Guidelines for Assessing the Effects of ITS on CO_2 Emissions

- International Joint Report -

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Introduction: The Aim of the Report

1. Background

This report is jointly written by three parties of experts; a party in Japan who are involved in the research project "Energy ITS" (short for "Development of Energy-saving ITS Technology" project) under the support from Ministry of Economy, Trade and Industry (METI) of Japan, a party in Europe who are involved in the research project "ECOSTAND" under the support from Directorate General Information Society and Media (DG INFSO replace by DG CONNECT at present) of European Commission, and a party of University of California in United States. The two projects, the "Energy ITS" and the "ECOSTAND", were funded and started based on the Cooperation Agreement between DG INFSO of European Commission and METI of Japan in March 2008.

The two projects both included the aim to establish a common assessment methodology of the impact of ITS for energy efficiency issues and international standardization of the methodology; this aim is also included in the Cooperation Agreement. The two parties invited the researchers in University of California for the international cooperation and they agreed to join the cooperative activities.

This report is considered as the foundation of the methodology requirements and standardization as a cooperative production of the three parties at the end of the project "Energy ITS" in March 2013.

2. Basic principles

This report does not intend to recommend one specific impact assessment method, but only to describe the approaches being adopted by the three parties. In particular, it sets out the areas of agreement which have been established in relation to methods for the assessment of the impact of ITS on energy efficiency.

The impact assessment methods should properly describe the impact of any ITS measures on traffic flow. The methods should properly describe the effects of the above mentioned traffic flow impact on energy consumption, which can be converted easily to CO_2 emissions. The meaning of 'properly describe' can be understood to be sensitive enough to ensure that the impact or effects of ITS applications are not obscured by errors of estimation. When variables are thought as independent one another, they should be described independently in the methods, unless the independency is not clear. The methods proposed for measuring energy consumption should be easy to understand, highly transparent, objective and verifiable. This implies that the same results may be easily reproduced by different parties as long as the methods are applied correctly.

3. Important agreements

To satisfy the above basic principles, there is a common understanding that the methodology should be composed of two major model groups:

1) Traffic Simulation (TS) Models: i.e. network traffic flow simulators, and

2) Emission Models (EM): i.e. CO_2 emission estimation models.

These have been selected because both are already well-established areas of modelling with many existing developments and research activities including methods, models and techniques which are internationally recognized.

There are many different kinds of ITS measures which can, in some way, influence the energy efficiency of transport and hence the amount of CO_2 emissions generated. However, these effects come about as a result of very different mechanisms according to the type of ITS measure concerned. In order to be able to work in a coordinated way towards the establishment of reliable impact assessment methods, a series of agreements have been reached among representatives in United States of America, Europe and Japan.

AGREEMENT 1: ITS applications and categories

1) A shared list has been drawn up consisting of the ITS applications to be considered and the main categories into which these can be divided.
2) Joint efforts produced a set of 'Reference Models', whose aim is to describe (in diagrammatical and written form) the causal mechanisms behind the impact of the above ITS applications on energy consumption.

AGREEMENT 2: Model verification and validation

These concepts have been defined as follows:

1) Verification is the process by which the correct functioning of both the TS and EM are established.
2) Validation is the process of comparison between the calculated variables of the model outputs from the inputs and the observed outputs.

AGREEMENT 3: Soundness and sensitivity of proposed methodology

Any commonly approved methodology must be scientifically sound, possess sufficient sensitivity with respect to the applications that are calculated, and respect the common basic concepts for individual impact assessment methods.

AGREEMENT 4: Acceptable methods and methodologies

Any methods developed by any parties or countries can be approved by other parties, if the methods satisfy the basic requirements (written in subsection 1.2) and are described with the common 'reference models' (written in AGREEMENT 1).

In other words, the three parties DO NOT intend to endorse only specified methods. They are always open to discussion and welcome the development of novel methods with new technologies in the future.

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Appendix A: Inventory of Energy-saving ITS Applications A-1

I. Categorization of ITS Applications and Whole Assessment Methodology

1. Structure of the report

This report provides instructions that should be followed by those who try to evaluate the effect of CO_2 reduction by ITS applications using simulation models. It consists of five chapters. Chapter I suggests categories of ITS applications and gives an overview of the assessment methodology. Target ITS applications are classified into five categories according to their characteristics and the whole process of assessment methodology is presented in this chapter.

Chapters II to IV are divided into two major parts: one focuses on the development of evaluation tools and the other focuses on the methodology when using the evaluation tools. In more detail, Chapter II and Chapter III give instructions of model development for model developers. This development section consists of a modelling part and a model verification part and they are organized along the lines of the "V model" which is commonly used in software development. Chapter IV provides instructions of assessment for model users. It focuses on the application of evaluation tools to a target area and relates to available data in that process. Fig. I.1 shows the steps of the assessment methodology, the scope of each chapter and the relationships between the chapters.

The last chapter of this report, Chapter V, describes application examples from Japan, Europe and US following the methodology presented in this report.

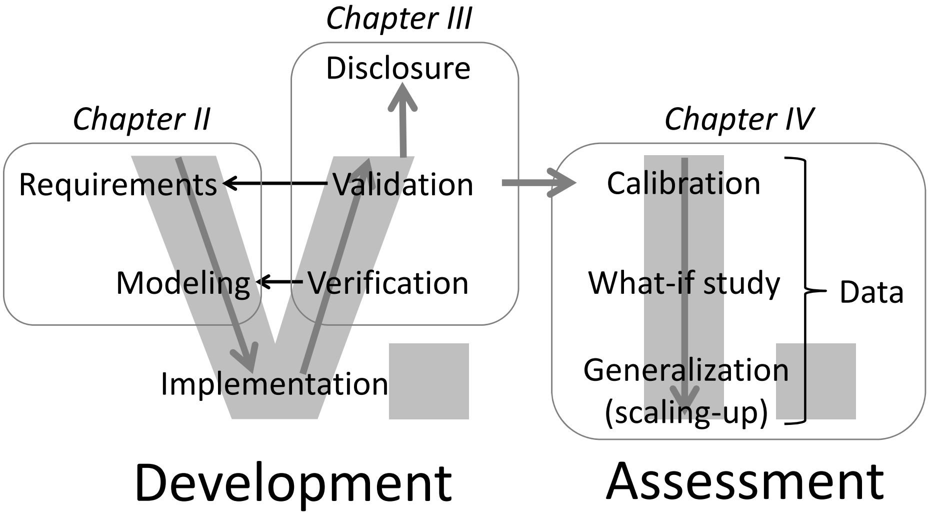

Fig. I.1 Structure of the report

2. Target ITS applications and their categories

A wide range of ITS applications lay claims to being potentially beneficial from the point of view of their impact on the energy efficiency of transport. Since the impact of different types of ITS on CO_2 emissions occurs through very different mechanisms, it is important that any internationally agreed methodology should be appropriate for all the relevant categories of ITS.

However, discussions between Europe and Japan in the context of the ECOSTAND[1] project and the Energy-saving ITS Project initiatives have revealed however, that while there is a considerable overlap in the type of ITS applications of interest in this context, there are also differences in focus between the two regions.

It was therefore essential as a preliminary step to come to an agreement on the target ITS applications for which the methodology should be designed. In addition, as it emerged that, even within the same general category, there are often significant variations with respect to the detailed features of a given ITS application, it was useful to find an unambiguous way of describing any given application.

For the sake of clarity, it was therefore decided that a shared classification of energy-efficient ITS should be drawn up. The result was a list of five main categories in Table I.1. An inventory of the typical ITS applications for each category is listed in Appendix A.

Table I.1 Categories for the Energy-saving ITS applications

Category		Example
1	Improving driving behaviour	Eco-driving instruction, adaptive cruise control, etc.
2	Traffic Control for Intersections & Highway Corridors	Advanced signal control, highway bottleneck measures, etc.
3	Traffic Management on a Network Scale	Navigation and route guidance, ramp metering, departure time coordination, safety and emergency system, etc.
4	TDM & Modal Shift	Multimodal support, road pricing, car sharing, etc.
5	Fleet Management	Commercial fleet management system, etc.

These categories are described in more detail in the following pages.

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[1] ECOSTAND has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 270332.

2.1. Category 1: Improving driving behaviour

The ITS applications in this category mainly work on drivers' awareness to change their vehicle operation to become eco-friendly by using on-board equipment or personal devices. Some applications such as adaptive cruise control may intervene in vehicle control for safe and smooth operation.

As the applications in this category aim to reduce unnecessary acceleration / deceleration or to suppress peak speed, the evaluation tools for this category have to take into consideration those driving behaviour changes.

2.2. Category 2: Energy-efficient traffic control for intersections and highway corridors

The ITS applications in this category aim to increase bottleneck capacity by means of dynamic performance adaptation of road & traffic control facilities, such as traffic signals, lane markings, variable message signs, guide lights, toll gates, etc.

The evaluation tools for this category may have the capability to emulate roadside sensors or probe vehicle sensors to activate control facilities in the simulation world. They are also required to model drivers' / vehicles' reaction to the environment changes caused by those facilities. Some applications, such as the 'Green wave' signal control, may change the driving behaviour and thus will use the driving behaviour changes which are also regarded in Category 1.

2.3. Category 3: Energy-efficient traffic management on a network scale

The ITS applications in this category aim to mitigate traffic congestion and to increase the average travel speed in a network context. Typical measures are to disperse traffic spatially and temporally via traffic information provision, such as a dynamic route guidance system. Others are to regulate traffic flows for the optimization of total traffic performance, such as ramp metering. The measures which work for an incident scene or parking scene are also included in this category.

The evaluation tools for this category have to model the drivers' route choice behaviour considering the dynamic aspects of the traffic situation.

2.4. Category 4: Travel demand management

The ITS applications in this category will influence travel behaviour and modal choice, aiming to reduce the volume of vehicle traffic demand. Typical measures are to encourage public transportation use. The pricing scheme for road use is included in this category as well.

The evaluation tools for this category need to take into consideration the travellers' mode choice behaviour. In cases where it is difficult to model the mode choice behaviour, the sensitivity analysis on travel demand should be coordinated in the assessment stage.

2.5. Category 5: Fleet management

The ITS applications in this category deal with goods transport and its related demand. Optimizing goods allocation may reduce the number of trips for fleet transport. The evaluation tools for this category should be able to take into consideration optimization schemes.

3. Outline of the assessment methodology

3.1. Modelling of CO_2 reduction effects

Chapter II recommends the preferable procedure for modelling the energy-saving ITS applications. The modelling stage corresponds to the downward stroke of the 'V' shaped model development[2] shown in Fig. I.1.

3.1.1. Description of the CO_2 reduction mechanism

As for the baseline of the assessment, all stakeholders must share what factors, which influence CO_2 emissions, need to be considered, and hence what factors are not considered, in the evaluation tool. For the sake of clear description, it is encouraged that users draw up a 'Reference Model' of the CO_2 reduction mechanism of the ITS application under investigation in a schematic diagram.

The reference model will be provided in a bi-level description — the category model and the instance model. The category model is prepared for each category of ITS applications. It provides a diagrammatic representation of the principal modelling 'targets' and the relationships between them. The instance model is specific for the individual ITS application of interest and provides a detailed analysis of the specific factors that influence the CO_2 reduction mechanisms. This analysis should result in a 'map' of the main causal relationships which affect CO_2 emissions and also the principal positive and negative effects on energy saving that are to be expected. All causal relationships which appear in the instance model are to be described in writing, and preferably are to be verified with some reasonable quantitative tests.

3.1.2. Clarification of the modelling requirements

The description of the CO_2 reduction mechanism above will provide the requirements for the modelling. Since the evaluation tool consists of a traffic simulation and emission model, the general requirements for both tools are summarized in Chapter II, followed by those specific to each category of ITS applications reflecting on the mechanism of CO_2 reduction.

3.1.3. Modelling

Modelling is a design process for data structure, algorithm, computational flow, etc., to

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[2] Model development in this definition is meant both as the development of new models and the adaptation of existing models.

implement the evaluation tool as software. The construction of the design process can be done in dozens of ways, but it originates with the developer. In Chapter II, state of the art traffic simulation modelling and emission modelling are introduced for the purpose of helping tool developers and users.

3.2. Verification, Calibration and validation

3.2.1. Philosophy

There is a wide variety of possible models to evaluate energy consumption, and each has its own characteristics depending on how it was developed. Therefore, this report does not specify a certain model but has prepared a standard framework for verification and validation that was agreed upon internationally by the experts involved. It gives an overview of traffic phenomena and variables that are especially relevant in the context of CO_2 assessment and for which the models are ideally verified, calibrated and validated.

Verification evaluates the function of the model by checking the reproducibility of assumed traffic phenomena using a hypothetical dataset and comparing the result with theoretical values. Calibration and validation evaluates whether the model can comprehensively reproduce actual traffic conditions using an observed dataset from the field. Even when using existing traffic simulation models, verification/validation is necessary because they are usually not intended to be used for CO_2 assessment and some important items such as acceleration behaviour might not be checked sufficiently.

This standard process does not include a process of "certification" but "disclosure" of the verification/validation results. This means the reliability of a model is not approved officially but model users and clients can judge the applicability of a model by examining the verification/validation results depending on their purpose.

3.2.2. Items to be verified/validated

In order to check the reproducibility of a model, specific items need to be verified and validated both for the traffic simulation models and the emission models. There are some additional items depending on the model's resolution, for example, acceleration and deceleration for microscopic traffic simulation, intermediate products for a meso emission model and so on. Table I.2 shows the typical items to be verified/validated for a traffic simulation and emission model (which are discussed in more detail in Chapter III).

Table I.2 Items in verification calibration and validation

		Verification	**Calibration and Validation**
Traffic Simulation Model (TS)		Vehicle generation Bottleneck capacity/ Congestion occurrence Shockwave propagation (Route choice) (Departure time choice) (Mode choice)	Traffic flow (volumes) Speed Number and duration of stops (not in macro model) Queue length and location
	micro model	Speed and acceleration Spacing among vehicles Speed choice (free flow, up/downhill) Start / stop behaviours Gear shifting	Speed and acceleration Driving modes VSP (Vehicle Specific Power) distribution
Emission Model (EM)		Model structure Vehicle type setting	CO_2 from individual vehicles Time-series CO_2 from individual vehicles Speed vs. CO_2 relationship
	meso model		Stepwise Speed Function (SSF)

3.2.3. Verification

The basic idea of verification is to compare the established theory and the results calculated by the model.

In the verification process of traffic simulation, fundamental functions which are essential for traffic simulation are to be verified to meet the knowledge of the traffic theory. Generally, the microscopic model has more flexibility in modelling of vehicle movement; therefore we need additional items to be verified in the case of microscopic models. There are a number of previous works which deal with the methodologies to verify traffic simulation models, and one of these is the “Standard Verification Manual for Traffic Simulation (SVM)”. The items are shown by situations: general items, intersections, highway/motorway driving, route choice, travel demand (OD matrix), departure time/mode choice and gear shifting.

In the verification process of an emission model, it should be verified whether CO_2 is estimated based on physical and statistical fundamentals. In addition, it is also necessary to check the vehicle categorization method.

3.2.4. Calibration and Validation

Validation is a process to check the applicability of models to an actual situation considering actual inputs and conditions, and calibration of model parameters is necessary in this process. For this purpose, observed data from actual fields have to be collected.

For the calibration and validation of a traffic simulation model, general items that should be verified at all times and special items that should be verified according to a situation, for which the simulation model will be applied, are set. A visual comparison between the real world and the model indicators can give an indication of how close the model approaches reality, and can show obvious differences between the model and the real-world. Even if a visual inspection shows that the distributions are very similar, it is still recommended to also carry out a quantitative validation. This is possible by using statistical tests suited to comparison of one- or multi-dimensional distributions.

In the validation process of an emission model, observed CO_2 emission should be compared with estimated CO_2 emission for individual vehicles. Fuel consumption data is also useful as it is highly correlated to CO_2 emission.

3.2.5. Benchmark dataset

As validation is the process to check the reproducibility of a model using actual data so that it can be compared with other models, a dataset of traffic conditions as well as CO_2 emissions observed from the real world is needed. However, it is not easy to obtain a comprehensive dataset because it requires a lot of cost and labour. To cope with that, benchmark datasets are currently being prepared under international collaboration. They are intended to be used widely for validation of various types of models, so they should include various kinds of data.

Benchmark datasets for model validation are to be stored in the ITDb (International Traffic Database; http://www.trafficdata.info/), which can serve as a warehouse of the benchmark datasets. It offers basic functions to upload, to store, to browse, and to download datasets both for data providers and data users.

3.2.6. Disclosure of the results

After verification and validation is conducted, the results should be disclosed so that model users can check the performance of the models, understand the characteristics of the models, and select one of them according to their purpose.

The basic information to be disclosed is: date of execution, responsible person/organization, model description, verified and validated items, verification results, the dataset used for calibration and validation, calibrated parameters, validation results, interpretation of the results, and so on. ITDb can be used as a clearinghouse for the disclosure of the verification/validation results.

3.3. Impact assessment

Chapter IV focuses assessment methodology and data to be used for the assessment and tool validation.

3.3.1. Assessment methodology

The principle of assessment methodology is to ensure transparency which allows the evaluation process to be traceable by a third party. This fundamental philosophy is similar to scientific experiments and may increase the 'reliability' of the evaluation result.

In the first section of Chapter IV, the following steps which the assessors should follow are described:

- 'Site specific calibration' – to fit the evaluation tool for the subject site, and to provide the baseline for the comparison in the 'what-if study' stage described in the subsequent section.
- 'What-if study' – to coordinate case studies by changing some input for the simulation according to the scenario.
- 'Generalization with scaling-up' – to confirm the representation of the traffic condition in the simulation study area and to expand the result of the simulation study to the whole subject area.

3.3.2. Dataset for tool validation

The data needed to support the validation for both modelling chain and site specific calibration can be divided into two main categories: (i) input data, (ii) calibration and test data. In this aim, the use of real-life data is extremely important. There are, however, large differences between regions in the availability of data.

The second section of Chapter IV discusses the data requirement for the validation of traffic simulation and emission models in terms of the data characteristics and its availability.

3.3.3. Monitoring with probes

Traffic monitoring through the use of probe vehicle technology is emerging as a viable means of developing comprehensive traffic monitoring systems without a large investment in physical assets deployed in the right-of-way. Although new methods for detecting speed and volume are lowering installation costs and minimizing maintenance, probe-based methods of measuring travel time can be easily scaled across large networks without additional infrastructure in the right-of-way and its associated costs and maintenance burden. Probe vehicle technology is fundamentally different to fixed-point detectors, in that probe technology provides a direct measure of travel time, while any method of fixed-point detection infers travel time from a network of speed sensors.

The last section of Chapter IV aims to show the potential of probes as an alternative source of useful data and more precisely to arrive at a common understanding of the contribution of probe data to “real-time” CO_2 monitoring. For this purpose, some definition and reference terms are first introduced before presenting the reasons for focusing on probes, their characteristics and related quality issues.

II. Modelling of CO_2 Reduction Effects

1. Description of the CO_2 reduction mechanism by the reference models

The five ITS application categories described in Chapter I reflect not only the objectives of the ITS applications in each group, but also the 'mechanism' underlying their influence on energy consumption. For this reason, the classification of the reduction mechanism should also provide a useful basis for identifying the most appropriate methodology for measuring the impact on CO_2 emissions. It was then agreed to draw up a set of Reference Models which would provide a bi-level description of the ITS applications.

1.1. Bi-level description of the reference models

1.1.1. Category level

A category level reference model is one to be produced for each category of ITS applications and to be shared among all the parties concerned. This should provide a diagrammatic representation of the principal modelling 'targets' and the relationships between them. The modelling target could be any objects relevant to traffic and emission conditions such as vehicles, drivers, traffic signals, sensors, ICT systems, etc.

Developers who model the ITS applications can delimit the diagram in order to highlight the subject targets within the scope of interest. Any targets considered to be out of the scope of the model may be replaced by assumptions or premises, but these will need to be supported by some adequate justification, such as validation or experimental results, reported studies, etc.

In order to ensure consistency in the description of the category models, a common syntax was drawn up.

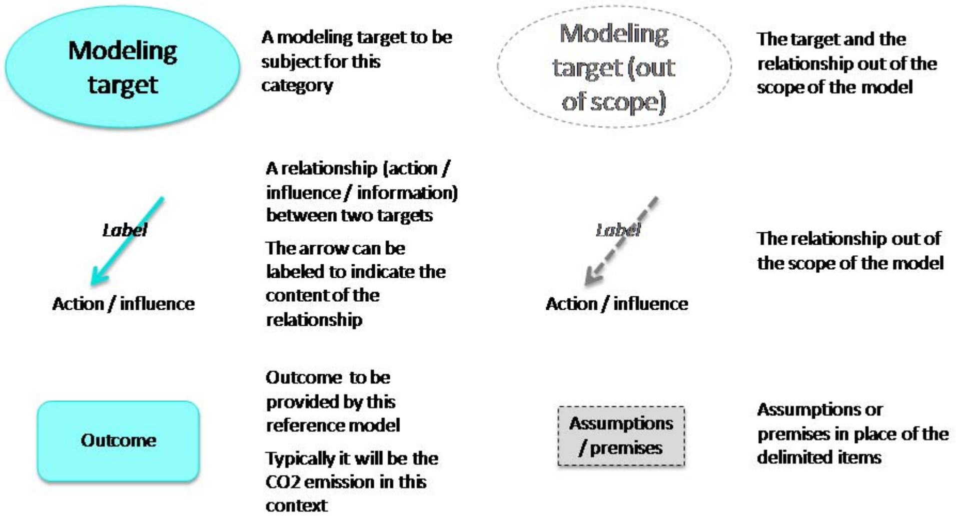


Fig. II.1 Syntax for the reference model diagram at category level

1.1.2. Instance level

An instance level reference model is one for each individual ITS application (or ITS-related strategy) of interest. The aim is to provide a detailed analysis of the specific instances of the category model. For instance, we may draw the instance model of 'eco-driving' support system by inheriting the structure of the category model for the 'improvement on driving behaviour'.

This analysis should result in a 'map' of the main causal relationships which affect CO_2 emissions and also the principal positive and negative effects on energy saving expected. The structure of an instance model is expected to inherit the category model to which it belongs.

All causal relationships which appear in an instance model are to be described in writing, and to be verified with some reasonable quantitative tests. The description should also identify any other relevant effects or issues.

Similar to the category model, the common syntax for instance models was drawn up.

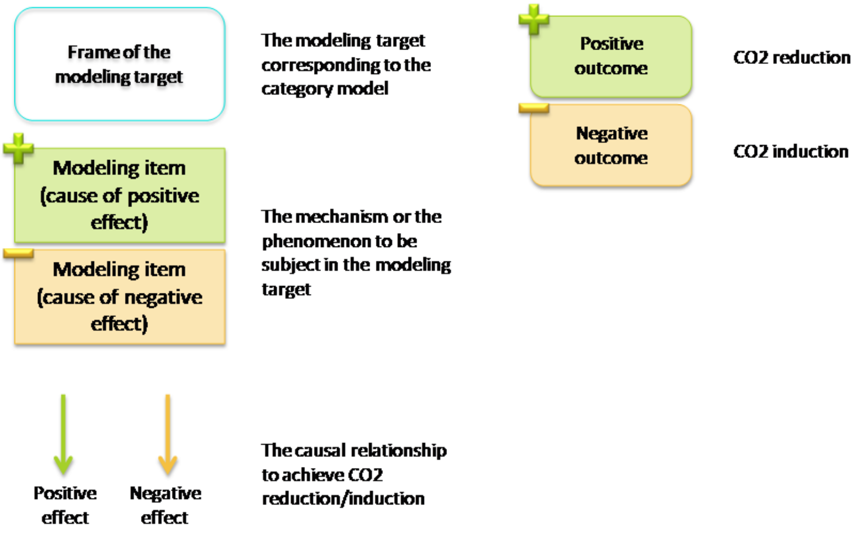


Fig. II.2 Syntax for the instance model diagram

1.2. The aim of the reference model

The aim of drawing reference models was to converge - as far as possible - on a commonly agreed general model for each of the five categories. The instance model on the other hand, explains the impacts of a specific ITS application in more detailed way using causal relationships associated with the application ('eco-driving', for example, is an energy saving strategy which can be implemented in numerous different ways). The advantage of drawing up an analytical representation of a given application/strategy is that it helps to clarify the modelling implications of such differences and to index the verification tests to support the modelling idea.

1.3. The reference models for the ITS categories

For each of the five ITS categories we provide a general description below, a list of typical examples and the category model diagram.

1.3.1. Improving driving behaviour

The elements in this category model are the 'driver', the 'vehicle' and the 'ICT system' aiming to improve driving behaviour.

The driver 'controls' the vehicle and may 'use' the ICT system at necessary time. The ICT system collects 'data' of vehicle's driving status and either 'controls' the vehicle or only 'informs' the driver affecting the 'control' of the driver.

Each of the 'other vehicles' has recursive structure consisting of three elements, i.e.

'vehicle' plus 'driver' plus 'ICT system'. Changes in a vehicle's driving behaviour may cause 'influence' to the 'other vehicles' near-by, and the control of the driver may be affected by the 'other vehicles' and vice-versa. An influence on the driver to the 'other vehicles', not via the 'vehicle', may exist but is omitted here.

Another entity 'infrastructure' (road, regulations, signals, etc.) with an influence on the driver exists, but might not be relevant here.

