM_i and $VKM_{i\text{-}5}$ are the total vehicle kilometres in years i and i-5 respectively, and the relative growth of the total covered area by transport infrastructure over five years, ΔTCA_5, as

$$\Delta TCA_5 = \frac{TCA_i - TCA_{i-5}}{TCA_{i-5}} \tag{26}$$

where TCA_i and $TCA_{i\text{-}5}$ are the total vehicle kilometres in years i and i-5 respectively, the land use KPI of proportionality of area covered by transport, I_{PCA}, can be defined as

$$I_{PCA} = \frac{\Delta VKM_5}{\Delta TCA_5} \tag{27}$$

The relative growths ΔVKM_5 and ΔTCA_5 can take any value, but would be typically expected to range between -1 and 1. Negative values indicate a decrease, positive indicate an increase and zero indicates stagnation in the growth of the respective parameter. Their ratio I_{PCA} can have positive values, indicating that traffic volume and total covered area have the same development trends, but also negative values, indicating that the trends of the two indicators are contrary. The reference area of the indicator is a geographical space which is scalable according to the needs of the assessment. The data for its calculation are macroscopic statistical data that are available from public authorities. ITS can contribute to the improvement of data availability concerning traffic volumes. The calculation of the area covered with transport infrastructure is possible by using functionalities of GIS.

This approach has a limitation to extreme scenarios. Large increases in traffic volume while investments in infrastructure stagnate or are declining cannot be simply explained by the capacity gain due to a traffic management or ITS application. It can also be an indicator for lack of actions to meet increasing traffic problems. For the correct interpretation of this KPI's values a broad assessment with data from several cities is necessary.

4.5 Determination of weighting factors

In order to calculate the weights required in almost all of the indices, an expert-based method is suggested as a methodological approach able to achieve a two-fold purpose: (i) providing a methodology to construct a performance measure that may be tailored to any transport plan or program, and (ii) providing a methodology that may be transferred across projects, provided that suitable experts are selected. The selected expert-based technique is the Delphi method [*39,40*].

4.5.1 Survey construction

The Delphi method is based on a series of questionnaires with a controlled feedback for the purpose of reaching a relatively narrow range of future images by comparing opinions in an iterative fashion. Specifically, this method is based on a series of questionnaires with the purpose of weighing the "between" and "within" components of each performance index. The process may result in either a consensus or several different opinions; a single solution is not mandatory.

Despite some criticisms in the early literature [*41*], the Delphi technique is still considered a valid method for judgmental forecasting [*42,43*]. Some drawbacks of the Delphi method described in the literature are: sensitivity to the clarity and phrasing of the questions; difficulty in evaluating the respondents' level of expertise; and dependency on selecting experts who must be properly informed in the appropriate area [*44*]. Moreover, the process of several rounds of questionnaires can be fairly time-demanding.

The proposed methodology uses complementary rounds instead of the traditionally applied repetitive rounds. The first round is intended to collect assessments about the relative importance of the different aspects considered in the KPIs by proposing an evaluation of the elements of each equation.

Each expert is expected to assign to the mentioned weights a value between 0 and 1, with the target weight sum set at 1. This definition allows dealing with extreme cases in which only one aspect is relevant to one plan or project (thus only one weight is equal to 1), and generic cases in which every aspect is important to one plan or project (thus all the weights are greater than 0).

The second round is an attempt to gather information with respect to specific aspects within the components of the individual indices constituting the KPIs. In this sense, this round verifies that the answers to the first round are consistent with the experts' vision. In fact, it is expected that experts who do not attribute relevance to one aspect will not assign weight to specific weights within that aspect. Not meeting this simple condition raises concerns about the expert's answers being controversial.

Several questionnaires constitute this second round. It should be noted that the input should be proposed by the stakeholder (e.g., national or local authority) according to the application that they would like to evaluate. An alternative possibility may be to leave the selection of these elements to the experts, though the number of alternatives is likely to be high in this case. For each element, the experts have to assign a value from 0 to 1 to the named weights, with the required sum set at 1.

Experts should be identified across the transport sector and other relevant fields, such as regional planning, economy, environment and geography, according to the objectives, goals and geographical scope of the examined plans and projects. It should be noted that the selection of the experts is a crucial factor in the Delphi method and can influence the results [*45,46*].

4.5.2 Data analysis

Data analysis of the two Delphi rounds should include frequency analysis and non-parametric statistical tests [*47*]. These descriptive statistical methods may be used because of the possibly small number of experts and the relatively detailed questionnaires.

The experts' responses in the first Delphi round may be analysed with a frequency analysis of the probabilities for weights between the components of the index. In the frequency analysis one expert may assign to a weight a value completely different from the others, necessitating a decision on the cause for this gap. Statistical measures may provide the mean value for the weights and their standard deviation: weights with low value of standard deviation are preferred, as these signify that experts agree on their definition, and accordingly the mean value of these weights may be taken for the calculation of the performance index; weights with high value of standard deviation are less preferred, as they signify that experts disagree on their definition, and accordingly the mean value does not represent the actual value of the weight, necessitating further consideration. In this respect, non-parametric statistical tests may help determining whether different experts (for example from different fields) provide different assessments with respect to the weights (for example Kruskal Wallis tests).