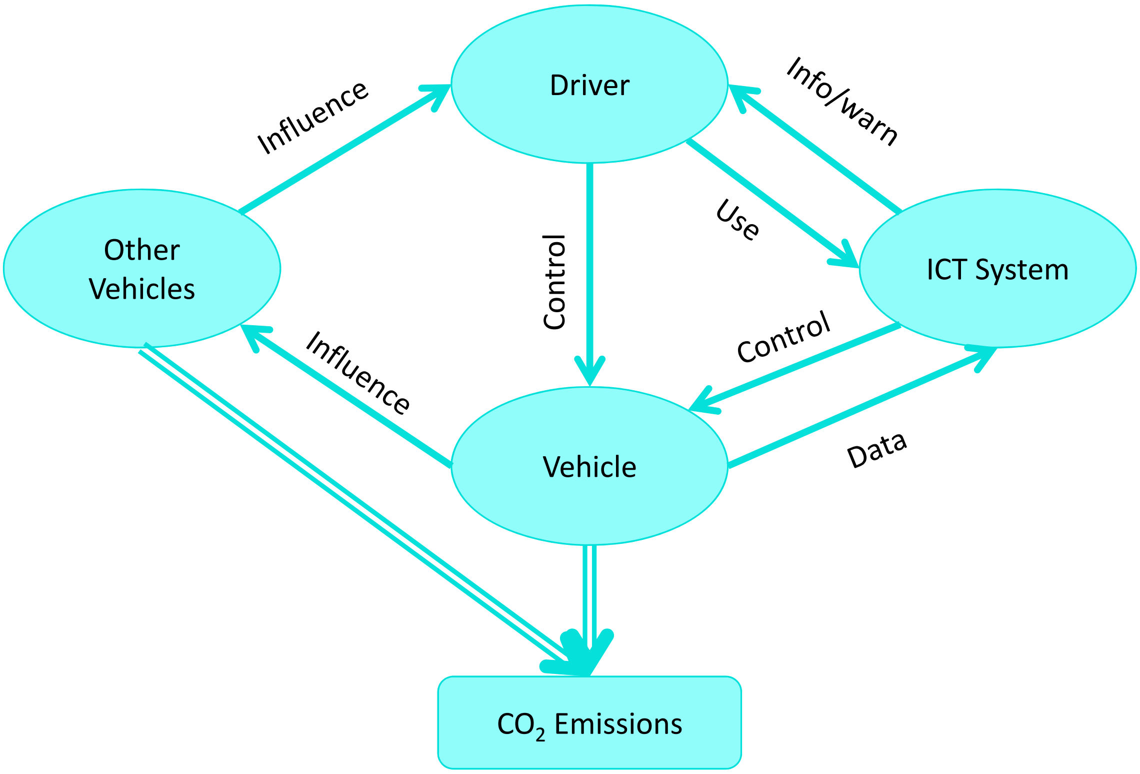


Fig. II.3 Reference model for Category 1

1.3.2. Energy-efficient traffic control for intersections and highway corridors

Adding to the category model for 'improving driving behaviour', the items 'traffic sensor' and 'road facility' are included for this category. The 'traffic sensor' collects traffic data at a roadside and sends it to the 'ICT system'. The 'road facility' including traffic signals, variable message signs, variable lane markings, etc. controls traffic in an efficient way.

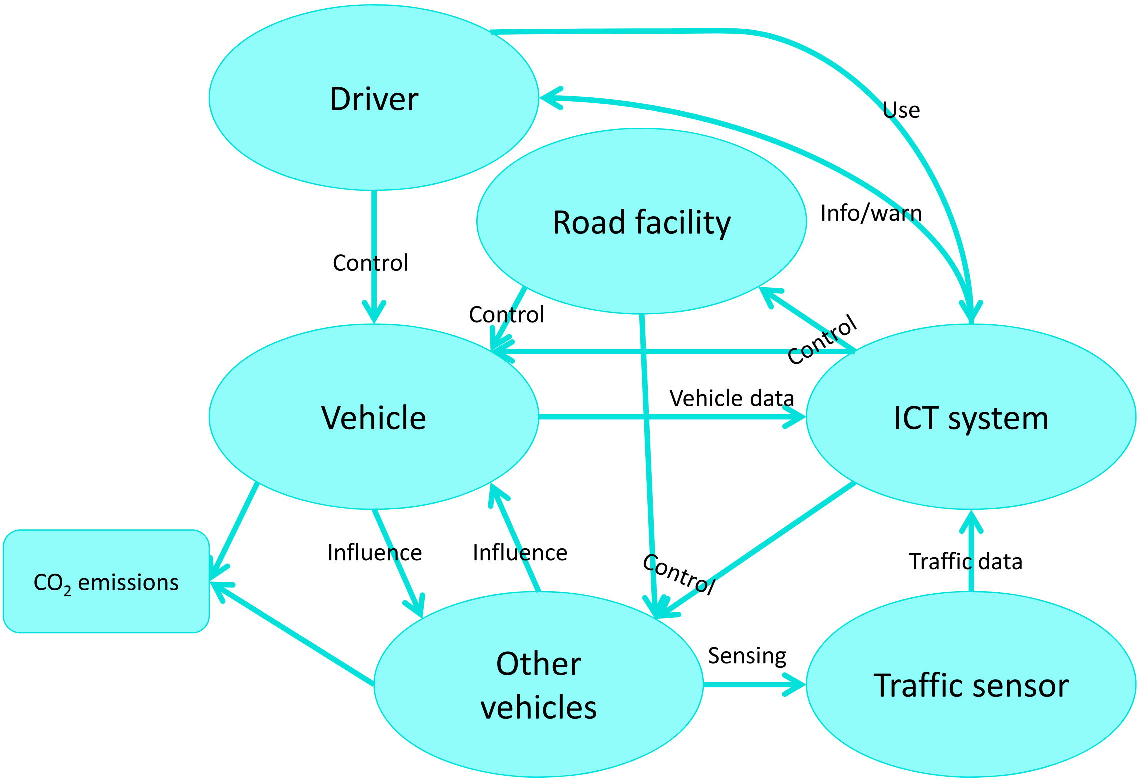


Fig. II.4 Reference model for Category 2

1.3.3. Energy-efficient traffic management on a network scale

The structure of this category model is similar to the 'Energy-efficient traffic control' but some arrows are changed or removed. For this category, the influence from other vehicles may be ignored at the driving behaviour level. The network scale effect such as spatial/temporal traffic dispersion is considered in the causal loop of 'vehicle – traffic – sensor – ICT system – (road facility) – driver – vehicle'.

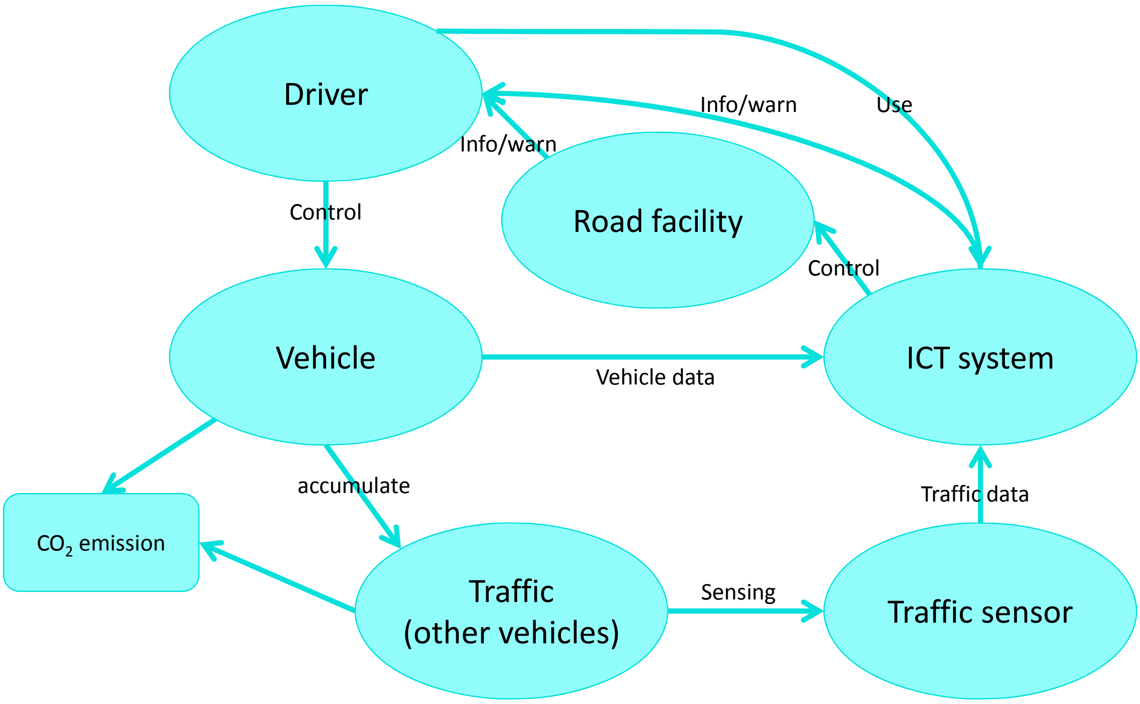


Fig. II.5 Reference model for Category 3

1.3.4. Travel demand management

For this category, the changes on the demand side should be considered. The extraction of the ‘vehicle travel demand’ from the ‘multimodal travel demand’ will be achieved by some modal choice model. As the modelling of the demand side itself is a huge and complicated topic, we may allow this section to be replaced with some adequate assumptions.

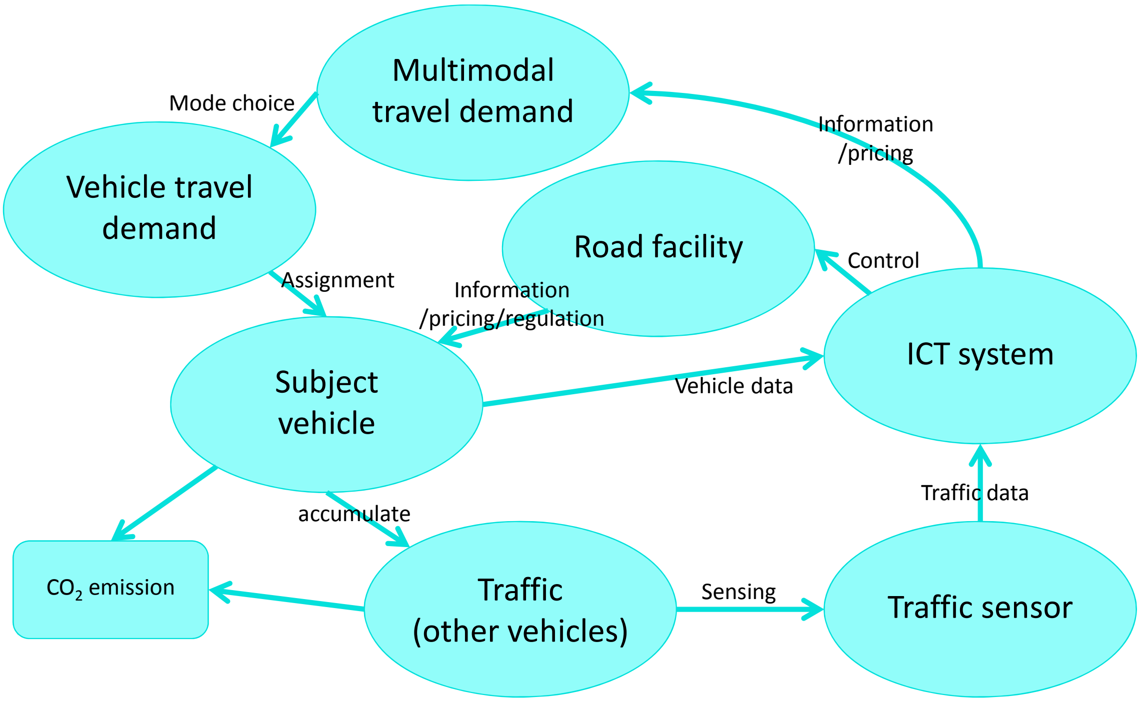


Fig. II.6 Reference model for Category 4

1.3.5. Fleet management

For this category, the connection from/to the goods transport demand should be considered. The CO_2 emission from a commercial vehicle should be discussed with the assigned load to each vehicle.

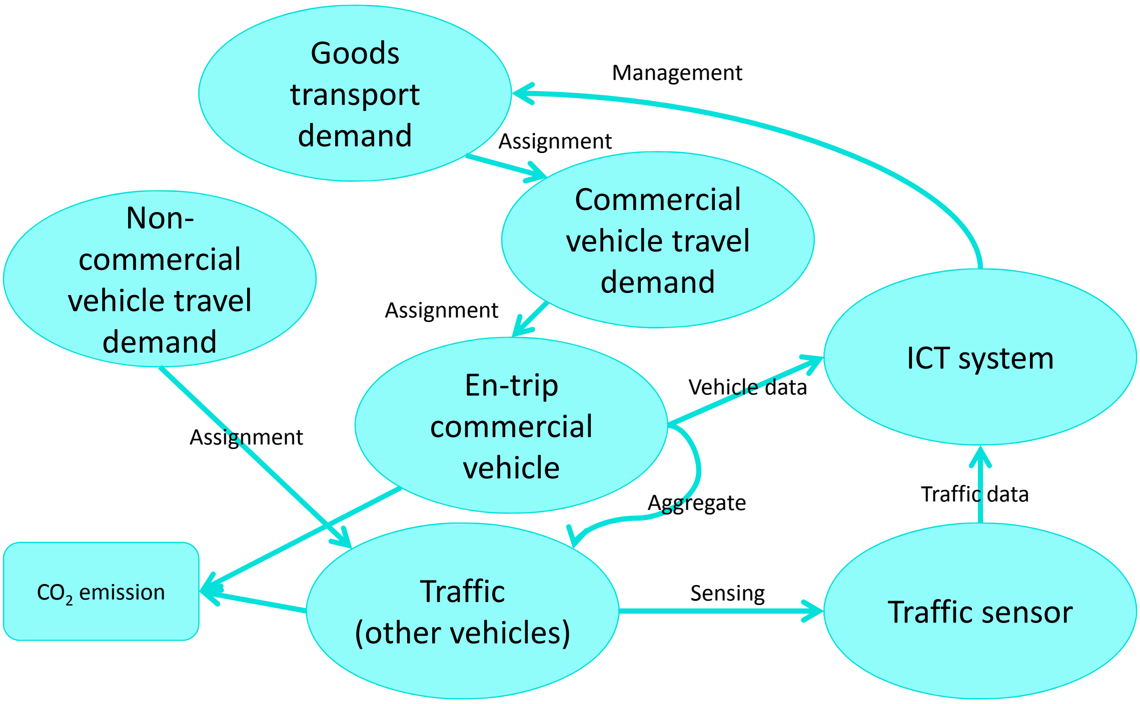


Fig. II.7 Reference model for Category 5

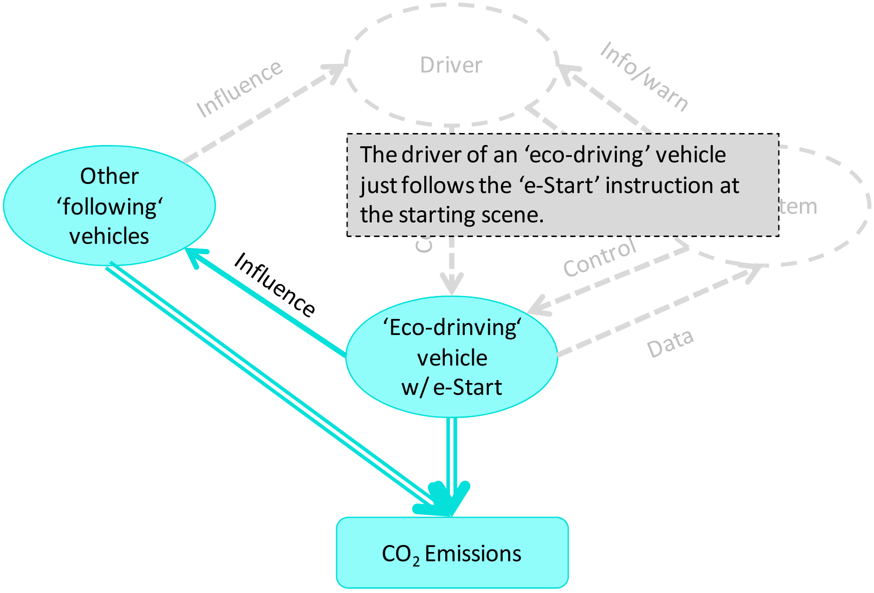
1.4. Examples of instance level reference models

For the understanding how to draw up an instance level reference model, let us list some instance models for a key application (i.e. an application considered by one or both regions to be particularly significant)

1.4.1. 'e-Start' assistance system (Category 1)

As an example of the instance model, the 'eco-driving' case which will be given in detail in Chapter V from the Japanese side is noted here. The purpose of this case is to quantify the total CO_2 reduction on an urban scale in proportion to the eco-driving vehicles doing the 'e-Start', moderate acceleration when starting.

Before presenting this instance model, it is helpful to clarify its modelling scope by delimiting the category model. As it is not intended to evaluate any specific 'eco-driving' support system, the 'ICT' and the 'driver' which would react to the information from the ICT were excluded from its scope. In place of these, a simple assumption is shown in the diagram. We may read from the diagram that the focus is not only on the direct reduction on the CO_2 emissions from the eco-driving vehicles but also on the indirect changes from the other vehicles which will be influenced by the eco-driving vehicle.



The driver of an 'eco-driving' vehicle just follows the 'e-Start' instruction at the starting scene.

Fig. II.8 Delimitation of category level reference model for an instance application

The instance model for this case inheriting the structure of the 'delimited' category model shows the modelling items and their relationships which are relevant to the changes in CO_2 emission. Since the instance model is regarded as the schematic expression of the modelling requirements, all boxes and arrows in the diagram are to be described and to be verified through the quantitative tests.

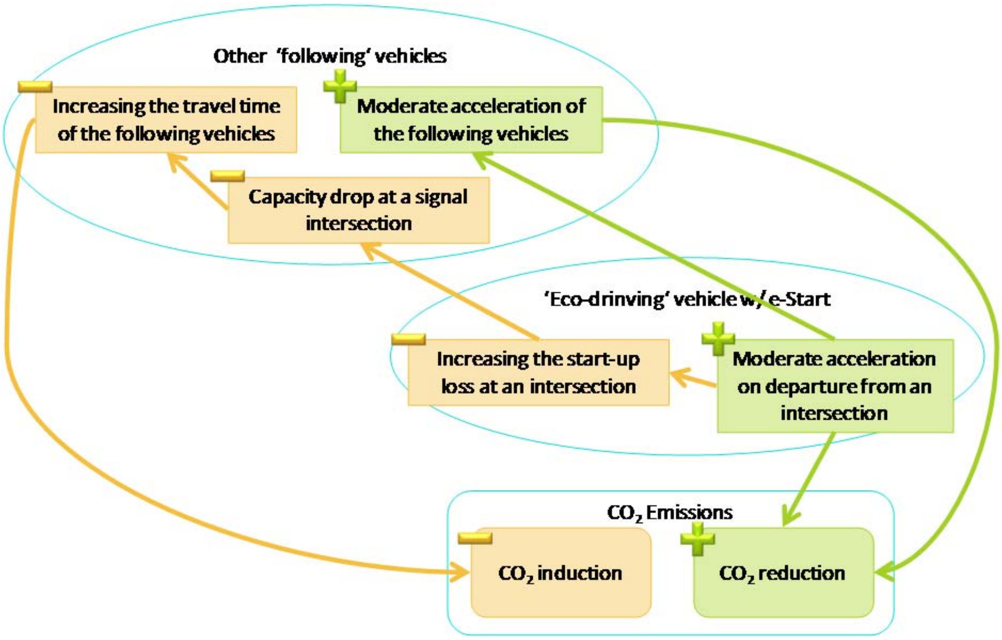


Fig. II.9 Instance level reference model for 'e-Start'

1.4.2. Energy efficient intersection control (Category 2)

Energy saving at an energy efficient intersection will be achieved by reducing the average number of stops, giving advice on approach to a stop line for cooperative vehicles (speed and lane choice), special handling of heavy goods vehicles (minor priority), energy-saving mode in the case of over saturation, and soft platoon formation for green waves.

In that sense ITS can support energy efficient intersection control by: cooperative communication such as vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (I2V).

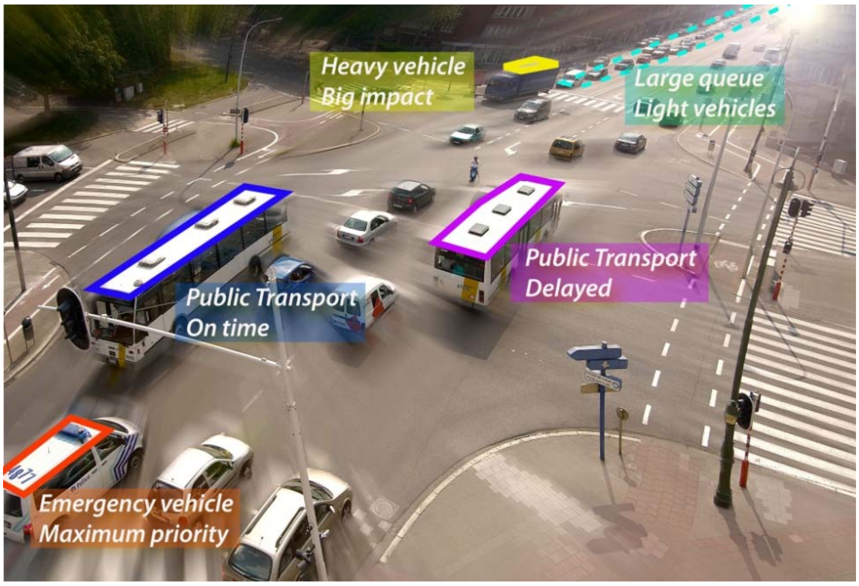


Fig. II.10 Example of the context of energy-efficient intersection control (EEIC)

The instance model for this case is given as follows:

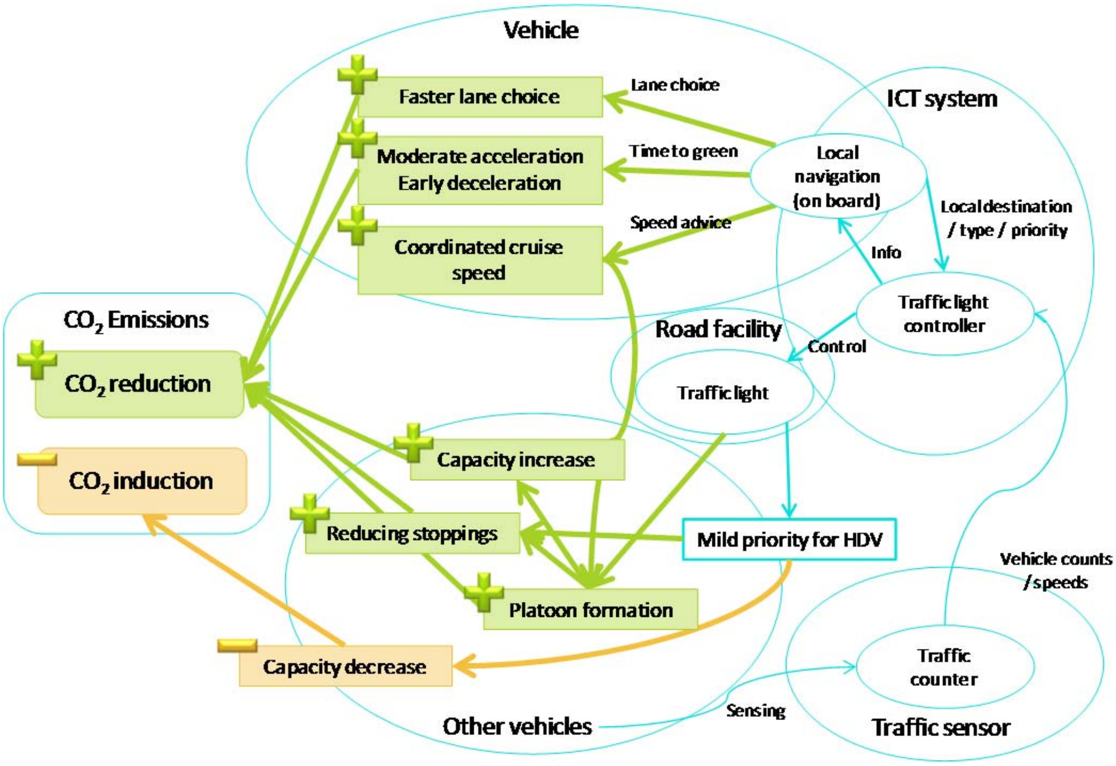


Fig. II.11 Instance level reference model for energy-efficient intersection control (EEIC)

1.4.3. "Spitsvrij" (Category 4)

Here is an example project in The Netherlands: avoiding the rush hour (“Spitsvrij”).

The goal of the "Spitsvrij" (= avoiding the rush hour) project, an on-going collaboration between the municipalities Hilversum, Utrecht and Amersfoort, was to increase the reachability of the region, as well as improving traffic flows by better usage of the existing infrastructure. This was achieved by enticing a portion of some 60,000 motorists to change their travel behaviour in the peak period. Preliminary results seem to indicate that this works (the target is to have 8.5% of the group change). Aside from this, the project also researches the influence of price incentives and innovative information on travel behaviour.

All subjects (up to 5000, which are enough for a statistical estimate for the area) were initially selected if they drove on average more than 5 times per week during the morning or evening peak, and lived more than five kilometres from their work place. To achieve this, teaser campaigns announced the project in social media and elsewhere.

In the system, each car is equipped with an OBU, the so-called S-Box (special installation days were organised). Each participant received a personal page on the website that contained 100% customised feedback on his or her travel behaviour. It also included a multimodal journey planner that gave combined advice on cycling, public transport and cars. In addition, travellers were also kept informed during their journey on delays, pollution, road works, etc.

The tariff in this project was given in the form of a monthly remuneration budget, being dependent on the characteristics per person, i.e. the distance to work and the number of times that the car was used in the peak period during the baseline work (the budget ranged from 60 euro up to 120 euro per month). The idea is that travellers can earn money and time as they avoid the peak periods on motorways, i.e. between 6h30 and 9h30 in the morning and 15h30 and 18h30 in the evening. So every time they drove in the peak period, a certain amount of their budget was withheld. A participant was allowed to keep whatever of the budget that was left at the end of the month (this amounted to an average value of some 30 euro).

The project entailed a close cooperation with employers in the region (around 60 at present), so that employees can work at different times and locations. For almost 90% of the subjects, this was the first time they saw alternatives for driving their car during peak periods. The project removes, according to preliminary figures, some 1.5% to 2% of all cars out of the peak period. The challenge will be to make the travellers retain their changed behaviour, after the financial incentive disappears.

Note that a similar approach is used in the mobility project "SMART pricing on the Arnhem Nijmegen regional ring", where participants receive a compensation if they are not driving in a particular area during the peak period.

The instance diagram of this example is given in the following Figure:

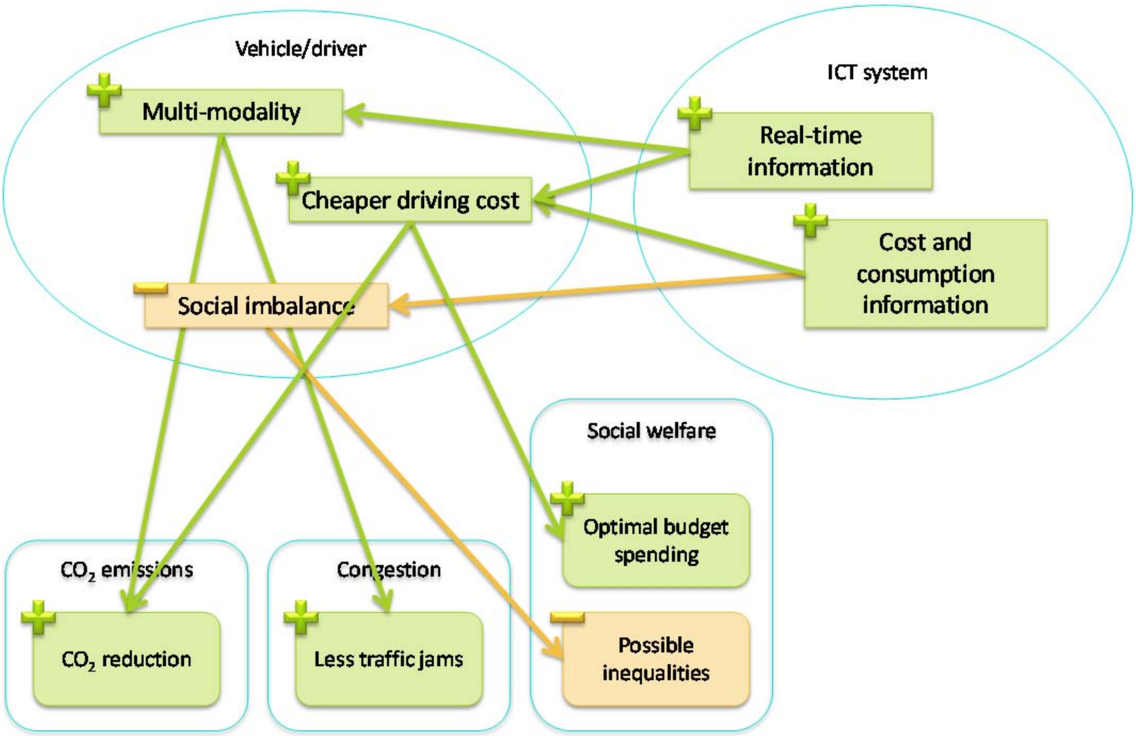


Fig. II.12 Instance level reference model for “Spitsvrij”

2. Modelling requirements

2.1. General requirements

As we discussed in Chapter I, the evaluation methodology consists of traffic simulation models and emission models. The general requirements for both models are summarized as:

2.1.1. Requirements for traffic simulation models

Many ITS applications aiming for CO_2 reduction may intend to mitigate traffic congestion and to consequently reduce travel time loss. This means that a traffic simulation model is at least required to evaluate the delay caused by traffic jams fairly and strictly. To ensure this requirement, any traffic simulation should have its modelling verified through a set of proper engineering tests (verification) and its reproducibility of traffic conditions validated with some reliable and precise data set (validation). Further validation at driving dynamics level will be required for the use of microscopic traffic simulation in some cases.

In respect to the harmonization of traffic simulation and emission model, traffic simulation should have the capability to output the time-space trajectory of individual vehicles with the necessary attribute information which is used in emission model, such as type, size, weight, load, etc. The required granularity of the time-space trajectory may depend on the category of ITS applications, which will be discussed later.

2.1.2. Requirements for emission models

Any emission models combined with traffic simulation should be able to consider the factors relevant to an individual vehicle's travel status, such as speed, distance, time, number of stops, acceleration, deceleration, etc. It is also required to have fair sensitivity in its output by the changes in a vehicle's travel status. The accuracy and the sensitivity in the estimation result of an emission model should be verified and validated with some rational test procedures.

2.1.3. Vehicle categorization for traffic simulation and emission model

Independent of the choice of a detailed, aggregated or intermediate approach for the emission modelling, the characteristics of the vehicles are paramount in the determination of the emissions; some segmentation is advisable in all cases:

- Essential: fuel type, transport mode (truck, bus, car, etc.).
- Additional: size classes, fuel economy standard, technology.

Note that if ITS measures influence each vehicle type in the same way, a segmentation of the vehicle fleet is not needed per se.

The vehicle types dealt in traffic simulation are restricted by the available OD matrix, while the vehicle categories considered in emission model are discussed to see how they represent similar emission characteristics. It is often seen that the number of vehicle types in traffic simulation is less than that in emission model. This gap should be filled by mapping the traffic simulation vehicle types to the vehicle category for emission model in proportion to the vehicle travel distance which may be given by statistics.

2.2. Specific for each category

2.2.1. Treating driving dynamics changes

As the ITS applications in Category 1 explicitly focus on driving dynamics, traffic simulation/emission model should model the driving dynamics changes reasonably. The driving dynamics changes should be modelled for the departing, cruising and slowing-down/stopping scenes respectively.

Some applications in Category 2 may influence driving dynamics but modelling is not mandatory unless the changes in driving dynamics will be substantial.

2.2.2. Time & spatial resolution in vehicle motion

For the applications in Category 1 and 2, the traffic simulation/emission model should have a spatial resolution, e.g. 10^1~10^3 meters, enough to distinguish in which section we may see the CO_2 reduction/induction. For applications in the other categories, the spatial resolution for the traffic simulation/emission model is not crucial for the modelling requirements but depends on the aggregation unit for the sake of the evaluation stage.

As for the time resolution, the traffic simulation may have 5~10 minutes resolution, at least enough to discuss the changes in traffic conditions.

2.2.3. Study area scale

The applications in Category 2 will be implemented with an intersection ~ a corridor scale, e.g. 10^2~10^3 meters. Some applications in Category 1 will be installed at some specific locations and may influence the traffic in a small area locally. However, there are other applications, such as eco-driving assistance, which may not be limited on a local scale but spread over a region ~ country scale, e.g. 10^3~10^6 meters. The applications in Categories 3 to 5 may cover a town ~ region scale network, e.g. 10^3~10^5 meters.

2.2.4. Traffic control facilities

For the applications in Category 1 and 2, traffic control facilities, such as traffic signals, VMSs, vehicle control devices, etc., are to be explicitly modelled in traffic simulation as much as possible, since they are the major means to change the driving dynamics. For other applications in Categories 3 to 5, the effect of those facilities can be indirectly considered in traffic simulation.

3. State-of-the-art evaluation tools

3.1. Traffic modelling

There are many points of view to classify traffic simulation models. Although we are going to summarize the flow modelling according to the conventional classes, macroscopic / mesoscopic / microscopic, let us here focus on the granularity of vehicle trajectory in the context of the traffic simulation-emission model harmonisation.

3.1.1. Macroscopic

This kind of model considers traffic as an invisible but compressible fluid. The most well-known model in this class is the first-order Lighthill-Whitham-Richards (LWR) model, which has closed analytical and bound numerical solutions. Considering this elegant first-order traffic flow model, its main advantages are that it is simple, and in a sense reproduces the most important features of traffic flows, i.e. shockwaves.

Some other models which have higher order fluid approximation, such as a gas-kinetic model, have been proposed to introduce more complex and non-linear dynamics such as the generation and dissipation of shocks, the different traffic regimes.

In spite of the sophisticated numerical solutions, the macroscopic models have crucial disadvantages to model the ITS measures and to be combined with the emission models. The most significant one is that they cannot distinguish individual vehicles, rendering them unsuitable for use with microscopic-like emission models. For this reason, the use of the macroscopic traffic simulation is not encouraged in this report; keep in mind though that they can prove useful when considering the impact of ITS applications on emissions on a larger geographical scale.

3.1.2. Mesoscopic

Considering the amount of literature that has been generated during the last few decades, it seems to us that no unanimous consensus exists as to what exactly constitutes mesoscopic traffic flow models. In this report, let us give them the definition that they deal with discrete vehicles in order to consider multiple vehicle classes but move vehicles in accordance with the mesoscopic flow models. It is the case, for instance, that moves vehicles along the speed-density relationship derived from the fundamental diagram (FD) of traffic flows.

From the nature of their macroscopic bases, even if they have higher order approximation, they do not guarantee realistic acceleration, deceleration, and/or speed fluctuation of vehicles. However, a well-calibrated mesoscopic model can reproduce the travel speed of individual vehicles within some distance with sufficient accuracy. In this sense, we may approximate an individual vehicle's trajectory with a piecewise linear line in time-space.

As for the granularity of piecewise linear trajectory, there are two possible classes; the section-wised linear trajectory and the state-wised linear trajectory.

The section-wised linear trajectory can be given by the mesoscopic model which revises the traffic density of each predetermined 'section' (or 'segment', 'block', 'link', etc.) by regulating the in/out vehicles across the boundary of the sections. For this class, as the traffic status within a section is regarded as homogeneous, the granularity of the trajectory depends on the section length, typically in the order of 10^1~10^2 meters.

The state-wised linear trajectory can be given by the mesoscopic model which updates each vehicle's position time by time. For this class, as the trajectory can be decomposed with the lines which have different 'average' running speeds including stopping, the granularity of the trajectory does not depend on the section length but on the scanning interval of flow calculation. If the interval is as short as 1 second, we may distinguish the running mode with sufficient resolution such as the stop-and-go behaviour of each vehicle.

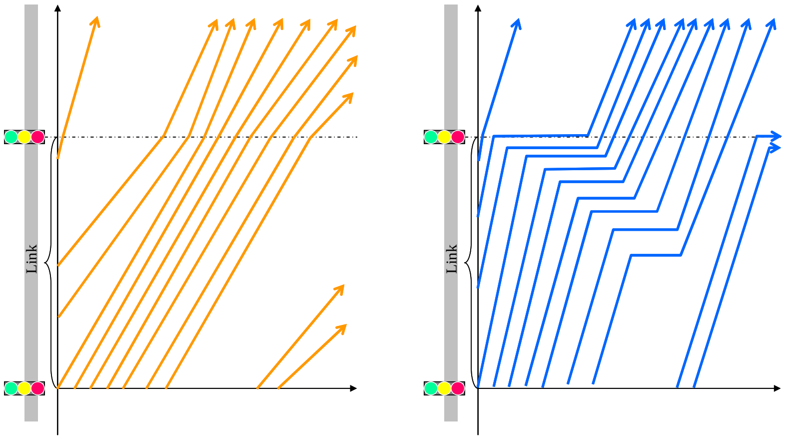


Fig. II.13 Section-wised linear trajectories and state-wised linear trajectories

3.1.3. Microscopic

At the other end of the spectrum reside the microscopic models, which are based on so-called car following models, the explicit consideration of the interactions between individual vehicles within a traffic stream. The models typically employ characteristics such as vehicle lengths, speeds, accelerations, and time and space headways, vehicle and engine capabilities, as well as some rudimentary human characteristics that describe the driving behaviour. Examples in this class are typical stimulus-response models, the General Motors non-linear model, the intelligent driver model (IDM), the human driver model (HDM), the optimal velocity models (OVM), Wiedemann's psycho-physiological spacing models, etc.

As the typical scanning interval of the car following calculation is in the order of 10^{-2}~10^{-1} seconds, the vehicle trajectory obtained with a microscopic model has a smooth curve shape. This fine grained trajectory provides smooth speed changes, i.e. the accelerations and the decelerations of a vehicle.

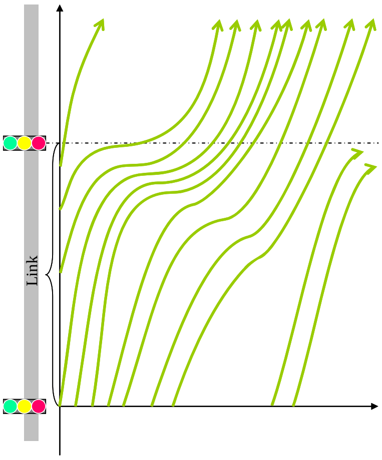


Fig. II.14 Fine grained trajectories

	Macroscopic traffic simulation	Mesoscopic traffic simulation	Microscopic traffic simulation
Traffic representation	Continuum fluid	Discrete vehicle	
Flow calculation	LWR, gas kinetics, etc.		Car following theory
Scanning time interval	10^0~10^2 sec [3].		10^{-1} sec
Multiple vehicle class	NG	OK	OK
Multiple route choice layer	NG	OK	OK
Granularity of time-space trajectory	-	Section-wised linear / state-wised linear	Fine grained
Harmonization with emission model	-	Macro/mesoscopic-emission model	Macro/mesoscopic/microscopic-emission model

3.2. Route choice modelling

As most of the ITS applications in Categories 3 to 5 have to deal with traffic flows on a network scale, a traffic simulation should model the route choice behaviour of drivers. Some traffic simulation models which have no route choice capability in themselves but are combined with static traffic assignment modules are insufficient to consider the dynamic aspects in those applications.

The route choice modelling in traffic simulation normally follows the Dynamic User Optimal (DUO) principle. DUO is to select the optimum route according to the route cost in the instant it is presented until the user reaches the destination. As traffic simulation reproduces the traffic conditions at respective time points, the modelling of DUO is relatively easy. This also can be applied to the modelling of ATIS. Note, however, that the content of the route cost is not defined in DUO. This means not only the route cost in the instant it is presented but also the cost from the travel experienced in the past run, such as for day-to-day simulation. Some ITS applications, such as peak load

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[3] Note that macroscopic models may take high time constants. In practice, most of them will be limited to the time constant of the smallest link in the network.

pricing, may aim to establish System Optimum (SO) traffic assignment through DUO, incorporating charge into route cost.

A probabilistic route choice model under the DUO principle which assumes human recognition error in the route cost may add realism to the simulation study. Despite the difficulty in parameter calibration, there are some popular models such as Dial's assignment, c-logit, path-sized logit, etc.

Unlike static traffic assignment, a vehicle in traffic simulation can choose the route not only at departure but also during travel on the network. Such dynamic route choice capability will be mandatory for Category 3.

3.3. Emission modelling

The emission modelling approach that is best fit to estimate CO_2-emissions depends on the level of detail in which the traffic/transport modelling was executed. Requirements for the emission modelling depend on the expected impact of an ITS measure on CO_2 emissions. In general, we suggest the following 3 types of approaches to model emissions:

3.3.1. Microscopic emission model

(a) Instantaneous speed/acceleration

Microscopic emission modelling aims to estimate emissions from driving, on a very fine temporal and spatial scale. The most direct approach is the use of instantaneous speed/acceleration emission models. For these, the required power output can be estimated from vehicle dynamics (e.g., speed, acceleration …), for which the emissions are directly estimated based on these fine data.

A number of more detailed modal models relate emission rates to vehicle operation during a one-second step. In theory, the advantages of instantaneous models include the following:

- Emissions can be calculated for any vehicle operation profile specified by the model user, and thus new emission factors can be generated without further testing.
- The models inherently take into account the dynamics of driving cycles.
- The models allow emissions to be resolved spatially, and thus have the potential to lead to improvements in the prediction of air pollution.

Some instantaneous models elate fuel consumption and/or emissions to vehicle speed and acceleration during a driving cycle, typically at one-second intervals. Other models use some description of the engine power requirement.

3.3.2. Mesoscopic emission model

(a) Based on mode

Mesoscopic emission modelling aims to use clustered data on traffic situations to estimate CO_2-emissions. A typical example of a traffic situation model is the Handbook Emission Factors for Road Transport (HBEFA).

The ranges of the temporal and spatial scales to which a mesoscopic-approach would be attributed are difficult to define. In any case, the input data for mesoscopic emission models is not on a per second basis as is needed for the microscopic approach.

In traffic situation models, the average emission factors are correlated with various driving cycle parameters. These, in turn, are referenced to specific traffic situations which are known by the model user. However, asking the user to define the traffic situation using a textual description of speed variation or dynamics may lead to inconsistencies in interpretation. Also, there are likely significant differences between the absolute characteristics of traffic in different cities and, importantly, there are few data (traffic and emissions) which correspond directly to real-world ITS implementations.

(b) Based on multiple linear regression for driving cycles

Another mesoscopic approach is the use of multiple linear regression (MLR) emission models. In an MLR model, each driving cycle data from one stopping to the next stopping used in its development is characterised by a large number of descriptive parameters, e.g., average speed, number of stops per kilometre, etc. A regression model is then used for each pollutant and vehicle category to determine the descriptive parameters which are the best predictors of emissions. Such an MLR model accepts driving cycle data as the input, from which it calculates the same range of descriptive variables and estimates emissions.

The Japanese approach, called stepwise-speed functions or SSF, using set intervals for time in which average speed is estimated, is similar to this.

3.3.3. Macroscopic emission model

(a) Based on average trip speed

In a macroscopic approach, the regression model characterized by average trip speed is used.

Under a certain traffic situation, the macroscopic emission models are created from the relationship between the average trip speeds and CO_2 emissions corresponding to the average driving behaviour (e.g. number of stops per kilometre, acceleration, etc.).

The macroscopic emission modelling estimates CO_2 emissions under the fixed driving behaviour. Therefore, it is possible to evaluate CO_2 emission resulting from the change of the average trip speed by ITS measures for which the vehicle behaviour is fixed clearly. However, the modelling class is not suitable to evaluate ITS measures which change the driving behaviour in the manner described in this Section.

(b) Constant emission factors

For a more simplified approach, average emission factors are used. The emission factors can distinguish between different types of transport activity, e.g., urban, non-urban, road type, etc. Aggregated emission factors are not suitable to assess ITS applications that affect driving dynamics, as they cannot take into account the subtle local changes of traffic conditions due to individual driving behaviours. In the case that ITS applications mainly influence route or mode choice on a more global scale (thereby influencing the total volume of traffic rather than an individual local effect) the constant emission factors are still not sufficient to assess the impact on CO_2 emission because they cannot take account the changes in traffic conditions.

4. Harmonization of traffic simulation and emission model

As mentioned above, there are different classes of TSs in terms of the granularity of vehicle trajectories. Accordingly, they should be combined with an adequate type of emission model to feed the trajectories. For the harmonization of traffic simulation and emission model, let us note the following issues.

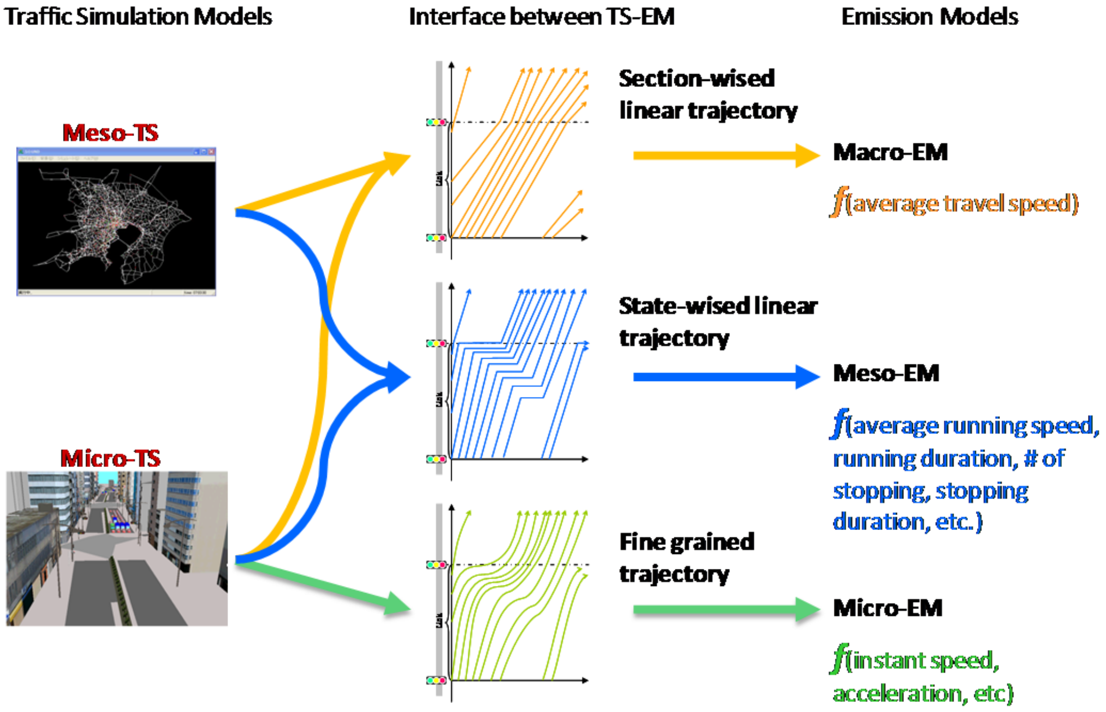


Fig. II.15 Harmonization of traffic simulation and emission model

4.1. Micro-scale harmonization with fine grained trajectory

Only the fine grained trajectories from microscopic traffic simulation can be accepted by microscopic emission model. In this case, the microscopic traffic simulation should be carefully validated not only at the aggregated flow level but also at the instantaneous speed and acceleration level. When the ITS measures influences driving dynamics, the microscopic traffic simulation should be verified to have reproducibility of the changes with sufficient preciseness.

4.2. Meso-scale harmonization with state-wised linear trajectory

When we use a mesoscopic traffic simulation which provides state-wised linear trajectories, the use of a mesoscopic emission model is approved, since the necessary inputs for each driving cycle such as average speed, running distance, number of starting / stopping, stopping duration, etc. can be given by those trajectories. When the ITS measures influences driving dynamics, the mesoscopic emission model should be revised by using new driving patterns which are collected with one of the options described in 4.4. In case that the effects of driving dynamics change on traffic flows are not negligible, the mesoscopic traffic simulation should properly model that effect.

As a fine grained trajectory can be easily converted into state-wised linear form, any microscopic traffic simulation can be rightfully combined with a mesoscopic emission model.

4.3. Macro-scale harmonization with section-wised linear trajectory

When the use of a macroscopic emission model can be approved, a microscopic traffic simulation or a mesoscopic traffic simulation which provides state-wised linear trajectories can be used. In this case, the aggregation size to take the average speed should fit to the popular trip distance of the driving patterns which are used for the development of the macroscopic emission model. If we are going to apply the macroscopic emission model to a short section, the average speed should be calculated over a certain time period in which the total vehicle distance becomes long enough. When the ITS measures influence driving dynamics, the macroscopic emission model should be revised as well as the mesoscopic emission model.

As a fine grained trajectory can be easily converted into section-wised linear form, any microscopic traffic simulation can be rightfully combined with a macroscopic emission model.

4.4. Adaptation of mesoscopic emission models for the changes on driving dynamics

Some ITS measures, such as eco-driving assistance, may change driving dynamics, i.e. acceleration/deceleration/cruising patterns. As for the use of a microscopic emission model which uses instantaneous speeds and accelerations, there is almost no need to change the model itself. In case of the use of a mesoscopic/macroscopic emission model, however, it is mandatory to revise the model parameters by using new driving cycle data under the ITS measures.

The most reliable way is to collect new driving data through a real experiment. It is, however, often difficult to coordinate an experiment when the implementation of the ITS measures are not achieved yet or are very costly. Let us here accept the following three options accordingly.

4.4.1. Option 1: Real experiment

The new driving cycle data under the ITS measures is collected through an experiment. The driving cycle comprises various scenarios with driving under different conditions, on different terrains, or on different road types. The driving patterns are measured by the speed data in the experiment. Corresponding CO_2 emission is obtained by rational methods, such as direct measurement of CO_2 emissions, measurement of a fuel flow and estimation by the microscopic emission model, etc.

4.4.2. Option 2: Use of microscopic traffic simulation + microscopic emission model

The new driving cycle data under the ITS measures is estimated by a microscopic traffic simulation and microscopic emission model. The driving patterns are reproduced by a microscopic traffic simulation which properly models the effect of ITS measures through various scenarios. Corresponding CO_2 emission is estimated by a microscopic emission model.

4.4.3. Option 3: Designed driving pattern + microscopic emission model

The new driving cycle data under the ITS measures is estimated by a desinged driving pattern and microscopic emission model. The driving patterns used in model development are modified from the normal driving pattern with an intended speed profile under the subject ITS application, e.g. the 'e-Start' in eco-driving. Corresponding theoretical CO_2 emission is estimated by a microscopic emission model.