The experts' responses in the second Delphi round may be examined using the same techniques. In both rounds, the sum of the weights has to be equal to 1 and the assignment of the values may require some adjustments on the basis of the responses obtained.

5 Conclusions

Performance measures and indices allow for the comparison of the performance of different urban traffic management and ITS applications in future scenarios and for the evaluation of the performance of the application at different scenarios over time. As the implementation of an urban traffic management or ITS solution has certain goals and objectives, the selection of data and methods allows generating performance measures and indices and applying them in a process of alternatives' evaluation, decision-making support and ongoing monitoring.

Accordingly, transport planning and project design should be performance-based in order to achieve the desired goals and objectives, and consequently improve transport systems. Performance measures should be objectively related to the goals and the objectives specified, should be classified according to dimensions or market segments, should be either a combination of various measures into a single indicator or a single measure, and should be customer-oriented. Accordingly, the development of performance measures involves the definition of goals and objectives, the specification of the dimensions of performance measures, the identification of the selection criteria for performance measures, and the description of data requirements and analytical tools for monitoring system performance.

With this in mind, the present report presented a new performance measurement framework for urban traffic management and ITS with respect to four strategic themes: traffic efficiency, traffic safety, pollution reduction, and social inclusion and land use. A number of KPIs were defined for each of the four themes, and operative definitions of the new indices were given, along with explanations as to their application. Careful consideration was given to data availability, with potential data sources being identified for each of the KPIs developed.

The proposed methodological evaluation framework is simple to be applied and elaborated for two main reasons: (i) national and local authorities can apply the KPIs without great difficulty and with resources readily available when commercial software and devices are used, and (ii) municipalities can market the results to the general public, who in turn can easily understand them in simple terms. The indices help simplifying the work of the engineers of the national and local authorities without requiring general knowledge of the subject and marketing the results to the public opinion with possible policy implementations.

The next step from this study includes the validation of the developed methodology through its application to specific traffic management and ITS case studies of European cities, as part of the final task of CONDUITS. Specific case studies from the cities of Paris, Rome and Barcelona will be selected and evaluated, in order in order to draw conclusions with respect to the measures as to their usefulness and applicability.

References

[*1*] Reed, M. F., Luettich, R. A., Lamm, L. P., and Humphrey, T. F. *Measuring state transportation program performance*. 357, NCHRP report, 1993.

[*2*] Poister, T. H. *Performance measurement in state Departments of Transportation*. 238, Synthesis of highway practice, 1997.

[*3*] Cambridge Systematics, Inc. *A guidebook for performance-based transportation planning*. 446, NCHRP report, 2000.

[*4*] Cambridge Systematics Inc., PB Consult Inc., and System Metrics Group. *Analytical tools for asset management*. 545, NCHRP report, 2005.

[*5*] Municipality of Tel Aviv-Yafo. *Tel Aviv-Yafo Strategic Plan*. 2005.

[*6*] MDOT Transportation Commission. *MI Transportation Plan:Moving Michigan Forward, 2005-2030 State Long-Range Transportation Plan*. 2007.

[*7*] Southern California Association of Governments. *2008 Regional Transportation Plan: Making the connections*. 2008.

[*8*] Missoula Office of Planning and Grants, the Non-Motorized Transportation Steering Committee. *2001 Non-Motorized Transportation Plan - Amendment to the Missoula Urban Comprehensive Plan*. 2001.

[*9*] Pima Association of Governments. *Mobility matters throughout our lives - 2040 Regional Transportation Plan*. 2010.

[*10*] Wilbur Smith Associates. *West Virginia Multi-Modal State-wide Transportation Plan*. 2010.

[*11*] Washington State Transportation Commission, Washington State Department of Transportation. *Washington Transportation Plan 2007-2026*. 2006.

[*12*] Ohio Department of Transportation/Division of Planning/Office of Urban and Corridor Planning. *ACCESS OHIO 2004-2030 - Ohio State-wide Transportation Plan*. 2004.

[*13*] European Commission. *White paper - 'European transport policy for 2010: time to decide'*. 2001.

[*14*] European Commission. *White paper - Roadmap to a single European Transport Area - Towards a competitive and resource efficient transport system*. 2011.

[*15*] Zhang, Y, Qin, X, Dong, S and Ran, B. Daily O-D matrix estimation using cellular probe data. *89th Annual Meeting of the Transportation Research Board*, 2010.

[*16*] Sohn, K and Kim, D. Dynamic origin–destination flow estimation using cellular communication system. *IEEE Transactions on Vehicular Technology*, Vol. 57, 2008, pp. 2703-2713.

[*17*] Elvik R, Høye A, Vaa T and Sørensen M. *The handbook of road safety measures*, Emerald Group Publishing Ltd, Bingley, UK, 2009.

[*18*] Ou, XM, Zhang, XL and Chang, SY. Scenario analysis on alternative fuel/vehicle for China's future road transport: Life-cycle energy demand and GHG emissions. *Energy Policy*, Vol. 38, 2010, pp. 3943-3956.