For example, in order to obtain the new driving patterns in which the moderate acceleration by eco-driving is reflected, the speed pattern from a start to constant speed is transposed to the theoretical speed patterns (for example, first order lag curve etc.) which reach constant speed with reduced acceleration. These results can then be used to benchmark or compare results from practice, e.g. a small scale experiment like Option 1 or Option 2.

III. Verification, Calibration and Validation

1. Philosophy of the verification, calibration and validation

1.1. Basic concept

There is a wide variety of possible models that can be used to evaluate energy consumption. Each model has its own characteristics depending on how the model was developed. Each model developer creates their own model and each model user selects a model for their purpose independently. They have their preferences according to their interests or concerns. It is impossible to determine a unique, universal model that can be used for all kinds of CO_2 assessments. Therefore, we do not specify a certain model to be used, but have prepared a standard framework for verification and validation that was approved internationally (Fig. III.1). This means that there is no official approval procedure by an authority. This is because it is not easy to determine unified criteria, and the level of reproducibility can be different depending on the purpose of the model usage.

The standard framework gives an overview of traffic phenomena and variables that are especially relevant in the context of CO_2 assessments and for which the models are ideally verified, calibrated and validated. It helps users prepare and document this process, and supports stakeholders in deciding whether the model is suitable for the proposed application. It does not currently provide quantitative criteria for which the model should meet – it is left to the stakeholders to decide how stringent the criteria need to be. The standardized process makes it easier for stakeholders to assess, document and communicate about the suitability of a model.

There are three major stakeholders in model verification/validation: model developers, model users and clients who commissioned the modelling study. Model developers should verify and validate their models according to this standard verification/validation process, and disclose their results. Model users can select a model for their evaluation purposes considering the verification/validation results of various models, and may use it by calibrating the model parameters according to the conditions of the site studied. Finally, clients need to approve the model used, based on the disclosure of results of the standard verification and validation process.

1.2. Definitions

1.2.1. Verification

Verification means to answer the following question: Did we build the model properly? This means, that we check if the model works as was intended to suit the well-established traffic flow theory, and that the mechanisms are modelled correctly. For example, vehicles do not collide with each other, the saturation flow rate at a signalized intersection is reproduced appropriately, a queue is built up according to the shockwave theory, route choice probability is consistent with the theoretical choice model, etc. A certain knowledge or expectation should exist about the mechanisms to be verified, though exact measurement data is not used.

For every newly developed traffic model, the verification process is mandatory. However, most traffic simulation studies start with an existing model, in which modifications are implemented to handle situations for which these models were not initially developed. Again, verification is necessary for the newly developed parts.

The verification process usually works as follows: You design a controlled, experimental situation with a certain specified input. Then you run the model and test if the model gives the expected output. The expected output should be based on principles founded in internationally well-accepted traffic flow theory, such as different types of congestion which are recognized and observed in real traffic.

1.2.2. Calibration

Calibration means: tuning the model parameters to make the model reproduce reality as closely as possible. For this, we need to compare outcomes from the model with results of observations in reality, and change the model parameters systematically until the outcomes are close enough to the real observations.

Ideally, the observations from reality are available as an accurate and reliable dataset, for example with average speeds, traffic flow counts, etc. However, when data or time/resources are limited, calibration is often skipped or only done based on visual inspection from the simulation or visual comparison of plots (fundamental diagrams). However, this is not a proper calibration. A proper calibration needs recent and a sufficient amount of reliable traffic measurements on the specific location.

1.2.3. Validation

Finally, validation means to answer the following question: Did we build the right model? A positive answer can be given when the model outcomes are similar to fresh real data when using the parameters as found in the calibration of the verified model. These fresh real data should be measurements made under the same conditions as the dataset used for the calibration. If they are not available, then common statistical practice dictates to split all the available datasets in 2 parts: a large part for calibration, and a smaller part for validation. Similar to the calibration process, statistical tests can be carried out in order to check if the results are sufficiently close to the real data. For this, several goodness-of-fit tests are available [MULTITUDE, 2012].

1.2.4. Disclosure

The results of the verification and validation should be disclosed after conducting the procedures. They are to be shown in the same format so that model users and clients can understand the characteristics of the model and judge whether that model is suitable for their use. It is desirable to set up an information sharing space (termed a "clearinghouse", which might be prepared on a certain website) for easier comparison by users.

1.3. Standard process of verification and validation

This section describes the process of verification and validation, as it is proposed for studies assessing the CO_2 reduction effects of ITS. This process is described for situations in which an existing model is used as well as for situations in which a new model (traffic simulation model and/or CO_2 emission model) is built. Also, it considers verification of both the base case (situation as it is without the ITS system) and the treatment case (in which the ITS system has been implemented and of which the effects are to be determined).

Fig. III.1 shows the steps to be taken for a CO_2 assessment model. Here, there are two stages of model verification/validation and implementation. The former is done in the model development process in order to show the model's reliability using common benchmark datasets so that several different models can be compared for model selection. The latter is done in the implementation process in order to show model's applicability to a certain specific site using a site-specific dataset. The steps are slightly different when an existing model is used to when a new model is built. The differences in what is needed in terms of verification, calibration and validation are described in Table. III.1. This table distinguishes between verification/validation of basic traffic phenomena, CO_2 relevant traffic phenomena and system and study area specific behaviour. This is because it is assumed that basic traffic phenomena have been verified and validated in commonly used traffic simulation. It needs to be checked whether this was done in compliance with the standard process, as part of the selection of a suitable traffic simulation (or traffic simulation-emission model combination). It is preferable to use common benchmark datasets so that several different models can be compared for model selection. For verification, a hypothetical data set can be used; for validation, a real-world data set is preferable.

Which models are appropriate depends on the purpose of the assessment and the system that is evaluated. In other words, a model which is not suitable for one case can still be suitable for another case. The reference model (either the category model or the instance model; see paragraph II.1) for the ITS that is studied can support the process of selecting a suitable model.

For CO_2 assessment, it is important that certain other traffic phenomena (not part of basic verification and validation) are considered as well. In addition, when a new system is implemented in (or linked to) the traffic simulation, the resulting traffic/driving behaviour needs to be verified when new functionality is added to the existing traffic simulation tool. Verification tests for new systems can be based on the system specifications. For instance, if a system giving route guidance is modelled, it needs to be confirmed that the vehicles which receive guidance change their route when this would be appropriate according to the system specifications, and that non-equipped vehicles do not change their behaviour (in cases when they would not be expected to do that). Another example: if an adaptive cruise control (ACC) system is modelled, it can be checked whether acceleration and deceleration patterns follow the ACC specifications and whether these patterns are different from those of non-equipped vehicles. Validation is only possible when suitable data sets are available, which is not likely for new systems. Calibration needs to be done at least for any new study area modelled and also for the new system implemented in the traffic simulation. For the model implementation phase, it is preferable to use a site-specific data set.

For emission model, verification and validation is a very different matter, and it will thus be treated separately from verification and validation of traffic simulation. For emission model, verification and validation are only relevant for the upper part of Fig. III.1 (the model implementation part is not relevant).

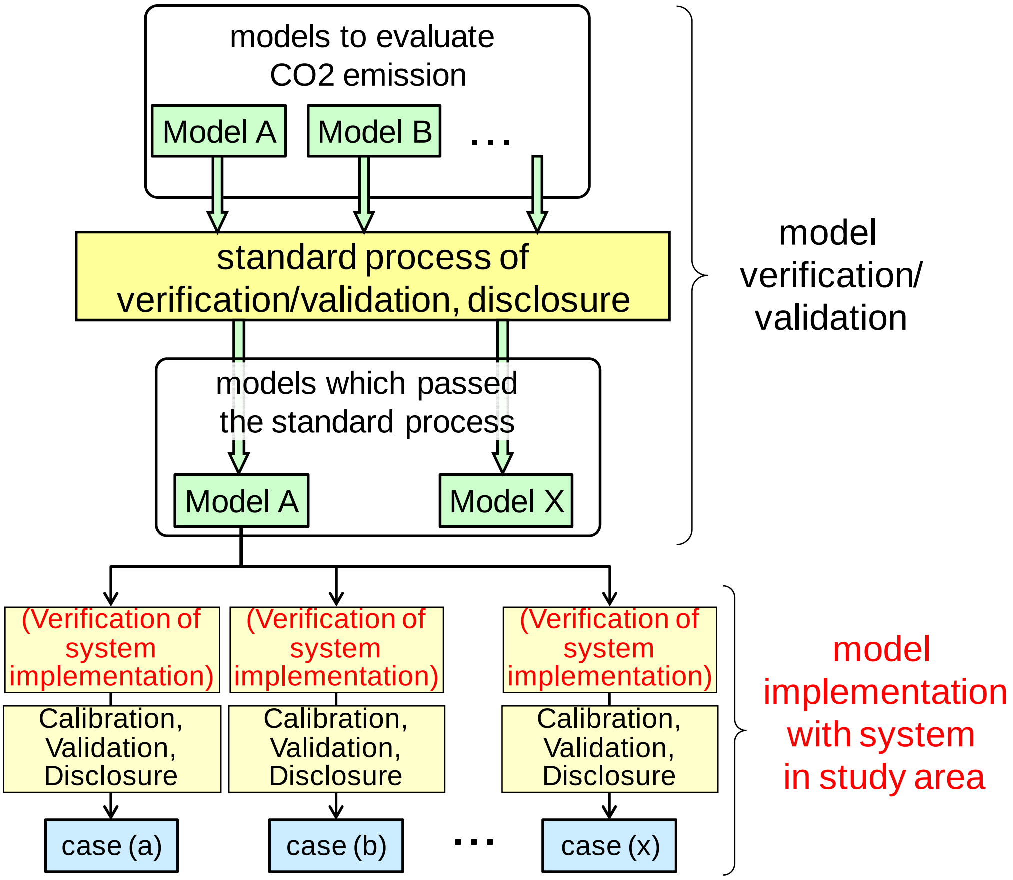


Fig. III.1 Standard framework of verification/validation, and system and study area specific implementation

Table. III.1 Need for verification and/or validation for existing and new traffic simulation models

	Existing model	**New model**
Basic traffic phenomena	N.a.	To be done (verification, validation), in compliance with standard process
CO_2 relevant traffic phenomena	To be done for base case (verification; validation when suitable data set is available) , in compliance with the standard process	To be done for base case (verification; validation when suitable data set is available), in compliance with the standard process
System and study area specific behaviour	To be done for base case and treatment case (includes verification of behaviour changes due to system; validation when suitable data set is available), in compliance with the standard process	To be done for base case and treatment case (includes verification of behaviour changes due to system; validation when suitable data set is available), in compliance with the standard process

Necessary verification/validation items can be different depending on the type, the scale and the (time and space) resolution of models. For example, microscopic phenomena such as vehicle acceleration and the number of stops are important in the case of microscopic models. On the other hand, uniquely customized variables which are the input to specific types of emission models are important in the case of mesoscopic models (See Fig. III.2 for an illustration of the difference between mesoscopic and microscopic models concerning the interface with emission model). Generally, traffic simulation models are not originally developed for environmental analyses and they may contain uncertain characteristics, therefore additional verification/validation is needed even though they are already verified/validated for their original purpose. Deceleration/acceleration behaviour at intersections is a commonly used example. Other user behaviours in traffic simulation models, such as departure time choice and route choice, are difficult to consider generally, because they are higher level choices in human behaviour modelling. However, they are influenced by some ITS applications, and in that case, the reproducibility of such user behaviours should also be checked.

This standard verification/validation framework does not include a process of “certification” but assumes a process of “disclosure” of the verification/validation results. That means the reliability of a model is not approved officially by a certain authority. Instead, model users and clients can judge the applicability of a model by examining the disclosed results of model verification/validation. This is because it is not easy to determine unified criteria, and the level of the reproducibility can be different depending on the purpose of the model usage

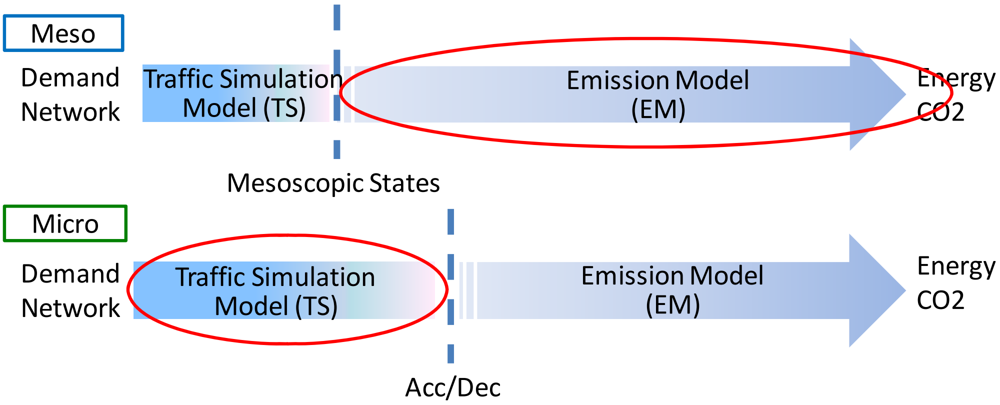


Fig. III.2 Difference between mesoscopic and microscopic models

2. Items to be verified / validated

For CO_2 assessments of ITS, several situations are important to model accurately. For example, traffic at intersections, high flow roads (highways, motorways – both in free flow and congestion), hilly roads, and traffic in congested urban networks (with certain mode, departure time and route choices). In order to check the quality of the modelling, specific items need to be verified and validated for the traffic simulation model (TS) and the emission model (EM). Table. III.2 shows these items. Note that for micro models, additional items are given that cannot be verified/validated in mesoscopic or macroscopic models. The details of how verification and calibration and validation can be done are explained in the following sections.

Table. III.2 Items in verification calibration and validation

		Verification	**Calibration and Validation**
Traffic Simulation Model (TS)		Vehicle generation Bottleneck capacity/ Congestion occurrence Shockwave propagation (Route choice) (Departure time choice) (Mode choice)	Traffic flow (volumes) Speed Number and duration of stops (not in macro model) Queue length and location
	micro model	Speed and acceleration Spacing among vehicles Speed choice (free flow, up/downhill) Start / stop behaviours Gear shifting	Speed and acceleration Driving modes VSP (Vehicle Specific Power) distribution
Emission Model (EM)		Model structure Vehicle type setting	CO_2 from individual vehicles Time-series CO_2 from individual vehicles Speed vs. CO_2 relationship
	meso model		Stepwise Speed Function (SSF)

3. Verification

This section describes the items to be verified for CO_2 evaluation and the procedures for verification. Here, the basic idea of verification is to compare “the established theory to describe phenomena” and “the results of dynamic conditions calculated by the model.” The purpose of the verification is to show the characteristics of the model by confirming correlation with the theory or by checking the relationship between certain model parameters and the model behaviour.

3.1. Traffic Simulation Model (TS)

In the verification process of traffic simulation, fundamental functions which are essential for traffic simulation are to be verified to meet the knowledge of the traffic theory. Generally the microscopic model has more flexibility in modelling of vehicle movement, therefore we need additional items to be verified in the case of microscopic models. There are a number of previous works which deal with the methodologies to verify traffic simulation models. One of these is the “Standard Verification Manual for Traffic Simulation (SVM)” (http://www.jste.or.jp/sim/manuals/VfyManE.pdf), which offers detailed explanations for several verification items. Below, additional items are discussed, but for these no standard (hypothetical) data sets are available yet. It depends on the instance model, where the emphasis of the verification lies – not all items included below may be relevant.

3.1.1. General items

Here are the general items to be verified in traffic simulation for general use as well as CO_2 emission assessment. SVM shows the procedures to verify them in a detailed way.

- Vehicle generation (see SVM)
- Bottleneck capacity (see SVM)
- Queue evolution / shockwave propagation (see SVM)

Check the following:

- The vehicles are properly generated at the entry point of the simulation to the network according to the assumed arrival pattern.
- The throughput at a bottleneck section is consistent with the specified capacity.

- The evolution of the queue or the propagation of the traffic flow boundary follows the shockwave theory.

3.1.2. Intersections

Basic behaviour concerning intersections is normally covered well enough in existing simulation models (controllers, giving way, lane/route choice, stopping for red light, moving at green light).

Possible shortcomings with regard to CO_2 emissions: speeds, accelerations, and vehicle fleet composition:

- Is the free speed realistic?
- Is the deceleration behaviour realistic?
- Is the acceleration behaviour realistic?
- Saturation flow rate and turning capacity at signalized intersection (see SVM)

Check the following:

- If speeds are between a certain range around the speed limit, and acceleration is mostly between -4 and 3 m/s2;
- If the speed on the intersection or roundabout is within certain margins;
- If the desired vehicle types are modelled.
- The maximum flow rate during green signal is consistent with the specified saturation flow rate.
- The throughput of turning movements which are regulated by the opposing traffic is consistent with the specified capacity.

3.1.3. Highway/motorway driving

The most important issues for highway and motorway driving modelling relevant for emissions calculations, are:

- Free-flow driving: in traffic simulation models, often there is too little variation in speed. Also, the free flow speed distribution should be realistic.

- Congestion: occurrence and nature of jams (e.g., stop & go waves, wide-moving jams), speed variance within congestion.
- Capacity and merge/diverge ratio at merging/diverging section (see SVM)
- Long slopes/hills: how is speed affected? E.g., the maximum power output may be calculated (limited for hills), but if the simulation model only takes into account the maximum possible acceleration, given a gradient influence, then the model gives the wrong results as in reality the vehicle may slow down more when going up, due to inattention or unadjusted driver behaviour. In VISSIM for example the maximum power output is modelled (as a crawling speed that a truck can maintain when travelling uphill).

Check the following:

- Is there any variation in speed of the individual vehicles when driving in free-flow conditions?
- Is the free-driving speed distribution realistic, also per lane, e.g., distributions around the speed limit, median-side lane fastest (if possible compare with local measurements).
- Is congestion formed at bottleneck locations (lane drops, merging/weaving locations)?
- Is congestion formed spontaneously at high traffic flows (due to e.g. lane changes and braking of individual vehicles)?
- Gradually increase the demand until congestion occurs. Is the highest (minute) flow before congestion occurs (estimator of the capacity) around 2500 veh/h (or conforms to the local situation)?
- Plot a fundamental diagram of flow against speed. Compare with a measured fundamental diagram. Are the shape and the values comparable? Are simulated values found for every branch of the fundamental diagram (free flow, bound or capacity flow, congested)?
- Does the propagation speed of shock waves match the documented propagation speed for the modelled location?
- Do vehicles slow down when driving up a hill?

- Do trucks slow down more than light duty vehicles when driving up a hill?
- Do vehicles accelerate when driving downhill?
- Do trucks accelerate more than normal vehicles when driving downhill?
- Is the share of trucks realistic?
- Do trucks (mainly) drive on the shoulder-side lane?

3.1.4. Route choice

Route choice is relevant for CO_2 calculations, since it influences the number of kilometres driven and ITS such as navigation systems and variable message signs influence route choice.

Many different types of route choice models exist. A distinction can be made between:

- Route choice models that are determined before the actual simulation based on (equilibrium) assignment, whereby drivers are distributed over several route alternatives such that (total or individual) travel times are minimised (= pre-route).
- Route choice models that enable the drivers to decide and change their route during the simulation, based on actual traffic conditions (= en-route).

Also the amount of information that people have concerning actual congestion may differ. For modelling of the effects of ITS, the en-route type is preferred, since the drivers may change their route based on the actual information from the ITS during their trip.

N.B. Mode, route, and departure time choice: this higher level decision is not just a matter of picking the quickest route, but it may also contain other factors such as familiarity and advice. However, this rapidly gets quite complex. More information on this can be found in Chapter 3 of [Maerivoet, 2006].

Check the following:

- Does the distribution over several route alternatives seem realistic (to people with local knowledge)?
- If congestion occurs on one of the routes, do drivers change their route?

3.1.5. Travel demand → OD matrix

Travel demand is very important for CO_2 calculations, because it has a large influence on the total vehicle kilometres. However, travel demand is difficult to estimate. Traffic models use an OD-matrix as input, in which each cell reflects the number of trips for that OD-pair. An OD-matrix cannot be measured directly, unless you could ask all people in a certain area how many trips they make, and to which destinations. Therefore, the OD-matrix is usually estimated based on sampled answers by questionnaire survey and/or measured flows at several locations in the simulated network. There are some new possibilities based on new technology, such as Bluetooth, mobile phone usage, etc., to estimate the OD matrix.

An important issue concerning travel demand are second order effects, or the attraction of new traffic demand on certain OD relations or links when the traffic load on these links has been reduced (or capacity increased) due to new developments or traffic measurements, such as new infrastructure or less congestion due to peak hour management. The amount of extra trips cannot be estimated with the traffic model, it should be estimated separately based on, e.g., an (economic) generation and attraction model.

Check the following:

- The simulated routes reflect the number of trips as given in the OD-matrix.
- The OD-matrix seems realistic to people with local knowledge, i.e., large number of trips for important/high populated areas to important/high populated areas (e.g., from residential areas to shopping centres, office areas, etc.) and low number of trips for less important OD-pairs.
- Second order effects: are they taken into account or not?

3.1.6. Departure time/mode choice

Departure times determine how much traffic will be loaded on the network in a certain time interval, and hence influence the amount of congestion and CO_2 emission. In turn, departure times are in practice also influenced by the amount of congestion on the road, for example people leaving earlier to work when they know that there is always congestion on their route after a certain time. Furthermore, some ITS also influence departure times, e.g., by giving real-time traffic information. However, traffic simulation models ask for a departure time profile (or time-dependent OD-matrices) as input, and congestion in the simulation does not influence departure times, while in practice it does.

ITS can also influence mode choice (e.g. a multimodal journey planner). If the TS includes a mode choice model, it needs to be confirmed if the ITS changes mode choice as expected (e.g. more public transport trips when there is heavy congestion and travellers receive up-to-date information on this).

Check the following:

- The departure time profile in the model reflects a realistic departure time profile.
- The modal split is realistic and can be manipulated (again in a realistic way) by the implemented ITS.

3.1.7. Gear shifting

The gear that a driver chooses for a certain speed, influences the amount of emissions. Generally driving in a higher gear gives lower accelerations and lower emissions. Also, certain ITS can influence the gear choice, such as gear shift indicator, eco-driving support systems, etc.

Most traffic models do not contain gear shifting models, except for some very detailed (sub)micro simulation models that contain an engine model (e.g., the MIXIC model).

If the traffic simulation model does not contain a gear shifting model, a (simple) gear-choice model may be added for better emission calculations. However, it should be checked that this does not introduce pseudo-accuracy.

Check the following:

- At which speed (and rpm if available in the model) the gear is shifted to which gear, compare with a list of average gear shifting speeds;
- If there is a variation in gear shifting between drivers and vehicle types (if data about variability within and between drivers are available).

3.2. Emission Model (EM)

In the verification process of emission model, it should be verified whether CO_2 is estimated based on physical and statistical fundamentals. In addition, it is also necessary to check the vehicle categorization method.

3.2.1. Model structure

Because CO_2 emission from vehicles is significantly related to energy for driving, it should be checked whether the structure of the model formula expresses the effect of 4 fundamental factors: acceleration resistance, rolling resistance, aerodynamic resistance and grade resistance physically or statistically. It is also recommended to conduct sensitivity analysis by changing these factors. For checking, various driving cycles are used. The following correlations should be checked about estimated CO_2 emissions from emission model.

i) Correlation between average speed and CO_2 emission.

ii) Correlation between vehicle weight and CO_2 emission.

3.2.2. Vehicle category composition settings

Generally, the vehicle categorization in emission model is more detailed than the vehicle categorization in traffic simulation model. Therefore, it is necessary to subdivide vehicle categories from the output of traffic simulation. Or it is necessary to merge the vehicle categories in emission model. In the verification process, the basic idea to set vehicle categories and their composition should be clarified. In addition, it should also be described how and based on what kind of information the vehicle category composition was set. The source of information, the benchmark year etc. should be clarified. The process of clarification of the vehicle categorization method is described below.

i) Check whether the vehicle is categorized by characteristics of CO_2 emission.

ii) Check whether the composition of each categories is based on Vehicle Miles Traveled (VMT).

iii) Check the clarified data source of VMT for each vehicle categories.

4. Calibration and Validation

This section describes the items to be validated for CO_2 evaluation and the procedures for validation. Validation is a process to check the applicability of models to an actual situation considering actual inputs and conditions. Here, the adequacy of the model specification, the accuracy of the model output and the possibility to calibrate model parameters etc. should be examined. For these purposes, observed data from the actual field have to be collected to conduct the validation process.

4.1. Traffic Simulation Model (TS)

For the calibration and validation of a traffic simulation model, general items that should be verified at all times and special items that should be verified according to the situation for which the simulation model will be applied are set.

For the calibration and validation, we distinguish between general items that should be considered for all traffic situations found in the study area, and special items that should be considered only if the instance model of the ITS system applied indicates that this is relevant (see Chapter II for the examples of instance models which explain the mechanisms via which ITS applications influence CO_2 emissions).

4.1.1. General items for calibration and validation

Common variables to be tuned (calibrated) are the speed and acceleration (distributions), per vehicle category. Also, parameters of the car-following model may be adjusted.

Visually, a comparison between the real world and the model indicators can be made with speed distributions, trajectories, space-speed-plots, speed-acceleration-plots (see the examples shown in the next sections). This gives an indication of how close the model approaches reality, and can show obvious differences between the model and the real-world. Even if a visual inspection shows that the distributions are very similar, it is still recommended to also carry out a quantitative validation. This is possible by using statistical tests suited to comparison of one- or multi-dimensional distributions (e.g. the Kolmogorov-Smirnov test, of which generalizations exist for more than 2 dimensions [Fasano & Franceschini 1987], [Siluyele 2007], or the t-test with the Hotelling's test as multidimensional generalization [Bubeliny 2010]).

For calibration/validation for CO_2 assessment, macroscopic data such as average speed is not sufficient, since especially the acceleration behaviour is important. However, microscopic data is difficult to obtain. It can be obtained, e.g., by observation with cameras and imaging analysis afterwards. Trajectory data can be used to derive speeds, accelerations, following behaviour, and braking initiation distance.

The following items need to be considered for all traffic situations that can be found in the study area.

(a) Traffic flow

Compare simulated and measured traffic volume per vehicle type (and if desired per lane) and show regression coefficient and coefficient of determination between those two values.

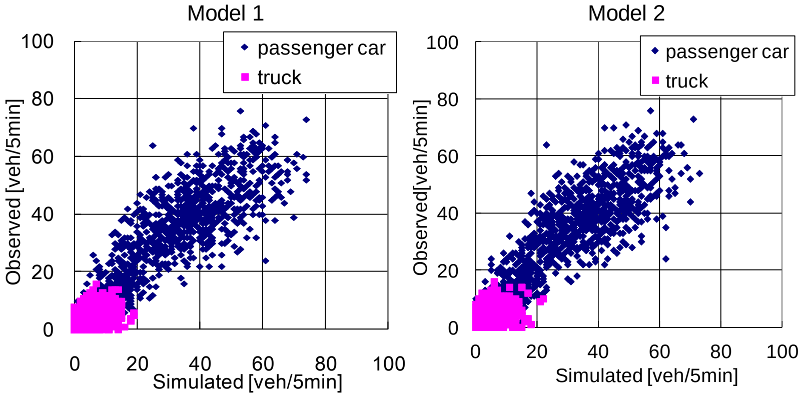


Fig. III.3 Example of traffic flow diagrams, compared for real data and results of simulation [Tanaka et al, 2011]

(b) Average speed (Travel time)

- Compare simulated and measured average speed of the individual vehicles according to the time of departure.
- Compare simulated and measured travel time of certain routes of the individual vehicles according to the time of departure.

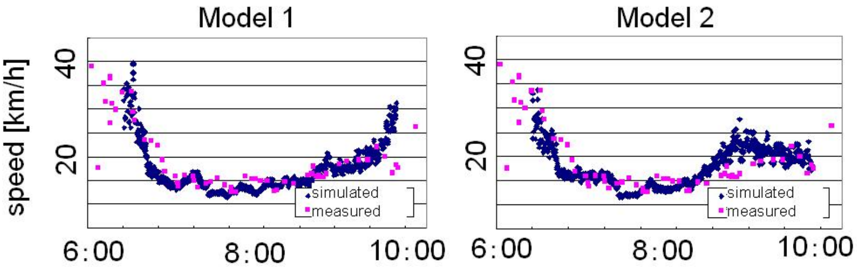


Fig. III.4 Example of average travel speed diagrams, compared for real data and results of simulation [NEDO, 2013]

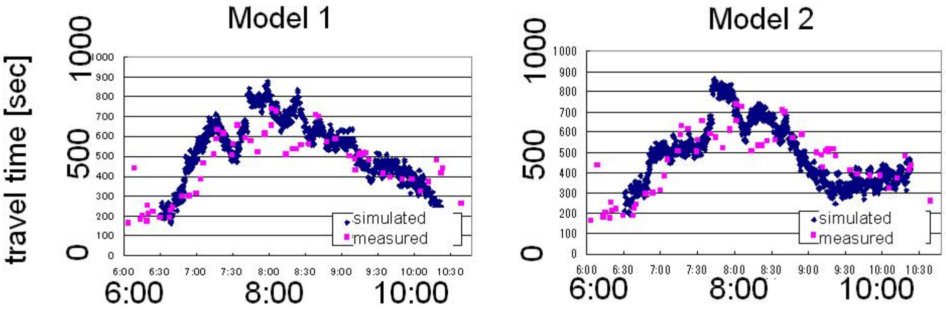


Fig. III.5 Example of travel time diagrams, compared for real data and results of simulation [Tanaka et al, 2011]

(c) Free (or desired) speed distribution per lane, per vehicle type.

- Compare the modelled desired speed distribution with speed of vehicles under free flow conditions (which are assumed to drive at their desired speed).
- Also compare the standard deviation of the free-flow speed of the individual vehicles as a measure of the vehicle's driving dynamics.

(d) Vehicle fleet composition

Compare simulated and measured composition of vehicle type. The vehicle type is according to the ITS application subjected to evaluation and definition of classification of the vehicle type given in Chapter II.

In addition, for microscopic traffic simulation models, the following items should be validated.

(e) Distribution of driving modes

Compare simulated and measured distribution of 4 driving modes that are defined as "stop" (velocity < 5 km/h), "acceleration" (velocity > 5 km/h and acceleration > 0.5 km/h/s), "deceleration" (velocity > 5km/h and acceleration < -0.5 km/h/s) and "cruise" (other).

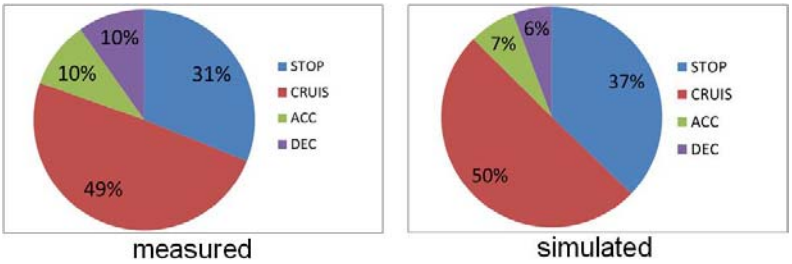


Fig. III.6 Example diagrams of distribution of driving modes, compared for real data and result of simulation [NEDO, 2013]

(f) Distribution of speed

Compare simulated and measured speed distribution, if desired per lane and vehicle type. It might also be useful to filter for different levels of service from free flow to congestion.

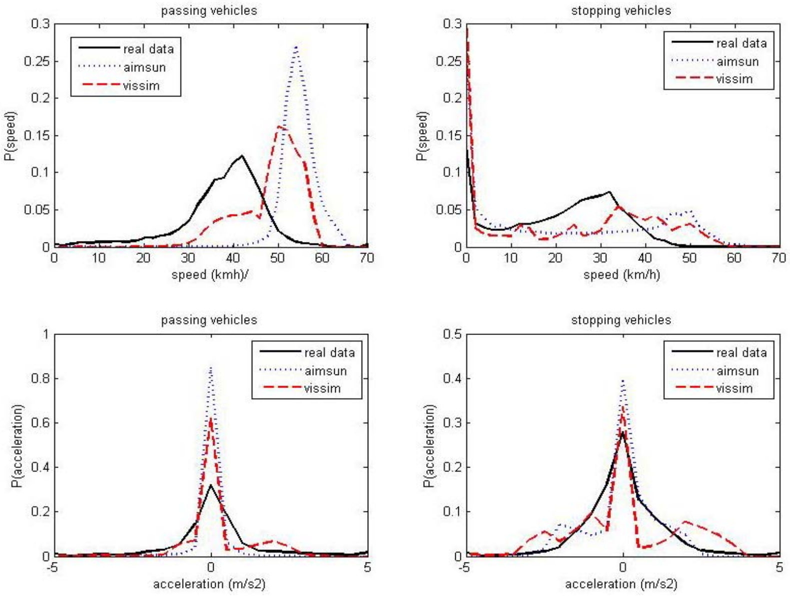


Fig. III.7 Example diagrams of speed distribution of passing and stopping vehicles at an intersection, compared for real data and results of simulation [Wilmink, 2009]

(g) Distribution of speed and acc/deceleration

Compare simulated and measured distribution of speed and acc/deceleration.

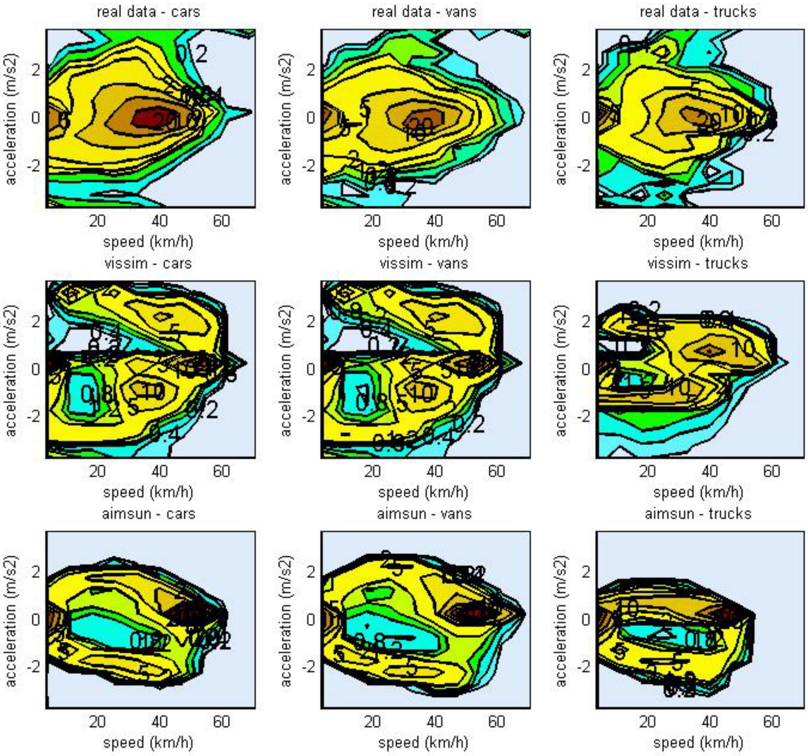
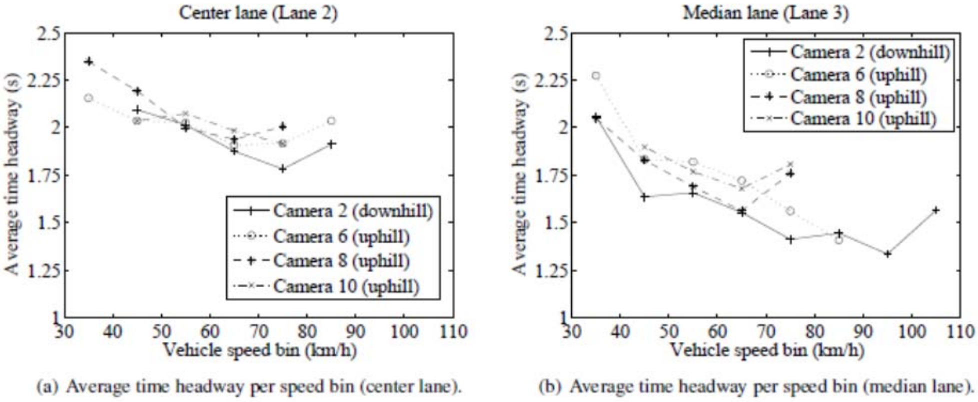


Fig. III.8 Example of speed-acceleration diagrams at an intersection, compared for real data and results of simulation [TU Delft & TNO, 2009]

(h) Headways

This has to do with the car-following model. The parameters of the car-following model that can be calibrated/validated depend on which car-following model is used. Headways generally depend on the speed of the vehicle and one or more predecessors. Headways can be measured with some in-car systems (distance to the rear-end of the preceding vehicle) or video data. Speed-headway plots (see Fig. III.9) or headway distributions can be used to compare real-world data with the model.



(a) Average time headway per speed bin (center lane). (b) Average time headway per speed bin (median lane).

Fig. III.9 Measured average time headway per speed bin on a sagged highway (Source: Goni Ros, B. e.a., Car-following Behavior at Sags and its Impacts on Traffic Flow. 92nd Annual Meeting of the Transportation Research Board)

(i) Uphill and downhill speed and acceleration.

Compare measured and simulated uphill and downhill speed and accelerations in the case of steep slopes.

(j) Distribution of speed and VSP(Vehicle Specific Power)

Compare simulated and measured distribution of speed and VSP. VSP is an abbreviation for Vehicle Specific Power, which is used in some emission models, that is calculated by the following equation:

$$VSP = \frac{P}{m} = \frac{Fv}{m} = v \times \left(a \times (1+\varepsilon) + g \sin\theta + Ag\right) + Bv^3/m$$

where:

m: is vehicle mass in kilograms

a: is vehicle acceleration in m/s^2

ε: is mass factor accounting for the rotational masses

g: is acceleration due to gravity

A: is rolling resistance

B: is aerodynamic drag coefficient

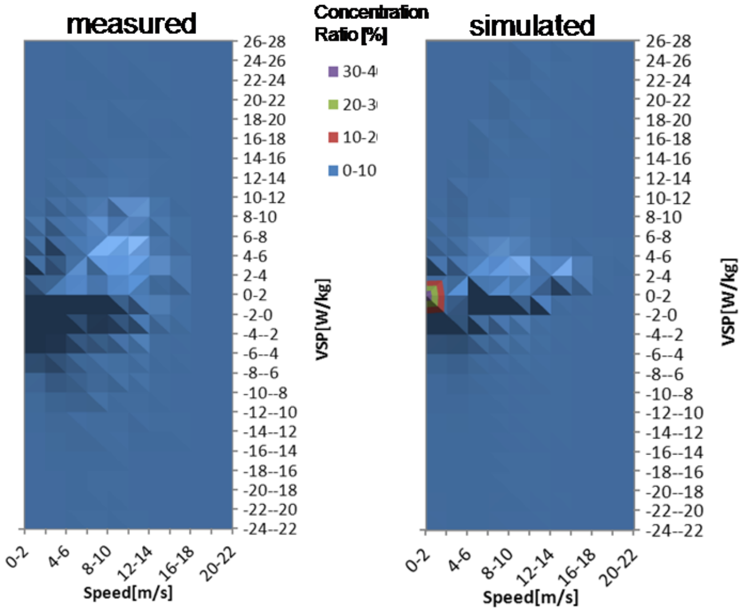


Fig. III.10 Example diagrams of distribution of speed and VSP, compared for real data and result of simulation [NEDO, 2013]

4.1.2. Intersections

For intersections, the following items are considered relevant:

(a) Queue length

Compare simulated and measured queue length at certain intersections of each time.

(b) Number of stops/runs

Compare simulated and measured number of stops/runs of the individual vehicles according to the time of departure.

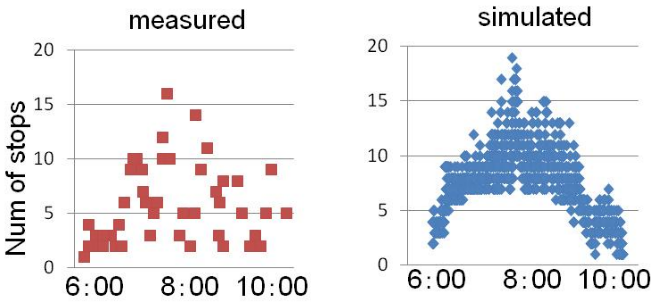


Fig. III.11 Example diagrams of number of stops, compared for real data and result of simulation [NEDO, 2013]

(c) Duration of stops/runs

Compare simulated and measured duration of stops/runs of the individual vehicles according to the time of departure.

In addition, for microscopic traffic simulation models, the following items should be validated.

(d) Average speed and standard deviation

- Compare the average speeds and standard deviations of vehicles approaching the intersection, passing the intersection, and leaving the intersection. A Similar figure to Fig. III.7 in 4.1.1(f) would apply here.
- As an alternative to giving just the average speed and standard deviation, a figure can be made that shows the frequencies of speeds over distance (see Fig. II.13; in this figure only a plot for measured data is given, but the same figure can be made from simulated data and compared to the one made from measurements). Relative frequency (or percentage) of vehicle speed at different distance from the stop line is shown as a contour map.

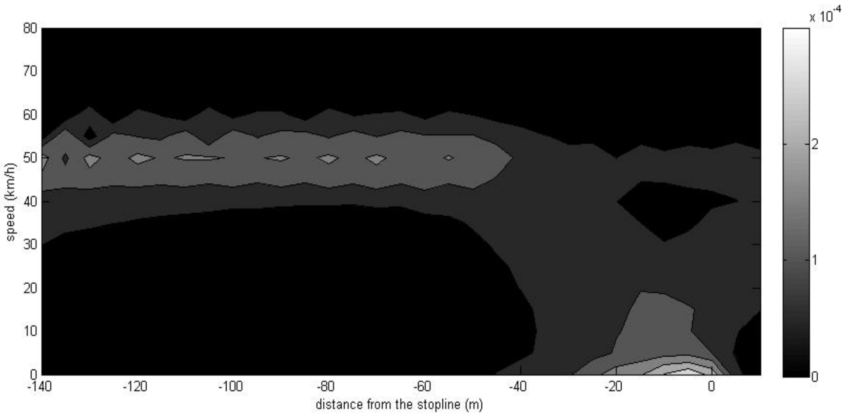


Fig. III.12 Speed profiles for different road sections before and immediately after the stop-line [Viti, 2008]

(e) Acceleration rate

Compare the acceleration rates of vehicles leaving the intersection (first in queue), as well as acceleration after standstill with predecessors.

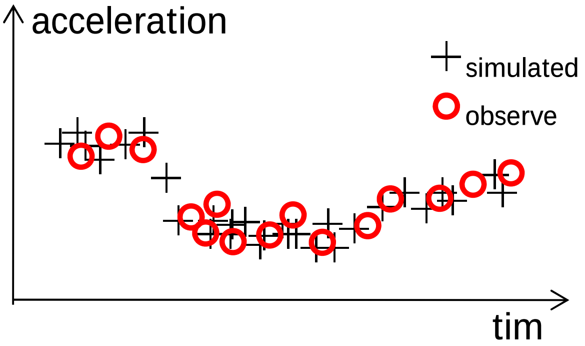


Fig. III.13 Example diagrams of acceleration rate of the first vehicles leaving an intersection [NEDO, 2013]

(f) Deceleration rate

Compare the deceleration rates of vehicles approaching the intersection. A diagram similar to the case of acceleration rate can be drawn.

(g) Braking initiation distance

The braking initiation distance (to the stopline) indicates the location where vehicles start to decelerate when approaching an intersection. This distance depends on the way the intersection is controlled and of the position of the vehicle in the queue. Filtering is needed; it is only useful to compare vehicles in the same situation (e.g. the first vehicle in the queue stopping for a red light).

4.1.3. Highway/motorway driving

(a) Congestion locations and length

Compare simulated and measured location, length and nature of congestion (e.g. shockwaves, stop and go, bottleneck jam). This can be done using pictures or movies (model run vs. measurements over time), as in Fig. III.14.

Fig. III.14 Measured (left) and simulated (right) congestion in a macroscopic traffic model of Amsterdam. The more purple, the longer the congestion is present over the day. (source: TNO report "Ontwikkeling Verkeersmodel in Indy voor A10-oost – A1")

(b) Distribution over lanes and share of trucks per lane.

Compare simulated and measured distribution of traffic flow over lanes and the share of trucks per lane.

In Fig. III.15, an example is given of validation of a microscopic simulation model of distribution of traffic flow over lanes compared with real-world measurements.

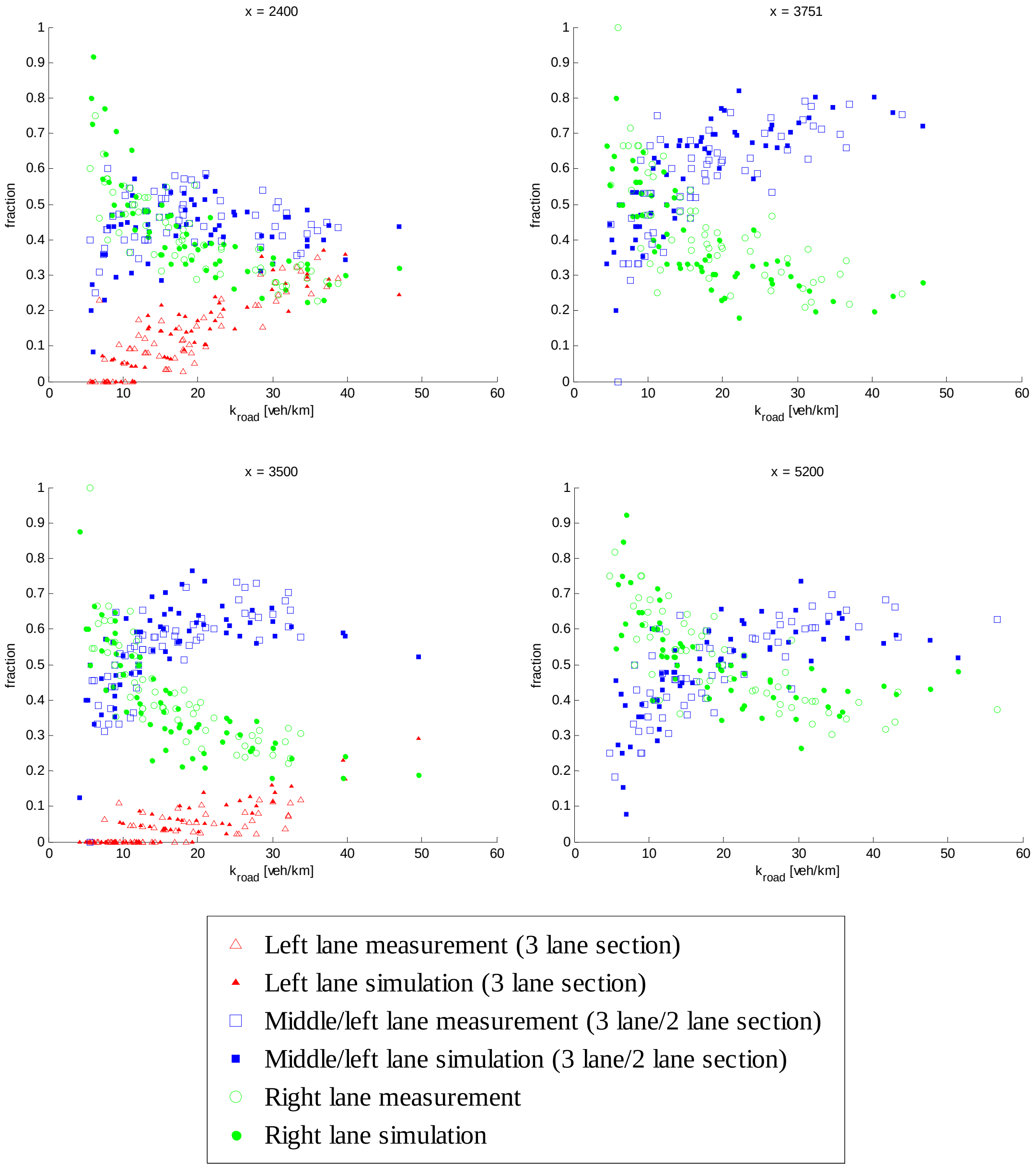


Fig. III.15 Comparison of simulated and measured vehicle fractions per lane at varying locations near a lanedrop from 3 to 2 lanes (lanedrop at x=3700). Source: Schakel, W. e.a. (2012) LMRS: An Integrated Lane Change Model with Relaxation and Synchronization. Annual Meeting of the Transportation Research Board 2012.

(c) Capacity, capacity drop

- Compare a simulated and measured fundamental diagram (maximum flow, drop from maximum flow to congested flow) at a bottleneck.

- Compare acceleration rates or distributions when driving out of congestion.

4.1.4. Route choice

Compare simulated and measured flows on different route alternatives and turn fractions at intersections, get the simulated flows and turn fractions as close as possible to the measured flows/turn fractions. (if route choice data are available, e.g., from license plate cameras or Bluetooth sensors, this can also be used)

The parameters that can be tuned are very specific to the type of route choice model. For example, it may be a variable that reflects the amount of knowledge that drivers have about actual driving conditions.

4.1.5. Travel demand → OD matrix

(1) Tune the OD-matrix in order to get the measured flows as close as possible to the simulated flows.

(2) Compare number of trips per OD-pair when routing information is available (e.g., from FCD, license plate cameras or Bluetooth sensors or user surveys)

For a simple network, e.g., a single motorway, the OD-matrix can easily be derived from traffic flow counts when counted at every on- and off ramp. For more complex networks, the problem is over determined, such that a unique solution cannot be found. However, numerous estimation techniques exist which aim to get as close as possible to the real OD-matrix, see for example [Djukic 2012] and [Multitude 2012].

4.1.6. Departure time/mode choice

Tune the departure profile (or time-dependent OD-matrices) in order to get the measured flows as close as possible to the simulated flows. If available, use information from a user survey about departure times.

4.1.7. Gear shifting

Check the speed (and rpm) for shifting to a higher gear for different vehicle types, or compare with engine maps.

4.2. Emission Model (EM)

The validation of emission models, like the validation of all models, basically consists of comparing real-world emission measurement results to emission modelling results and showing that for sufficiently comparable situations, these match or do not adequately match. As emission models are (to be) applied to data of traffic models of varying scale - i.e. micro-, meso- or macroscopic traffic models - and the available vehicle or traffic data in these models widely differ in type and time scale, validation differs. Hence, this section has been divided into corresponding subsections: micro, meso and macro.

4.2.1. Validation of Micro Emission Models

In micro emission models, the emissions of individual vehicles are modelled on the basis of detailed vehicle and ride information per individual vehicle. For vehicle emissions, first of all the vehicle type, e.g. passenger car, van or truck etc., is important. Similarly, the actual vehicle model, technology level, fuel, load and age are important factors which should be accounted for in the emission model. Next, situation (city, rural, highway, terrain, height etc.) and driver dependent driving behaviour, i.e. speed and acceleration as a function of time, are very important as vehicle dynamics are known to be a crucial factor in all vehicle emissions.