[*19*] OECD/International Energy Agency (IEA). *Key World Energy Statistics 2009*. 2009.

[*20*] Wang, G, van den Bosch, FHM and Kuffer, M. Modeling urban traffic air pollution dispersion. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXVII, 2008

[*21*] Cimorelli, A. J., Perry, S. G., Venkatram, A., Weil, J. C., Paine, R. J., and Wilson, R. B. *AERMOD: Description of Model Formulation*. EPA-454/R-03-004, Research Triangle Park (NC): United States Environmental Protection Agency (US), 2004.

[*22*] European Council. *Joint Report by the Commission and the Council on Social Inclusion*. 2004.

[*23*] Henry, XL, Xinkai, W, Wenteng, M and Heng, H. Real-time queue length estimation for congested signalized intersections. *Transportation Research C*, Vol. 17, 2009, pp. 412-

427.

[*24*] Yan, XY and Crookes, RJ. Reduction potentials of energy demand and GHG emissions in China's road transport sector. *Energy Policy*, Vol. 37, 2009, pp. 658-668.

[*25*] Barnitt, R. and Chandler, K. *New York City transit hybrid and CNG transit buses – final evaluation results*. NREL/TP-540-40125, Golden (CO): National Renewable Energy Laboratory (US) report, 2006.

[*26*] Davis SC and Diegel SW. *Transportation Energy Data Book*, Oak Ridge National Laboratory, 2009.

[*27*] Yan, XY and Crookes, RJ. Energy demand and emissions from road transportation vehicles in China. *Progress in Energy and Combustion Science*, Vol. 36, 2010, pp. 651-676.

[*28*] People's Republic of China - General Administration of Quality Supervision, Inspection and Quarantine AQSIQ Standardization Administration SAC. *Limits of fuel consumption for light duty commercial vehicles*. GB 1997-2007, National Standard of the PRC, 2007.

[*29*] China Automotive Energy Research Center. *Annual report of China automotive energy research*. Tsinghua University, 2009.

[*30*] Energy Research Institute. *Scenario research on low carbon development by 2050 in China*. NDRC, 2009.

[*31*] Boulter, P. and McCrae, I. *Assessment and reliability of transport emission models and inventory systems*. Deliverable D15, ARTEMIS project, 2007.

[*32*] Keuken, MP, Jonkers, S, Wilmink, IR and Wesseling, J. Reduced NOx and PM10 emissions on urban motorways in the Netherlands by 80km/h speed management. *The Science of the Total Environment*, Vol. 408, 2010, pp. 2517-2526.

[*33*] Zvirin, Y., Tartakovsky, L., Aronov, B., Veinblat, M., and Gutman, M. *Fuel effects on emissions by heavy duty vehicles*. WP 400, ARTEMIS project report, 2003.

[*34*] Perujo, A. and Ciuffo, B. *The introduction of electric vehicles in the private fleet: Potential impact on the electric supply system and on the environment. A case study for the Province of Milan, Italy.* Report of the European Commission-Joint Research

Center, Institute for Environment and Sustainability, 2010.

[35] Nicol BD and Rand DAJ. *Power sources for electric vehicles*, Elsevier, 1984.

[36] Robert Bosch GmbH. *Automotive handbook*, John Wiley & Sons Ltd, 2007.

[37] Cole, G. H. *SIMPLEV: A simple electric vehicle simulation program – version 2.0*. DOE/ID-10293-2, Idaho National Laboratory report, 1993.

[38] American Conference of Governmental Industrial Hygienists. *2010 Threshold Limit Values and Biological Exposure Indices*. 2010.

[39] Linstone HA and Turrof M. *The Delphi method - Techniques and applications*, Addison-Wesley Publishing Company, 1975.

[40] Nijkamp P, Rienstra S and Vleugel J. *Transportation planning and the future*, Wiley & Sons, Chichester, UK, 1998.

[41] Hill, KQ and Fowles, J. The methodological worth of the Delphi forecasting technique. *Technological Forecasting and Social Change*, Vol. 7, 1975, pp. 179-192.

[42] Richey, JS, Mar, BW and Horner, RR. The Delphi technique in environmental assessment. *Journal of Environmental Management*, Vol. 21, 1985, pp. 135-146.

[43] Tolley, R. The future of walking in Europe: A Delphi project to identify expert opinion on future walking scenarios. *Transport Policy*, Vol. 8, 2001, pp. 307-315.

[44] Rowe, G and Wright, G. Expert opinion in forecasting: the role of the Delphi technique. In *Principles of forecasting: A handbook for researchers and practitioners*, Kluwer Academic Publishers, 2001.

[45] Preble, JF. The selection of Delphi panels for strategic planning purposes. *Strategic Management Journal*, Vol. 5, 1984, pp. 157-170.

[46] Taylor, R and Judd, L. Delphi method applied to tourism. In *Tourism marketing and management handbook*, Prentice Hall, New York, USA, 1989.

[47] Sheskin DJ. *Handbook of parametric and nonparametric statistical procedures*, CRC Press, 1997.