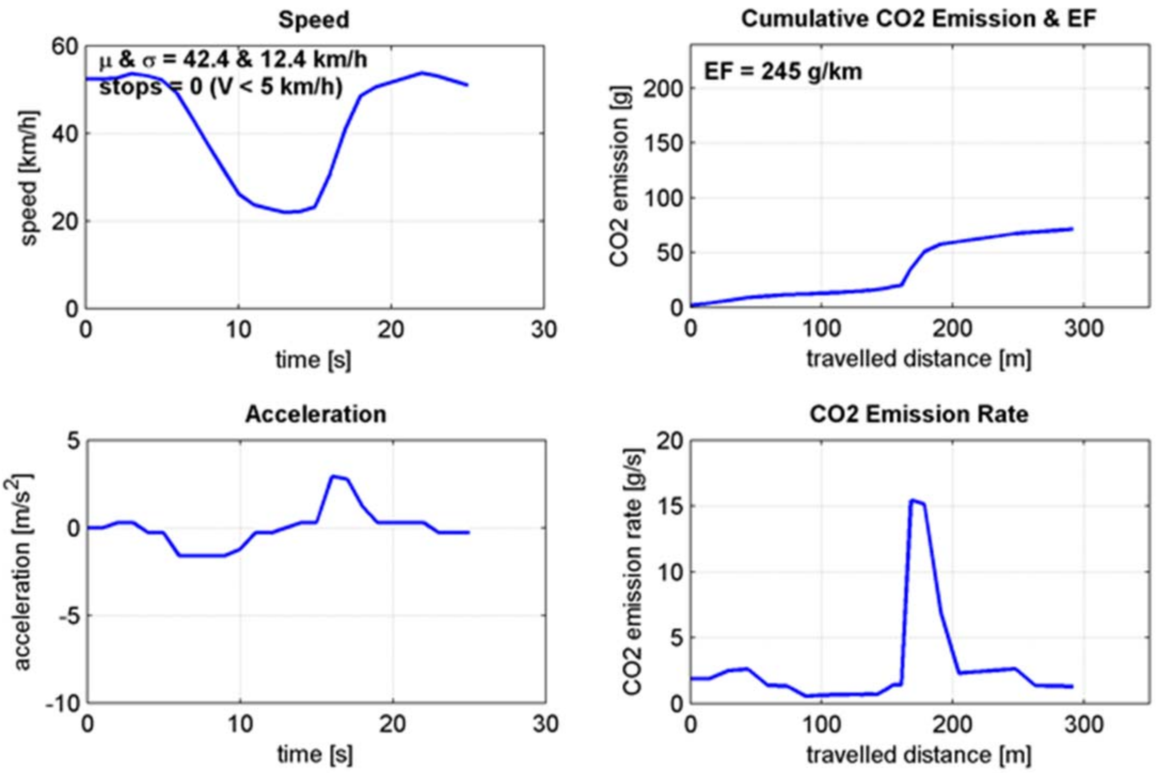


Fig. III.16 Example of VERSIT+ model CO_2 emission calculations for an average Dutch passenger car and a simulated ride. Top left: vehicle speed as function of time. Bottom left: vehicle acceleration as function of time. Bottom right: CO_2 emission rate as function of travelled distance. Top right: cumulative CO_2 emission as function of travelled distance from which the emission factor (EF) is readily calculated by dividing the total emission by the total distance travelled.

A micro emission model like for example VERSIT+ (Ligterink 2009) computes the emissions of an individual vehicle as a time resolved (Δt = 1 s) time series of the emission rate in grams per second, from which other emission results are readily derived. An illustration of such emission modelling is given in Fig. III.16, where vehicle speed and acceleration were calculated with a micro traffic model VISSIM.

On a true micro emission modelling scale, i.e. for an individual ride of an individual vehicle, validation of the emission model would mean comparison of measured time resolved real world emission data, e.g. as measured with PEMS (Portable Emission Measurement System) for an individual vehicle during a real-world ride, to modelled time resolved emission data for that vehicle, e.g. with VERSIT+ using the PEMS measured vehicle speed data and the acceleration derived thereof. An example of such a validation for a truck is given in Fig. III.17.

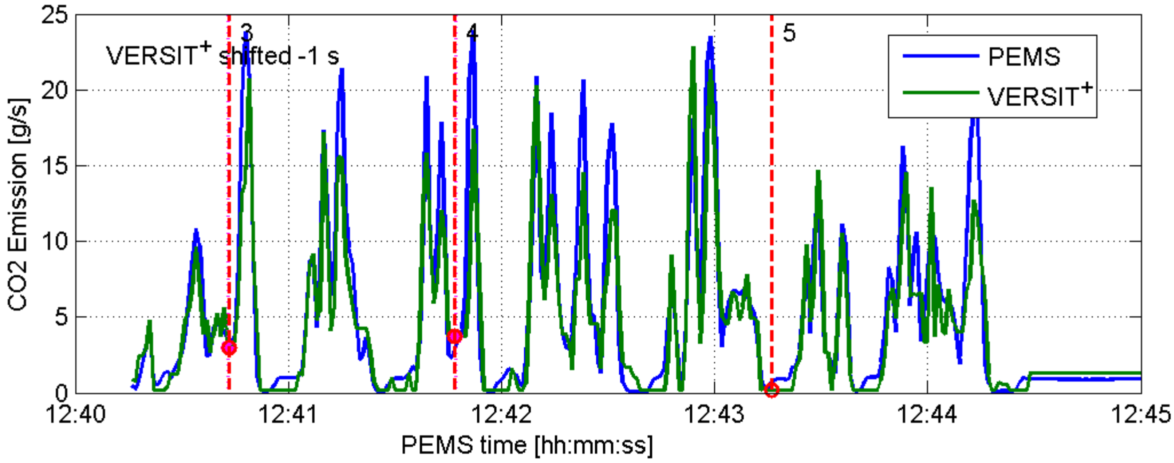


Fig. III.17 Example of VERSIT+ validation by comparing measured CO_2 emission rate data (blue curve), as acquired with PEMS during a real-world vehicle ride of a truck, to VERSIT+ modelled CO_2 emission rates for a vehicle of that particular vehicle class (green curve).

Still on a micro scale, i.e. still using micro traffic and emission modelling as basis, but at a higher level of data aggregation, another type of validation can be performed by comparing the measured total emissions for real-world vehicle rides to the modelled total emissions for these rides in various ways.

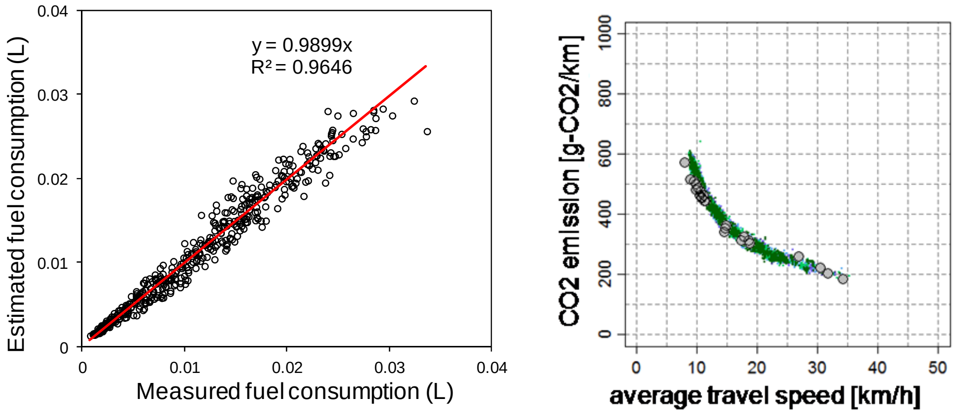


Fig. III.18 Examples of micro emission model validations at a higher level of aggregation, i.e. by comparing measured total emission data per ride to corresponding modelled data. Left: modelled fuel consumption versus measured fuel consumption, which is directly proportional to CO_2 emission. Right: measured and modelled CO_2 emission factors as function of average travel speed. [NEDO, 2013]

Examples of such micro emission model validations at a higher level of aggregation are given in Fig. III.18 and Fig. III.19. As shown in these examples, various aggregated emission parameters, e.g. total emission or average emission factor per ride, can be chosen for validation and can be plotted as modelled against measured values or both of these against another useful parameter such as average speed, time of day etc.

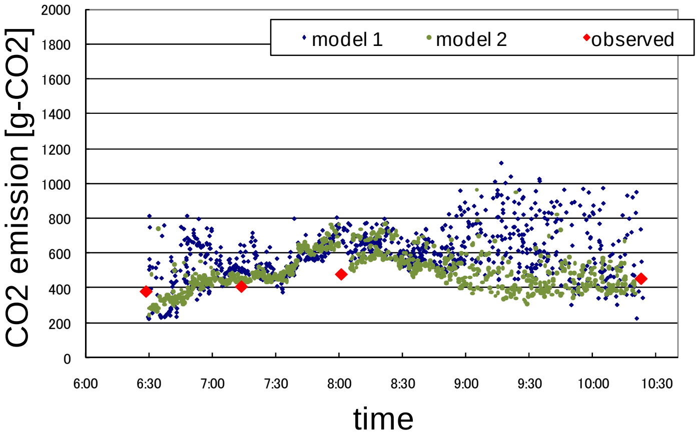


Fig. III.19 Example of micro emission model validation by comparison of measured total CO_2 emissions per ride (red diamonds) to modelled total CO_2 emissions (blue and green dots). [Tanaka et al, 2011]

4.2.2. Validation of Meso Emission Models

In mesoscopic models, the driving data interface between the traffic model and emission model is neither average vehicle speed nor time-resolved vehicle speed for each individual vehicle. Each model may employ its own intermediate products to connect the traffic and emission model. One mesoscopic model proposes to use a so-called Stepwise Speed Function (SSF), each of which is a rectangle-shaped function with height equal to average speed and width equal to the time duration of short trip subsections. In this case, the items to be validated are the number, heights, lengths and intervals of SSFs that are generated from the traffic model and from probe vehicles.

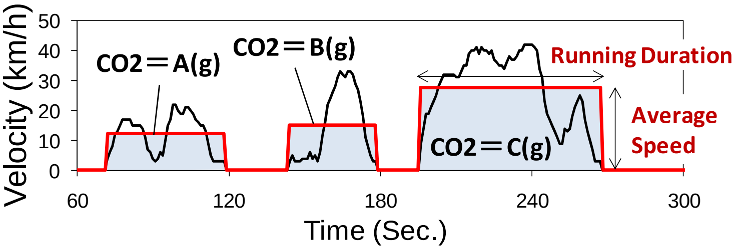


Fig. III.20 An example of intermediate products (SSF) validation in mesoscopic model [NEDO, 2013]

4.2.3. Validation of Macro Emission Models

In macroscopic traffic models, vehicles are not individually modelled but rather traffic flows using parameters such as road capacity, traffic demand (number of trips per origin destination combination), vehicle flow, density and average speed per road section etc. Hence, when coupling a macro emission model to a macro traffic model, the emission model should be able to calculate macro emissions, from macro traffic parameters such as, for example, the mean vehicle speed and mean vehicle flow for specific network (sub)sections together with information (road and intersection types) of these network sections and, if available, information on the vehicle fleet composition.

An example of a macro emission model, for use with macro traffic models, is the recently by TNO developed VISSIM/VERSIT+ based macro emission model (Klunder 2013). In this model, macro emission relations are derived from micro traffic (VISSIM) and emission (VERSIT+) simulations for small characteristic traffic network subsections such as roundabouts, intersections and road sections. As any macro traffic network can be thought as built from these smaller network subsections, in principle, the emissions on macro scale can be calculated from the modelled emissions for these subsections. An illustration of the macro emission relations, derived for and used in this model for passenger cars on a single lane roundabout, is given in Fig. III.21. Each of the curves gives the derived macroscopic relation between the mean CO_2 emission rate per vehicle (here an average Dutch passenger car) and the mean vehicle speed on a single lane roundabout of varying size (as indicated in the legend). The varying mean speed reflects the traffic intensity on the roundabout, i.e. a low mean speeds means a high traffic intensity and a high mean speed a low traffic intensity. The various colours designate emission rate curves for roundabouts with start/end links (i.e. the roads to and from the roundabout circle) of varying size (the roundabout circle itself is constant in size). This size dependency is caused by the averaging of speeds of all vehicles over the entire roundabout (including its start/end links). The size dependent emission rate curves are bounded by the zero acceleration emission rate curve (the lowest curve) as calculated with VERSIT+. For differently sized single lane roundabouts the emission rates are readily calculated from the given curves by size dependent interpolation between the curves.

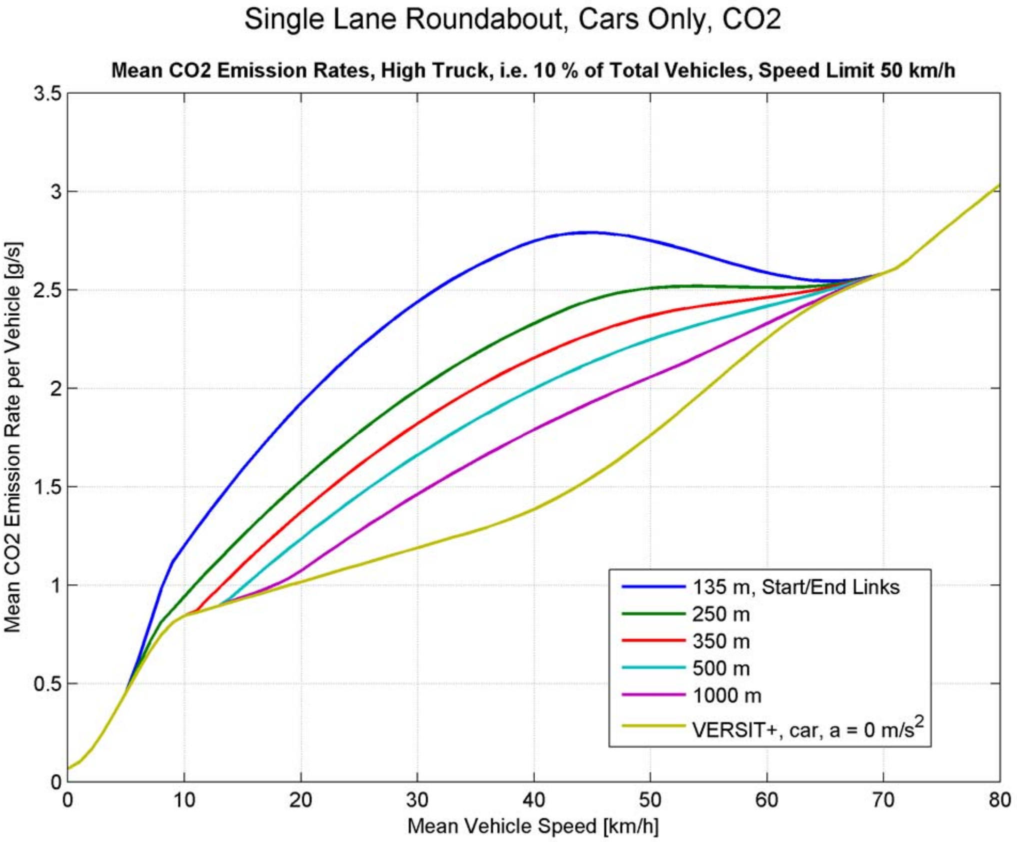


Fig. III.21 Macro CO_2 emission relations for cars on a single lane roundabout as used in the VISSIM/VERSIT+ based macro emission model recently developed by TNO.

A direct validation of a macro emission model, i.e. by comparing measured and modelled emission data is impossible. First of all, because of the sheer scale on which emission measurements should be performed on many individual vehicles even for the smallest useful macro traffic models. In addition, it is generally very difficult to obtain the volume emitted from vehicles by measuring the concentration of gases in the air.

Hence, for macro emission models only indirect validations are possible. For example, first work on a micro scale for the combination of a micro traffic and emission model as explained in section 4.2.1. Next, perform a validation for one network, or even better, for several representative traffic networks, small enough to be both accurately modelled with a micro and a macro model. Then compare representative traffic and emission parameters which may be calculated from both the micro and macro modelled results.

Another possibility is to utilize statistical information such as fuel sales volume. The total volume of emission can be estimated roughly by this method. However, there are still problems if the location of purchasing and consuming the fuel is different. The focus area has to be limited by clear boundaries.

5. Summary of relevant situations and items for verification/validation/calibration

A summary of the proposed items in section 3 and 4 to be verified/ calibrated/ validated with regard to CO_2 assessment is given in Table. III.3 below:

Table. III.3 Summary of relevant situations and items to be verified/ calibrated/ validated with regard to CO_2 assessment

Situation	Verification	Calibration/Validation
Traffic Simulation model (TS)		
General items	• Vehicle generation • Bottleneck capacity • Queue evolution / shockwave propagation	• Traffic flow • Average speed (Travel time) • Free (or desired) speed distribution • Vehicle fleet composition • Distribution of driving modes • Distribution of speed • Distribution of speed and acceleration / deceleration • Headways • Uphill and downhill speed and acceleration • Distribution of speed and VSP (Vehicle Specific Power)
Intersections	• Speed range • Acceleration behaviour • Deceleration behaviour • Saturation flow rate • Turning capacity	• Queue length • Number of stops/runs • Duration of stops/runs • Average speed and standard deviation • Acceleration rate • Deceleration rate • Braking initiation distance
Highway/motorway driving	• Variation in speed in free-flow conditions • Speed distribution per lane in free-flow conditions • Congestion at bottleneck	• Congestion locations and length • Distribution over lanes and share of trucks per lane • Capacity and capacity drop

	locations (lane drops, merging/weaving locations) • Congestion at high traffic flows (due to e.g. lane changes and braking of individual vehicles) • Capacity at bottleneck • Shape of fundamental diagram • Shockwave propagation • Speed drop at an uphill • Speed drop at an uphill by vehicle type • Speed up at a downhill • Speed up at a downhill by vehicle type • Share of heavy vehicles • Lane distribution of heavy vehicles	
Route choice	• Route choice distribution route choice depending on congestion	• Route flow • Turn fractions
Travel demand (OD matrix)	• Traffic assignment corresponding to OD-matrix. • Share of OD pairs in the OD matrix	• Link flows generated by OD-matrix • Route flow
Departure time	• Departure time profile • Modal split	• Link flows generated by departure profile (or time-dependent OD-matrices) • Trip information about departure times.
Gear shifting	• Correspondence of speed and gear position • Variation in gear shifting between drivers and vehicle types (if available)	• Gear shifting speed (and rpm) for different vehicle types compared with measurements or engine maps.

Emission Model (EM)			
All type models		• Model structure • Vehicle type setting	• CO_2 emission of individual vehicles • Time-series CO_2 from individual vehicles • Speed vs CO_2 relationship
	meso models		• Intermediate products between traffic simulation and emission model (e.g. Stepwise Speed Function (SSF))

6. Benchmark dataset

As validation is the process to check the reproducibility of a model using actual data so that it can be compared with other models, we need a dataset of traffic condition as well as CO_2 emission observed from the real world. However, it is not easy to obtain a comprehensive dataset that includes network configuration, traffic demand, various traffic measures, and fuel consumption etc. comprehensively, because it requires a lot of cost and labour. Therefore, it would be very useful if there are datasets for validation commonly available to anybody who develops or uses a model. Such datasets would play a role of a benchmark as a lot of developers and practitioners refer to it and validate their models using it.

Based on this idea, benchmark datasets are currently being prepared under international collaboration. They are intended to be used widely for validation of various types of models, so they should include various kinds of data. The greater the number of datasets that are available, the greater the number of models that would refer to them, and the reliability of models would become better. Therefore the contents of the datasets should be enriched more and more.

Such benchmark datasets have advantages both for model developers and model users. Model developers get benefit because they can save cost to show the validity of their model. A model is regarded as more reliable if it is validated by datasets collected by third parties. Model users can also benefit if they provide a dataset from their region, because model developers will show the applicability of models to their region. The more visible the benchmark datasets become and the more they are used, the more benefit is provided for all participants.

Benchmark datasets for model validation are to be stored in the ITDb (International Traffic Database; http://www.trafficdata.info/), which can serve as a warehouse of the benchmark datasets. It offers basic functions to upload, to store, to browse, and to download datasets both for data providers and data users. For the details of the ITDb and other datasets, please refer to Section IV.2.

7. Disclosure of the results

After verification and validation is conducted, the results should be disclosed so that model users can check the performance of the models, understand the characteristics of the models, and select one of them according to their purpose. It is desirable to make a standard format so that model users can compare different models easily.

The process of disclosure is mainly required for model developers, because their models may obtain publicity and get benefits after they show the reliability of their models by disclosing the verification and validation results. However, it is also requested that model users disclose the verification/validation results because it can give feedback to model developers and allow them to improve their models and such practices can improve the CO_2 assessment environment.

This section explains how the verification/validation results should be disclosed. ITDb (http://www.trafficdata.info) can be used as a clearinghouse for the disclosure of the verification/validation results.

7.1. Information to be described

The following elements are basic information that should be described as model verification/validation results. In some cases, verification results might not be included when model users employed existing models, for example.

- Date of verification/validation execution
- Responsible person/organization
- Model description
- Verified and validated items
- Verification results
- Dataset used for calibration and validation
- Calibrated parameters
- Validation results
- Interpretation of the results

7.2. Disclosing procedure

Here is a typical procedure to disclose the verification/validation results.

1) When verification and validation are conducted and the information mentioned above is prepared, model developers can disclose the results to the public. It may be on their internet website, but any form of disclosure is possible as long as it is accessible to the public.

2) Model developers can apply to the administrator of the clearinghouse (e.g. ITDb) for registration of their models. The clearinghouse administrator checks the submitted information and registers it to the clearinghouse if the required information is given.

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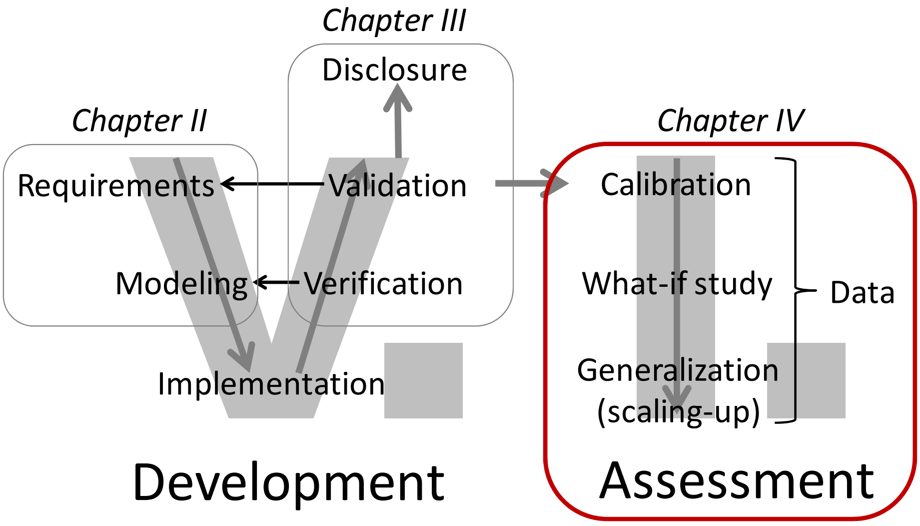
IV. Assessment Methodology and Data Requirements

Previous chapters investigate the role of modelling and tool validation in the estimation of CO_2 emissions. They discuss some general categories of traffic and emission models along with an assessment methodology, identifying aspects that require further development. This chapter focuses on how the evaluation tools can be properly applied for assessment, and on the data needs of the various models, including information which can be acquired from probe (i.e. instrumented) vehicles.

Section 1 describes evaluation through three stages: (i) 'calibration', (ii) 'what-if study', and (iii) 'generalization' with scaling-up issues. Section 2 exposes the issues of datasets for tool validation to support the assessment of both traffic and emission models. Data requirements for both traffic and emission models are discussed, as well as data characteristics. Next, an overview of data already shared and potentially usable is given for Europe and Japan. Section 3 is devoted to how probe data can be used to monitor both traffic and emissions in real time. This part aims at describing issues concerning probes as an additional source to the conventional sensors.



1. Assessment methodology

The principle of assessment methodology is to ensure transparency, which allows the evaluation process to be traceable by a third party. This fundamental philosophy is similar to scientific experiments and may afford ‘reliability’ to the evaluation result. In this section, the steps that the assessors should follow are described for each stage in the assessment.

1.1. Site specific calibration

The aim of the site-specific calibration is to fit the evaluation tool for the subject site, and to provide the baseline for the comparison in the ‘what-if study’ stage described in the subsequent section.

1.1.1. Building a road network

At the beginning of the study, the road network in the subject site is replicated in the simulation world. One of the popular data sources is a digital road map (DRM), which consists of nodes and links with their locations and shapes. When the assessor uses a certain DRM product, the product name and version should be clarified with the list of the subject links included in the network. The attribute information not included in the DRM product, but necessary for the simulation study, should be provided as well. If the assessor draws the road network by hand, the shape of the network should be pictured. In any case, the copyright issues should be clarified.

1.1.2. Setting traffic signals and regulations

The control parameters for traffic signals, i.e. phase, cycle, split and offset, should be given as they were in the subject site. The most direct way is to collect the real parameters through survey or through a control system. If an adaptive control system is installed at the site, it is preferable to implement the controlling algorithm on simulation as it is. In the case that the details of the algorithm were difficult to access, typical signal settings for each time slot should be collected through a survey. When the size of the network becomes large and it is difficult to observe signal settings for all intersections, the use of an indirect method that estimates reasonable settings should be allowed.

1.1.3. Providing O-D matrix for travel demand

Providing an accurate O-D matrix is the most important but difficult issue for the demand side. For small-scale networks, it is feasible to measure the O-D of each vehicle directly by matching plate numbers at boundary sections. However, for large-scale networks, the O-D matrix will be estimated through flow level calibration described further.

Travel demand for traffic simulation should vary time by time for each subject vehicle type. Adequate width of the time step would be 5 to 15 minutes or at most 1 hour for a large-scale network. The number of vehicle types should be decomposed into the subject vehicle types for the combined emission model.

1.1.4. Calibrating traffic flow

As is the case for all simulation models, it is a necessity to perform calibration when applying them to real-world case studies. For all ITS applications, it is necessary to fit simulation results with observed data in terms of traffic volume and travel speed or queue length for major sections in the subject network. These data can be derived from measurements stemming from sensors such as single and double inductive loop detectors, cameras, probe vehicles, etc.

In general, mesoscopic models are relatively easy to calibrate. Due to their structure, they have a feasible amount of parameters, such as link capacity, that need to be tuned. In many cases, an explicit automatic optimisation of the parameter set is possible within a reasonable computation time. Therefore, it is feasible to apply the mesoscopic models to relatively large-scale networks.

However, the use of mesoscopic simulation may cause some inconsistency when the characteristics of driving dynamics change with an ITS application in future. As the mesoscopic models have to be re-calibrated for the new traffic conditions but there is no data with the ITS application. In such case, the special observation should be organized through the FOT with feasible scale, or the effect of the ITS application should be estimated by using microscopic models.

As to microscopic models, due to the large number of parameters typically involved in their traffic flow models, their computational complexity is often a significant disadvantage when compared to mesoscopic models. From the point of view of model calibration and validation, this poses an interesting conundrum, as in many cases not all parameters are equally influential on the results. In this sense, microscopic models contain a real danger of purporting to convey a kind of fake accuracy. Different parameter combinations can lead to the same phenomenological effects, leaving us pondering as to what exactly is causing the observed behaviour. Note that there is no clear roadmap on how to calibrate properly microscopic traffic flow models, although some efforts are on going in this direction[4].

It is important to take into account the spatial nature of the study area, i.e., a detailed description of the road infrastructure, with bottleneck locations as well as up- and downstream boundary conditions. With respect to the model that is created within the computer, it is paramount to know how the model behaves on both the link as well as the node level. Because the models are most of the time working with fairly homogeneous road links, e.g., constant elevations, no road curvature, it might be necessary to allow for small deviations from reality.

1.1.5. Driving behaviour level

For the applications in 'Category 1: improving driving behaviour' and some applications in 'Category 2: Energy-efficient traffic control for intersections and highway corridors', it is necessary to calibrate the following measurements for:

- Speed and acceleration distribution for major corridors
- Average running speed and distance for short travel (between stops)
- Number of stops, stopping duration

1.1.6. Route choice behaviour level

For the applications in 'Category 3: Energy-efficient traffic management on a network scale', it is necessary to calibrate the route choice model parameters to fit the simulated link flows to the real world. If we need to deal with different types of route choice behaviour, the route choice model should be calibrated. As it is often hard to identify a route choice model that can be generally applied over the subject network, the calibration process could be a kind of sensitivity analysis on major 'uncertain' parameters of the route choice model. It is also possible to use already-calibrated parameters adopted in past but 'reliable' studies. In this case, the assessor must list the source of the parameter settings.

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[4] http://www.multitude-project.eu/

1.1.7. Travel demand level

Adding to the calibration for the supply side, the demand side calibration is effective for large scale study. For this purpose, the optimization process can be utilized to minimize the errors in link flows by adjusting each cell in time-dependent O-D matrix. For some applications in 'Category 4: Travel demand management', vehicle OD matrix after modal-split should be fit to the real data by calibrating the parameters in the modal choice model.

1.1.8. Goods transport level

For the applications in 'Category 5: Fleet management', goods transport volume should be fit to the real data by calibrating the parameters used in the goods assignment model.

1.2. What-if study

The 'What-if study' here is to coordinate case studies by changing some input for the simulation according to a specific scenario.

1.2.1. Scenario setting with sensitivity analysis for uncertain parameters

The first step is to set up a scenario. The most important issue is to fix the baseline of the comparison. In many cases, the 'present' case, which is fitted to the real world through the calibration stage, can be regarded as the base. However, it is sometimes expected that a future situation may be the base. In such cases, the O-D matrix and/or the network can be modified based on rational assumptions.

For some uncertain parameters, which may largely influence the result, such as the penetration of ITS measures in the future, they need to be evaluated through sensitivity analysis with an adequate value range and an increment step size.

1.2.2. Multiple runs with difference random number series

Since most traffic simulation models use pseudo random number series, the simulation results with different random seeds may vary under the same setting. To remove the unexpected effect from this variation, the assessor is required to run the simulation several times, normally 5 to 10 replications, for each scenario and to cut off the extreme data for both upper and lower results. The average value from the rest of the results can be used for comparison. It is valuable to show the variance or the standard deviation for each scenario in order to evaluate whether the differences in the average values are significant.

1.2.3. Performance indexes

As for the performance indexes, CO_2 emission and fuel consumption are the most essential. Other indexes concerned with traffic performance, such as total travel time, will be valuable when discussing the social benefit of an ITS application. Highlighting the time saving effects for certain driver groups or certain routes may give incentives to promote the use of ITS applications.

1.3. Generalization with scaling-up

Very often, the road networks in simulation studies only cover limited zones of the subject region because of various practical issues of data acquisition, computational resources, time and labour constraints, etc. In such cases, we need to generalize those simulation studies and scale-up the results to the whole region through the following steps.

1.3.1. Preparation of statistics

The first step is the preparation of statistics supporting the traffic condition representation of the area under investigation to the whole region. For each subarea decomposing the whole region, the following statistics should be given:

- total section length per road type
- total travel distance per vehicle type and per road type (daily / hourly)
- total travel time per road type (daily / hourly)

In place of the statistics relating to total volume, probe data can be used to know the travel distance and the average travel speed.

1.3.2. Confirming the representation of simulation study area

The second step is to classify the subareas into several groups according to the similarity of the statistics. The assessor is required to confirm that each of the groups contains at least one simulation study area.

1.3.3. Factorization of performance index

The factorization unit, which is used for scaling-up, can be prepared so that the performance index, mostly the CO_2 reduction amount, for each simulation study area is divided by total travel distance per vehicle type and per road type of the area. However, only those static factors are not enough to take into account the difference in traffic conditions, thus it is encouraged to use more dynamic factors for the factorization. For instance, time-dependent average travel speed given by probe data will be useful.

1.3.4. Scaling up

The factorized index of the simulation study area is applied for each subarea classified into the same groups as above. It is multiplied by the total travel distance per vehicle type and per road type of each subarea to estimate the performance index. The estimated index will be summed up to the total performance.

2. Dataset for tool validation

The data needed to support model validation (i.e., the process of checking to what extent the model replicates reality) of the modelling chain can be divided into two main categories: (i) input data, (ii) calibration and test data.

In this aim, the use of real-life data is extremely important. There are, however, large differences between regions in the availability of data. Therefore the following are needed:

- An analysis of the data needs for accurate simulations that include situation- and human behaviour - sensitive emission models,
- An analysis of available traffic databases (public and private) in the various locations,
- Access tools for the various traffic databases (possibly with a conversion to a standardized format),
- Real-world driving data enabling the characterization of the influence of detailed traffic conditions and human driving behaviours on emissions, as well as the development of appropriate emission models.
- There is also a lack of basic data for setting up accurate simulations:
- Information on roads (curvature, slopes, traffic calming measures),
- Information on rules and regulations in the network (e.g. speed limits)
- Specific modes can have a considerable impact on the results of the simulations; therefore (easy access to) the following data would be useful:
- Public Transport schedules: information systems used by public transport operators to maintain their schedules could be useful a source of data,
- Freight movements: data on commercial vehicle movements generated by logistic systems could be extremely valuable, but such information is normally confidential. Acceptable ways would need to be found for gaining access.

The optimization of mobility from the environmental point of view is subject to intensive study and experimentation. Large-scale tests can produce valuable data. This data should be feed into traffic databases and made available for future work.

The clear definition of data needs and availability is of major importance. The following actions are therefore recommended:

- Clarify the implications of Data Protection and Privacy legislation in Europe, Japan and US regions with respect to the collection of data for modelling and validation, especially with regard to probe information,
- Make a detailed analysis of the availability of relevant traffic databases (public and private),
- Develop a common access tool for traffic databases in Europe, Japan and US regions,
- Develop a standard database for calibration and validation purposes.
- Agree on common parameters for information used to characterize roads (curvature, slopes, traffic calming measures),
- Agree on the most appropriate approaches to the collection of probe vehicle data for use in validating traffic models and emissions monitoring systems. Investigate the potential of using instrumented fleet vehicles (buses, taxis, public service vehicles, etc.) as probe vehicles.
- Compile a common database with representative vehicle mixes for use in simulations. This database should enable predictions to be made for future vehicle mixes (in which hybrid and electric vehicles will play a bigger part).

2.1. Requirement on data for traffic simulation model and CO_2 emission model

The types of traffic model envisaged for CO_2 emissions assessment, and described in previous chapters, rely on micro-scale simulation. This, in turn, requires detailed traffic information (data on individual vehicle behaviour, dynamic OD matrices, etc.). Sophisticated micro-simulation traffic models need additional empirical information, such as acceleration and gear changing behaviour, for the proper validation of the new algorithms.

Particular attention needs to be paid to ensuring consistency between the modelling approaches (i.e. traffic and emissions) and their underlying assumptions, and the definition of their input and output parameters. Most current emission models assume average driver behaviour, normal engine operation, and average driving conditions, or at best address these through implicit distributions. In the same way, the notion of speed, acceleration, cruising speed and, more generally, vehicle trajectories or traffic dynamics, can differ considerably according to the different approaches to traffic and emissions modelling. This can lead to inconsistent model chains.

Traffic models are not usually configured in a way, which is optimal for emission modelling. Possible differences in definitions, initial aims, time and spatial scales, etc… as well as the underlying assumptions of the models, can lead to inappropriate model chains and erroneous assessment results. For example, traffic assignment models tend to only cover specific periods of the day (i.e. peak and inter-peak), and do not have as detailed a system of classification for vehicles as emission models. The harmonization of traffic and emission models is therefore clearly vital.

To estimate the fuel consumption (and CO_2 emissions) accurately, the following are needed:

- A detailed representation of the infrastructure.
- A detailed representation of traffic management measures.
- An accurate model of driver behaviour in response to the infrastructure and traffic management measures.
- An accurate model of engine behaviour in response to driver behaviour and infrastructure characteristics.
- A representation of the travel and transport demand, with details of the trip purpose and the vehicle mix.

In order to simulate the effects of ITS measures on travel/transport demand (e.g. modal split, route choice, and trip timing) we need a behavioural model of mode, route and trip timing in response to ITS measures and the network status (i.e. traffic and transport conditions).

The data required for traffic simulation depend heavily on the type of model employed. While macroscopic models need information about the area modelled, such as the number of inhabitants per zone, microscopic models need to be validated against real-world data on traffic flow. Typical input data include speed distributions, routing information and time-dependent volumes. Traffic control (e.g. signal timing) also forms an integral part of a microscopic model.

In order to ensure consistent outputs, traffic models must be calibrated and validated properly for the given task. It must be proven that they reproduce traffic as it happens in reality. Data for such calibrations are usually traffic data sampled on cross-sections. The minimum requirement for a (microscopic) model is to correctly reproduce macroscopic features such as speed-volume relationships and speed distributions. For the investigation of ITS measures, however, available traffic measurements yield insufficient detailed data. Only dedicated experiments will provide such data, as e.g. speed profiles of equipped vs. non-equipped vehicles. Driver behaviour is, in many cases, important, which adds another dimension to the required data. It is expected that dedicated experiments provide such detailed information. Although it is desirable to have data from such a large-scale experiment, these models can be and generally are efficiently calibrated based on much more limited data.

Fuel consumption depends upon the details of driving behaviour, which in turn depend upon the traffic management. To set up simulations able to realistically depict the impact of traffic management on a useful scale (area, city or region), an important modelling effort is required. Although this effort increases with the complexity of the area to be simulated (e.g. single controlled intersection vs. city scale extrapolation) smart and efficient approaches can be used in order to reduce modelling effort making it well-suited for large-scale applications and mainly for CO_2 emission.

In some European countries estimates of road transport emissions have been made on a national basis, and more locally as part of pollution impact studies, since the 1970s. The methods used have gradually been improved and developed with respect to the amount, type and quality of data available.

All emission models must take into account the various factors affecting emissions, although the manner in which they do so, and the level of detailed involved, can vary substantially. Models for estimating emissions from road vehicles can therefore be classified in several different ways, although models can generally be described in terms of the following (Boulter et al., 2007, Barlow et al., 2007):

- The type of application, such as estimating local air quality, emission inventories),
- The geographical scale of application, from an individual street to a country,
- The operational basis for estimating emissions. For example, some models use vehicle speed, some use a combination of speed and acceleration (or more variables), and others use vehicle power.
- The nature of the emission calculation. Some models use continuous functions to describe emissions, whereas others use discrete values.

In conclusion, existing emissions models are sometimes based on a rather limited number of emissions measurements and generally refer to average driving cycles which were conceived to represent traffic conditions and driving behaviour. Due to the cost of the experiments, the representation of traffic conditions and behaviour is envisaged with just a few driving cycles. The models therefore cannot easily reproduce the detailed features of traffic behaviour and are not designed to simulate detailed changes in driving style. In their present form they are thus not really ideal for measuring changes in these driving conditions and behaviours, i.e. the type of modification like to be induced by ITS or eco-driving measures.

Depending on the ITS measures concerned, different levels of accuracy are required. It is necessary to determine whether existing emissions models can make a valid contribution to their assessment. The coherency with the traffic and simulation models and the scales (time and distance) need to be examined carefully. For ITS measures that induce significant changes in the traffic conditions (traffic dynamic) and above all changes in human behaviour, improved or new approaches and models should be envisaged.

2.2. Data characteristics description

Because traffic related data includes a wide variety of data such as probe data, detector data, video data, signal control parameters, weather, population, land use, and so on, it is difficult to build a database for collecting all these data with unified format. Under this situation, to collect such various data in an integrated way, meta-information structure is needed and proposed in Fig. IV.1. This figure exhibits the meta-information structure used in the International Traffic Database (ITDb) platform.

Each data's meta-information is arranged by country can be browsed for network descriptions, projects, measurements, environment and incident data in certain locations and time spans. This structure allows efficient queries for users and fast access to the desired information. Further, it allows users to link data from different data sources together if they are looking for regional data provided by various institutions.

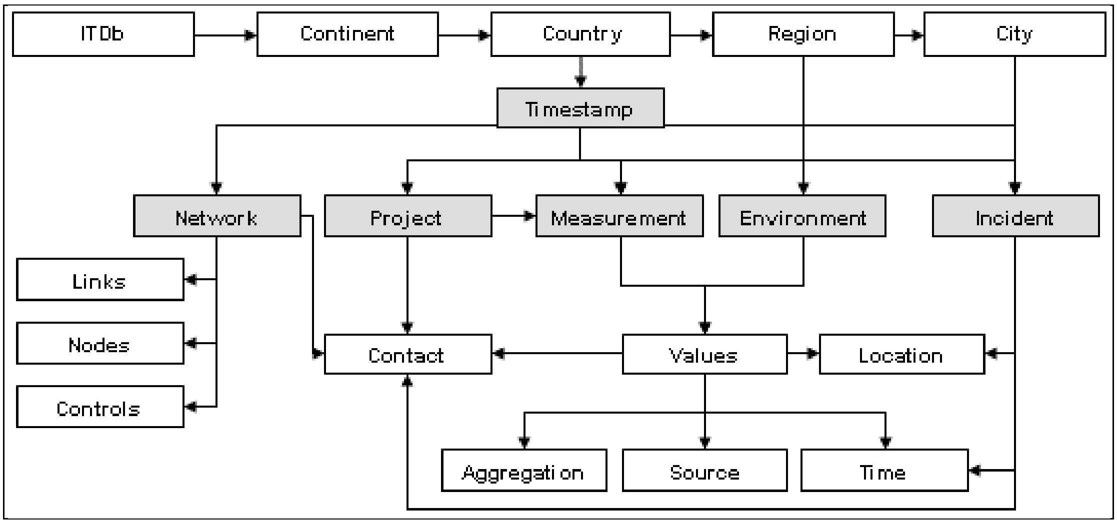

Fig. IV.1 ITDb Meta-information structure

2.3. Available data sources for tool validation

As highlighted in the previous section, issues on data set are of paramount importance. The goal is to provide easy access to the data required for estimating the impacts of ITS applications on CO_2 emissions, and for validating models, and to enhance current international traffic databases.

In order to have an overview of data already shared and potentially usable, some European, Japanese and US projects have been listed, which provide data resources with shareable data, accessible and using mainly probe data.

2.3.1. Japan

In Japan, a field survey and collected data comprehensively in an urban street in Tokyo was conducted in Energy ITS Project and the obtained data is available through the International Traffic Database (ITDb[5]).

The survey area is in the South West of Tokyo downtown, which is densely populated. The survey section (Komazawa-dori) is 1.7 km length and there are 10 intersections along this section. There is a bottleneck intersection near the downstream end of the section. The data collection was conducted from 6:30 am to 10:30 am on weekday. The data collection was based on videos versus manual recording and probe vehicles. The collected data was processed to eliminate data errors and outliers, and was arranged into one package as a dataset together with explanatory documents. It was supposed to be used as a standard benchmark dataset in order to validate newly

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[5] www.trafficdata.info/

developed models.

2.3.2. Europe

From the European side, the following resources have been identified. These resources are of two types: (i) archived/real-time traffic databases (ii) dedicated traffic datasets.

i. Archived/real-time traffic databases

- The regiolab-delft[6] archived database, with 6 years of 1min averaged speed and aggregate flow data from different sources,
- The DLR-Institute of transportation systems, with firstly FCD position data for November 2009 in Berlin and secondly real time traffic data set collected from an urban road research laboratory which contains data like image and sensor data and also environmental data,
- IFSTTAR databases: Two separate databases form this resource: the first one deals with traffic data every seconds by loops, camera and GPS from an urban site in Versailles. The second one, contains aggregated traffic data from both loop detectors and probe on an urban motorway.
- The Imperial College London with their TPEG messages' database for London with data every 15 min since April 2007. TPEG stands for Transport Protocol Expert Group and is a new standard format for delivering real-time traffic information to drivers over digital radio channels.

ii. Dedicated datasets

- The University of Southampton with (i) driving performance data in different cars and cities and (ii) collection of traffic data from the national traffic control centre and contains almost 2 years of data on strategic roads networks of England,
- The IFSTTAR: (i) a study on trajectories for two urban roundabouts in Toulouse. Four sets of two hours data mainly video and Origin/Destination matrix were collected, and (ii) traffic data from two motorways around Paris with 4 years of data mainly detectors data but also accident report all together each 6 min,
- The Centre for Transport Studies University College London, with two years of

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[6] www.regiolab-delft.nl

data aggregate every minute on a motorway,

- The Delft University of Technology datasets: (i) a study of 19 drivers during 5 months in instrumented vehicles recording all possible data like speed, travel time, trip but also consumption and (ii) a study on vehicles trajectories from helicopter images which is similar to the NGSIM dataset,
- The DLR simulation network data of Cologne.

The main point of this non-exhaustive list is that there are a lot a shareable data, already available, spread all over the regions. These data come from different sources, and mainly now from probes. Note that, some innovative tools emerged. As an illustrative example, one can mention the satellite-based data, coming from the collaboration of DLR and IFSTTAR: TerraSAR-X[7].

More recently, the MoCoPo platform[8] - a new collection effort by the IFSTTAR Transport and Traffic Engineering Laboratory (LICIT - http://goo.gl/dzIcU), motivated to support the environmental assessment of Traffic management measures and ITS strategies. MoCoPo, which stands for "Measuring and mOdelling traffic Congestionf and pOllution", collected high-quality primary traffic, trajectory data and emission measurements intended to support traffic simulation and CO_2 emissions. This platform will serve as an Open Source community with the intent of sharing data for all kind of modelling efforts including traffic and CO_2 emissions.

2.3.3. USA

USA has been a pioneer in collecting detailed traffic data. As part of this effort one can mention the flagship initiative of the Federal Highway Administration's called NGSIM (Next Generation SIMulation). The NGSIM[9] program was initiated by the United States Department of Transportation (US DOT) Federal Highway Administration (FHWA) in the early 2000's. The program developed a core of open traffic behaviours in support of traffic simulation with a primary focus on microscopic modelling, and collected high-quality primary traffic and trajectory data intended to support the research and testing of the new algorithms. More than 5 data sets are available containing vehicle trajectories.

Each data set contains 15 - 45 minutes of usable vehicle trajectory data recorded on 500 m - 600 m long road segment.

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[7] http://elib.dlr.de/74652/

[8] http://mocopo.ifsttar.fr/

[9] http://ngsim-community.org/

3. Monitoring with probes

Traffic monitoring through the use of probe vehicle technology is emerging as a viable means of developing comprehensive traffic monitoring systems without a large investment in physical assets deployed in the right-of-way. Although new methods for detecting speed and volume are lowering installation costs and minimizing maintenance, probe-based methods of measuring travel time can easily scale across large networks without additional infrastructure in the right-of-way and its associated costs and maintenance burden. Probe vehicle technology is fundamentally different than fixed-point detectors, in that probe technology provides a direct measure of travel time, while any method of fixed-point detection infers travel time from a network of speed sensors.

The goal of this section is to show the potential of probes as an alternative source of useful data and more precisely to arrive at a common understanding of the contribution of probe data to "real-time" CO_2 monitoring. In this aim, some definition and reference terms are first introduced before presenting the reasons why focusing on probes, their characteristics and related quality issues. Then, traffic and emission monitoring are exposed and this part ends with some guidelines for probe data-based monitoring.

3.1. Definition and reference terms

In order to design appropriate traffic management strategies, monitoring the performance of the transport network as a whole is necessary. One can define monitoring as assessing dynamically the state of network in terms of traffic conditions and emission: real time – short-term (up to x min) or mid-term (1 day) depending on the available data.

The goals of monitoring traffic are directly tied to specific functional objectives, so the type of data and its level of spatial or temporal aggregation vary depending on the ultimate use of the data. Examples of some of the uses of traffic data include the following:

- Predicting where roads should be built or expanded in the future
- Analyzing air quality in urban areas
- Alerting drivers to congestion and accidents
- Controlling traffic signals

Three basic variables, volume or flow rate, speed, and density, can be used to describe traffic on any roadway. In addition to these variables, travel time and delay are used to describe the traffic movement on any section of roadway.

The methodology of traffic (and emission) monitoring is composed of the following two steps:

- Direct measurement: equipped cars to monitor both traffic and emission. This will only target small sample of vehicles.
- Model-based estimation: extending to the whole traffic and network-wide.

3.2. Why focus of probes?

Technological advances in the area of road transport have favoured a significant enhancement in the ability to collect cost-effective and detailed traffic data. Indeed, in recent years we have been witnessing the emergence of alternative data sources in addition to roadside sensing equipment such as on-board sensors able to offer data on engine status, driver behaviour, the situation “surrounding” the vehicle, environmental conditions and so on, crowd sourcing alternatives, etc…

These technologies enable the collection of basic macroscopic traffic characteristics such as flows, speeds, occupancies, and for some of them also path travel time, queues and vehicle trajectories. On-board instrumentation with access to the OBD (on-board diagnostics) can also provide detailed information on the engine (Perotti et al., 2003) and vehicle operations, which could be valuable for the driving behaviour characterization. Moreover, this permits to obtain high-quality data an accurate picture of traffic on any road section at any time.

Currently this data is measured at static points on the roadway using technologies that have significant maintenance requirements (stationary traffic detectors). Vehicle probe technology is now recognised as a mature means of monitoring traffic without the need for deploying and maintaining equipment in the right-of-way. In contrast to stationary traffic detectors, vehicle probes directly measure travel time using data from a portion of the vehicle stream.

Since vehicles are used to take traffic measurements, we can report speed, travel times, and delays without needing approximation even in low market penetration rates, and can report volume and density in high market penetration rates. In addition to reporting traffic measurements, it can also be used to inform vehicles about the latest traffic conditions and other useful information.

This results in a shift in the role of vehicles from a passive to an active one, since they act as 'mobile sensors', continuously feeding information about traffic conditions to a Traffic Management Centre (TMC). Probe data, a.k.a. Floating Car Data (FCD), are similar to the moving observer method which is used to collect data such as travel time, average speed, delay and stops, acceleration noise and the occurrence of incidents.

One can distinguish three main categories of probe data, according to the technology used:

- Floating Mobile Data (FMD): mobile phone handover detection (no in-vehicle device required).
- Floating Car Data (FCD): vehicle with positioning system (GPS) and wireless communication capabilities (e.g. GPRS). Extra equipment always has to be installed on the vehicle.
- Extended Floating Car Data (xFCD): FCD with build-in vehicle sensor data. In additional to FCD equipment, a vehicle bus interface is also needed.

By itself, the continuous monitoring of vehicle speed (from equipped vehicles or probe cars) can also provide a valid basis for the calculation of CO_2 emissions. Combined with the vehicle position (obtained from GPS information), it can enable an assessment of the influence of the context (local traffic management, traffic conditions, etc.) as well as other impacts (e.g. health effects from pollutants).

Table. IV.1 Strengths and Weaknesses of Probe-based Data Collection

Strengths	Weaknesses
• Traffic volume by lane* • Turning movements* • Travel times • Intersection delays • Trajectories • Arterial, freeway, rural road facilities • Other data also available**	• Only one vehicle is tracked • Data quality is subject to level of fleet penetration • Data privacy issues may be raised by the use of such data.

*This information can only be extracted from probe data when there is a high market penetration of probes.

**Additional data can be also deliver based on xFCD such as weather, engine operation, fuel consumption, and CO_2.

With regard to the use of probe information for estimating CO_2 emissions, existing initiatives show potential. It is, however, important to be aware that the use of operational data from private vehicles (when individual identification is possible) requires permission from the vehicle owner. In the case of private drivers this is clearly a serious drawback.

It therefore seems more practical, at least under current conditions, to gather probe data from fleet vehicles (bus, coaches, trucks, taxis, etc.). A growing number of fleet managers appear willing to install the equipment necessary to enable the monitoring of vehicle behaviour to enable the fuel/energy consumption estimates as well as environmental information, including CO_2 modelling. It would be of great interest to have such information for hybrid and electric vehicles as well as conventional fuels.

In conclusion regarding CO_2 emission estimates, considerations on the use of speed measurements are, firstly that the speed detected by radar systems, video, or loops is not satisfactory for assessing CO_2 emissions as it does not take into account stops, acceleration/deceleration, and other transient driving behaviour. Integrated speed information is necessary (over a trip, over a certain distance, etc.). In the other hand, speed measurements continuously measured or monitored by vehicles, probe cars, etc. are a useful data source for estimating CO_2 emissions. It is better if it is localized (i.e. combined with GPS information) to assess the influence of the context, and to assess the local impacts (for local air pollutants, not for CO_2). Note that in this aim, the Field Operational Tests supported by the European Commission, such as the FOTNET[10] initiative are of interest in this respect.

3.3. Probe characteristics and quality issues

The probe vehicle techniques discussed in the previous section are unique in that they are a building-block of ITS applications designed primarily for collecting data in real-time. Their applications encompass real-time traffic operations monitoring, incident detection, route guidance applications and travel time data collection.

In order to derive meaningful information from probe data, the data quality is critical. In this section, probe data quality issues are described with sampling issues that is of paramount importance in the context of probe data.

3.3.1. Data quality

Karr et al., 2006 define data quality as “the ability of data to be used effectively, economically and quickly to inform and evaluate decisions - fitness for use”. It can also be seen as the adequacy of data and information provided compared to user

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[10] http://www.fot-net.eu

requirements. Note then that data quality is defined relative to requirements or needs, e.g. data can have good quality for a type of user as drivers, but not for network managers[11].

The evaluation of data quality thus requires knowledge of the context, and is frequently carried out without the opportunity to review the data set itself. The shorter the time period between measurement and quality assessment, the more difficult is its evaluation (real time against historical data).

Data quality can be assessed by thresholds, which are defined on two differing scales:

1. Qualitatively: 1 to 10 or "good". This assessment is often subjective, or
2. Quantitatively using different indicators that measure the dimensions of quality, which will be detailed later

The information received by a user has been obtained thanks to a series of transformations. The first step is the collection of raw data through the various collection systems. Raw data quality is evaluated before any treatment. This data is then processed and used for estimates of travel time. Finally, these data are transformed into information for different users. Quality of the information provided can also be evaluated.

3.3.2. Considerations when using GPS probe vehicles

There are several additional considerations when using GPS probe vehicles for travel time data collection. The main factor is the communication capabilities between vehicles and traffic management centres. Many technologies exist for the transmission of position information. These include conventional radio, cellular systems, satellites, beacons and signposts, and paging systems. Conventional radio is the most commonly used communications system throughout the world.

The coverage area is another consideration when developing a system, and the larger the area that must be covered with the system, the more towers that may be necessary to cover the area. It is also necessary to consider what tower will be used for setting up the antenna for the system (i.e., will a private transmission tower be used or

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[11] see QU4TTRO project – “Defining Data Quality and Sampling Methods for Travel Times in Urban Road Networks”.

will a locally-owned tower be rented).

For GPS probe vehicle systems, a modem combined with a conventional radio bandwidth converts data to an analogue signal for transmission. Some applications of GPS that are currently in use for buses or emergency vehicles, utilize several radio channels to provide more capacity. Some configurations called Time Division Multiple Access (TDMA) schemes allow for the transmission of data in a given time slot. Time slots can actually be assigned for smaller fleets. Conversely, large fleets may operate with a communication system in which the time slots are dynamically assigned to optimize the effective use of the transmissions. Generally, GPS probe vehicle systems will provide location information about a vehicle every 10 seconds.

3.3.3. Sampling issues

Data quality has to be assessed relative to user requirements or needs. In the same way, sampling methods depend on user requirements. For traffic information systems, which disseminate information on travel times on different routes in a road network, this means that requirements actually depend on individual route choices of traffic participants.

Sampling GPS data in the transportation network can be handled in at least two ways:

1. Temporal sampling: Equipped vehicles report their information (position, velocity, etc.) at specific time intervals T, regardless of their positions.
2. Spatial sampling: Equipped vehicles report their information (time, velocity, etc.) as they cross some spatially defined sampling points. This strategy is similar to the one used by inductive loop detectors or license plate readers, in which data are obtained at fixed locations. It has the advantage that the phone is forced to send data from a given location of interest.

From a traffic estimation perspective, it is desirable to have a substantial amount of information available. Therefore, with a satisfying GPS accuracy, small T or very closely placed fixed measurements would yield more accurate estimates of traffic. However, these objectives conflict with the communication load constraints and privacy preservation. As suggested in the literature (Ygnace et al., 2000; Yim, 2003; Qiu et al., 2007; Krause et al., 2008), one of the main issues is the problem of penetration, i.e. percentage of vehicles equipped vs. total number of vehicles. Indeed, probe vehicles represent samples in a traffic stream, and hence, probe-based traffic monitoring relies on effective sampling of vehicles. The literature has addressed this issue primarily by examining the minimum necessary network wide sampling rate (often referred to as the penetration ratio). If the required equipment ratio is specified as 1%, then during a specific analysis period, 1% of vehicles in the network are randomly sampled from all the routes in the network during this period (see e.g. Torday, 2005). In Tanikella and Smith, 2010, this approach is referred to as network wide sampling. Given that a traffic network is not homogeneous, this approach is not likely to be the ideal approach for sampling.

Using network wide sampling, samples drawn are likely to be biased with respect to strata and roads categories. Tanikella and Smith, 2010, describe a research effort that identified and extended stratified sampling as a method for increasing the efficacy of probe-based traffic monitoring. A methodology for application of stratified sampling for probe-based traffic monitoring is developed and implemented using a heavily travelled suburban traffic network simulation as a case study. Also, the authors discuss results of the implementation and the future direction of research.

As a conclusion, one can mention that although network wide sampling is simple to implement, it suffers from the following inherent limitations:

1. Traffic networks have significant variations because of differing geometric and traffic conditions and specification of a single sample size for the entire network may not ensure that samples are drawn effectively from all sub-regions in the network.

2. Smaller routes in the network, such as the minor arterials are possibly less monitored using this method. Because minor arterials may form an important component of a traffic network, deriving accurate traffic information for these roads is essential for traffic management strategies such as congestion management and integrated corridor management.

To address the issues of accuracy and variation, usually the total sample size is increased, but this action results in additional costs per sample in terms of the bandwidth of the wireless communication method used for probe-based traffic monitoring. In some cases, there may not be enough probe vehicles in the network for accurate estimation of traffic parameters for all routes in the network.

In general, the penetration rate is difficult to determine for probe vehicles specifically because it depends on the number of equipped probe vehicles, the total traffic flow, and the evolution of the traffic flow in space and time. Typically, only the total number of equipped probe vehicles is known to probe data providers. Similarly, the total traffic flow can only be estimated from counts recorded by inductive loop detectors at predefined locations. Finally, due to the dynamic evolution of the traffic flow, it is nearly impossible to a priori specify a penetration rate, which is both uniform in space and time.

3.4. Traffic Monitoring with probes

Monitoring the traffic situation on the urban road system is one of the most important basic principles of transport management and traffic planning, due to ever increasing individual and business traffic.

The data needs of traffic operators and managers have, until now, generally been met through conventional measurement techniques, and have involved a single or small number of sensing systems. However, in the present context, where highly accurate information is needed, it is likely that a number of data sources may need to be integrated to provide information of sufficient quality. In fact, as explained above, a wide spectrum of different data sources can be potentially used for building the models required for assessing CO_2 emissions. This suggests that new data fusion techniques will possibly have to be developed[12].

Historically, traffic monitoring systems have been mostly limited to highways and have relied on public or private data feeds from a dedicated sensing infrastructure, which often includes loop detectors, radars, video cameras. For highway networks covered by such an infrastructure, it has become common practice to perform both system identification of highway parameters (free flow speed, traffic jam density and flow capacity) and estimation of traffic state (flow, density, length of queues, bulk speed and shockwave location) at a very fine spatio-temporal scale. These highway traffic monitoring approaches heavily rely upon both the ubiquity of data and highway traffic flow models. For arterials (the secondary network) and highways not covered by dedicated sensing infrastructure, traffic monitoring is substantially more challenging: probe vehicle data is the only significant ubiquitous data source available today with the prospect of global coverage in the future.

Depending on the intensity with which measures can be collected, probes for traffic monitoring can be grouped into two main situations: (i) direct data-driven for traffic state estimation and (ii) model-driven for traffic state online calibration to assess traffic status. For the first situation, it is necessary to have a large sample of probes in order to have a relevant monitoring. However, when the sample size of probes is not

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[12] Klein L., L. Mihaylova, N.-E. El Faouzi (2012). Sensor and Data Fusion: Taxonomy, Challenges and Applications. Handbook on Soft Computing dor Video Surveillance. Chapman and Hall, CRC 2012.

sufficient, then one can use those data for online calibration.

3.4.1. Direct data-driven state estimation from probes

Travel time is the most intuitive indicator of traffic conditions on urban arterials. The efficiency of congestion management strategies can be evaluated directly through observation of the travel time. Travel time on urban streets can be measured directly using probe vehicles. High-frequency probe data (one measurement approximately every 20 seconds or less) contains much richer information and allows for reliable calculation of speeds, travel times and even vehicle trajectories.

As mentioned already, the quality of travel time information from probe vehicles depends on the frequency of probe vehicles traversing a road link. A large sample of probe vehicles per link per unit time would provide travel time with a higher level of confidence. However, the frequency of probe vehicle is a function of the number of probe vehicles and distribution of probe vehicle trips over the network.

3.4.2. Model-driven state estimation from probes

When only sparse probe data is available, which represents the vast majority of the data available on arterial roads, data assimilation and fusion process were used to process in real-time both stationary detectors data probe data.

One of the major challenges in this case is the use of probe data for traffic estimation is the difficulty to incorporate this data into traffic models, which are traditionally used to describe highway traffic. Several types of models can be used, for instance statistical models, and flow models. When a flow model is used, this process is known as data assimilation: it consists in incorporating data in the mathematical model of a physical system, in order to estimate the current state of the system and forecast its future state. Traditional approaches such as Kalman Filtering (KF) have been applied to traffic models to perform estimation, in particular using first order models such as the Cell Transmission Model (CTM). Extended Kalman (EKF) filtering has been used to handle second order models, when the discretization scheme used allows it. For more complicated problems involving partial differential equation models, Ensemble Kalman Filtering (EnKF) has been used for speed estimation on the highway. All the aforementioned methods produce a best estimate of traffic (in the least square sense), sometimes with associated confidence intervals of the estimates.

In more recent years, another filter emerged, known as article filter (PF) or equivalently Sequential Monte-Carlo filter (Canaud et al. 2012). Its main advantage is its suitability for complex and nonlinear dynamic systems as it relaxes the underlining linear conditions which governs the optimality of kalman filter.

In summary, data fusion process when only sparse probe data is available allows the update process and online calibration of the model parameters in order to achieve accurate traffic state estimation. Then, the output of this monitoring could be used as input for emission model. The more accurate the traffic state is, the more precise the emission model will be. In this respect, the use of traffic count and probe trajectories has shown useful potential in many studies. The literature on data process is really spread depending on the model chosen, the goal of the study and the available level of data. This topic of research is still ongoing with the emerging technique like Probability Hypothesis Density filter for example.

3.5. Emission monitoring with probes

Despite sparse air quality measurements, the air pollution can still be estimated using appropriate models. As vehicle emissions are a major source of pollution in urban environments, emission models that use real-time traffic state estimates can provide valuable information. Models of roadway emissions and their dispersion are important tools that can be used both to study the impacts of vehicle emissions, and as an input to more sophisticated air pollution models that account for other sources of pollutants. Static maps of air pollutant concentrations can be easily estimated by using average traffic and weather conditions, but these maps are crude estimates, which do not account for the temporal variance in the pollution levels.

Real-time estimates of traffic and weather conditions are required for an accurate dynamic environmental monitoring and modelling system. Advances in traffic estimation, and sensing technology, make it possible to generate real-time pollution estimates that are accurate and rich enough for such emissions models. Accurate estimation algorithms require large amounts of traffic data, which include counts, usually measured from loop detectors or radars, and probe data, which provide reliable speed estimates. The increasing deployment of smartphones, which now provide mobile monitoring capabilities (GPS, accelerometers) and wireless connectivity (GPRS, Wi-Fi, bluetooth), enables such large-scale collection of traffic data.

Thus, even if probe vehicle are originally devoted to traffic conditions monitoring, one can extend this amount of data to environmental issues as emission or consumption estimation. In this respect, two approaches have to be considered: (i) the direct measure of consumption given by the probe CAN bus if available, and (ii) the indirect measure of emission, in which probe data and resulting traffic state estimation are used as input for emission model.

3.5.1. Direct methods

The automotive industry has introduced various electronic control systems in pursuit of safety, comfort, pollution prevention, and low cost. Beside the vehicle speed, there is a whole range of other operating and switching data available in digital form on the bus systems of modern vehicles. They are obtained from switches, sub-systems or sensors that are either standard or optional equipment on the vehicle. Being available in digital form, they can be registered on the vehicle without undue complexity and used for the process of obtaining traffic and environmental information.

These data are referred to as Extended Floating Car Data (xFCD). Data from those emerging sources are of particular interest. By acquiring and evaluating these data it might be possible to obtain information on the traffic and the general situation that goes far beyond what was available initially with FCD. Following data and activities will be collected from appropriate sensors in the car, most from the CAN bus: steering, brake pedal and gas pedal activities; fuel consumption; the actual position through GPS; weather information; lighting information.

In technical terms, CAN stands for Controller Area Network (CAN), a serial data bus standard designed to combine electronic drive units. Put more simply, the CAN bus enables vehicle components and devices to communicate with one another via message communications. The CAN protocol is an ISO standard (ISO 11898) for serial data communication. The protocol was developed aiming at automotive applications. Today CAN has gained widespread use and is used in industrial automation as well as in automotive and mobile machines. The CAN bus in trucks, for example, helps register fuel consumption and driving style. In this way, the network allows one to develop a policy aimed at encouraging an economical, eco-friendly and efficient driving style.

The CAN bus offers an overview of each driver's driving style. In this way, it could directly help reduce fuel consumption and CO_2 emissions; cut maintenance costs and restricts vehicle damage and accidents.

Note that today, the CAN bus is integrated into every truck as standard. Thanks to the FMS standard, which all the leading truck manufacturers have agreed on, it is relatively simple to extend the CAN bus with additional applications. Over 50 per cent of the trucks on the road today measure and register truck performance and driver behaviour by means of the CAN bus.

Thereby, modern telematics solutions can give much more than simple vehicle tracking. CAN bus Onboard Vehicle Diagnostics (OBD) systems provide driver profiling data and comprehensive engine management information. Driver profiles provide a relative assessment of each vehicle and also provide records of CO_2 and particulate emissions from vehicle exhausts in line with developing requirements.

CAN bus connectivity can also enable the reporting of engine fault codes. This information would warn fleet maintenance managers well in advance that a particular type of fault may be about to arise. This knowledge could help prevent breakdowns or potential vehicle shortages that can ultimately impact profitability by a failure to meet customer fulfilment and delivery requirements. When current faults are reported, fleet maintenance managers assess the fault criticality and where appropriate, order the relevant spare parts before the vehicle is even returned to base.

In summary, CAN bus allows monitoring of all vehicle data such as driver characteristics, trajectory-based, engine fault and fuel consumption. All those information are locally pre-processed and prepared for an efficient wireless transmission to a central server. There, appropriate algorithms extract a series of interesting spatio-temporal information attributes and patterns: spatio-temporal real-time “road safety” assessment; driver classification; spatio-temporal eco-driving; fuel-economic routes as well as both “driving skills” and “real-time-safety” sensitive road selection through an appropriate recommender system.

3.6. Guidelines for probe data-based monitoring

In this section, guidelines for probe data-based monitoring are given. Advantages and disadvantages of each vehicle type as a probe are exposed. Issue on processing and cleansing of probe data is also introduced as well as the question of reference data.

3.6.1. Pros and cons of each vehicle type as a probe

In section 3.1, the probes classification has been presented. The ITS probe vehicle systems described are:

1. Automatic Number Plate Recognition
2. Automatic Vehicle Identification
3. Cellular Geo-location
4. Global Positioning System

For each of those types of probe, a list of advantages and disadvantages are listed.

(a) Automatic number plate recognition

Automatic number plate recognition has the following advantages:

- The automated license plate recognition does not require addition of any vehicle equipment, which is probably its biggest single advantage;
- The automated license plate recognition dramatically decreases data reduction time;
- The video provides a permanent record (if saved) that can be reviewed at any time; and
- The video captures a large sample of the total vehicle traffic.

Automatic number plate recognition has the following disadvantages:

- The accuracy of license plate recognition is sensitive to ambient conditions (e.g. adverse weather conditions);
- The equipment is costly for small studies; and
- The method is technologically intensive and typically requires outsourcing.

(b) Automatic vehicle identification

The advantages of AVI probe vehicles for travel time collection are:

- Continuous data collection - Travel time data may be collected for entire 24-hour periods for each day of the year since personnel are not required for field data collection. Data may be collected during weekends and holidays, as well. The AVI allows data collection during all types of weather and environmental conditions as long as probe vehicles are detected.
- Minimal personnel requirements - The AVI data collection process is completely automated. Personnel are not necessary to collect data from the field. Very few personnel are needed to maintain the system and process data.
- Accuracy of data collection - For small sample sizes, 100 percent of AVI tags can be captured. The AVI technology has demonstrated itself as immune from interference from cellular telephones, citizen band radios, and electric generators.

- Lane specific - Can collect travel time data corresponding to particular lanes.
- Vast amounts of data - Since data can be collected continuously and since the system has the potential to collect data from many probe vehicle drivers, the potential exists for vast amounts of travel time data. Data can be collected over an entire year and through all types of environmental conditions.

The disadvantages of the AVI probe vehicles for travel time collection are:

- Infrastructure dependent - The system can collect travel time data only along freeway or arterial street segments that are within the coverage area of AVI infrastructure.
- Electronic tag dependent - Data collection is limited to the number of tags in use within the study area.
- Clock drift problems - Several agencies have reported that maintaining the antennas or ETC booths is expensive and may affect data quality. A common maintenance problem is keeping the clocks, which place the time stamp on each transponder read, in synchronization.
- Privacy issues - The technology requires that unique tag IDs are tracked between sequential detectors to determine travel times. The IDs correspond to individual drivers of probe vehicles, as the drivers are often registered to use an ETC system. The technology may allow individual vehicles to be tracked along the system.
- Large data storage requirement - In the AVI systems, especially systems with many antenna locations and probe vehicles, a large amount of data storage space is needed.

(c) Cellular geolocating

The advantages of cellular geolocating for travel time collection are:

- Driver recruitment not necessary - The system utilizes samples from the existing population of vehicles equipped with cellular telephones. It is not necessary to recruit volunteers or designate personnel to collect data.
- No in-vehicle equipment to install.
- Large potential sample - Studies have suggested that cellular telephone use

increases as congestion increases (Summer et al., 1994). As cellular telephone ownership increases, the number of potential probes vehicles increases.

The disadvantages of cellular geolocating for travel time collection are:

- Experimental technology - To date, cellular geolocating has been tested in few studies.
- Privacy issues - The nature of cellular geolocating may offend persons concerned that cellular telephone calls may be monitored and that their vehicles may be tracked.
- Infrastructure dependent - Since the system is constrained by the existing cellular infrastructure, it is impractical to readily modify the study area for data collection. Extending or adjusting the study area requires moving cellular towers and/or the geolocating equipment. The study is limited to links within the coverage area of the cellular network.
- Cellular phone use dependent - Travel time data collection can break down during periods of low cellular telephone use.
- Low accuracy – The testing of this technology has suggested it is adequate to determine if a probe vehicle is on a particular road, however, it was shown to be accurate at estimating travel times in 20 percent of all instances. Often geolocating a vehicles position is impaired by topography and line of sight barriers. The testing of the geolocating system reported average geolocating errors between 107 to 650 meters.
- Potentially biased sample - Sample is biased towards motorists who have and use cellular telephones. There may exist personality aspects of cellular phone users, which may or may not affect driving behaviour.

(d) Global Positioning System

The GPS probe vehicle technique has the following advantages:

- Relatively low operating cost after initial installation.
- Provides detailed data that are collected continuously along the entire travel time corridor.
- GPS is becoming increasingly available as a consumer product.

- Data collection is automated.

The GPS probe vehicle technique has the following disadvantages:

- Privacy issues become a concern when installing GPS receivers on the vehicles of volunteer motorists.
- Signals can be lost in urban areas due to large buildings, trees, tunnels, or parking garages.
- It is difficult to have consistency between drivers due to differences in driving behaviour.
- It is necessary to install two-way communication systems to send and receive signals.
- Relatively high installation cost. Since the hardware investment may be initially purchased for a purpose other than travel time data collection, coordination is necessary with the agency that installed the system.

3.6.2. Smart processing and cleansing of probe data

This section focuses on the data cleansing of probe data. The detail study of link characteristics such as travel time variance and the development of a travel time prediction model using probe data is still under investigation. The steps involved in the cleansing of the probe car data and the trip distribution of the probe car are presented.

Before the probe data can be used to determine, for example, the OD estimation, the data needs to be cleansed since probe data is a continuous trajectory and also there are gaps in the data. Therefore, the data cleansing process for the OD analysis is to cut the “continuous” trajectories into trip ends by detecting the following events.

- Gap with parking brake event,
- Long gap,
- Gap with unrealistic speed,
- Long stop,
- Short stop with hazard light,
- U-turn.

The data cleansing process starts by considering gaps in the data in step 1 to step 3. It then searches for stops, which are trip ends in steps 4 to 6. Details of each step are explained below. To illustrate those steps, the case of taxi fleet is used since this source of probe data appears as one of the most relevant.

(a) Step 1: Gap with parking brake event

Gap in the data could be due to communication error or engine being switched off. However, when there are simultaneous events of a long gap and parking brake event during the gap, it is highly likely that the engine is being switched off. In other words, this occurrence can be considered as a trip end and the trajectory can be cut at this point. Note that parking brake event is checked before and after the gap as no information is obtained during the gap. Most of the gaps with parking brake event occur when the gap is more than 10 minutes, therefore supports the above reasoning. In the data cleansing process, all gaps with parking brake event are considered as trip end.

(b) Step 2: Long gap

There are also instances where a gap occurs without parking brake. When a gap is small say 2 minutes and a vehicle is moving, it is fairly safe to bridge the gap by connecting the points before and after the gap with the same travel speed. However, when the gap is large say 15 minutes, numerous combinations of possibilities could occur during this time, such as:

- The vehicle/taxi dropping of and picking up passengers,
- The driver waiting at a taxi rank,
- The engine being switched off,
- The driver taking a meal break,
- The vehicle/taxi is on a job.

In this step, 15 minutes is the threshold for gap duration when the gap is considered as trip end. In reality this may not be a true trip end but the lack of further information makes this the best alternative.

(c) Step 3: Gap with unrealistic speed

After removing the long gaps, the remaining gaps are checked for their speed. Since the location and time of the events before and after the gap are known, the speed taken to traverse the gap distance can be computed. From all the data in this experiment, there was no speed greater than 60 km/h. This speed value is used as the upper bound for the speed check and data points above the upper bound are eliminated. For the remaining gaps, if the computed gap speed is greater than 75% of the short travel (ST) speed before the gap, the trajectories before and after the gap will be connected. Otherwise, the gap is considered as a trip end.

(d) Step 4: Long stop

The first three steps consider the gaps in the data and steps 4 and 5 search for stops that are trip ends. Stops could happen when a taxi is dropping off or picking up a passenger, stopping at an intersection or taxi rank. Obviously picking up and dropping off passenger are considered as the beginning and end of a trip, respectively. To differentiate between stopping at an intersection and a true trip end can be difficult. Firstly, it takes more than 20 seconds to drop off a passenger i.e. the time for a taxi to stop and for the driver to collect the taxi fare. A taxi waiting at a signalized intersection could range from a few seconds to over 100 seconds. It is therefore difficult to distinguish between a genuine trip end and just stopping at intersection.

However, from the time distribution of stops with and without parking brake event, 95% or more of the stops are less than 150 seconds. This indicates that it is unlikely for a vehicle to stop at an intersection for more than 150 seconds. In this step, short stop of 180 seconds with parking brake is adopted as the threshold for cutting the trajectories (i.e. accepting the long stop as a trip end). From the calibration of maximizing the number of correct trip end and minimizing the number of false trip end, it was found that cutting a trajectory at short stop greater than 30 seconds without parking brake event gives the best results.

(e) Step 5: Stop with hazard light

The previous step does not recognize stops for dropping of or picking up passengers. In Japan, taxi driver’s turn on the hazard light when picking up and dropping off passengers. However, the hazard light is also used to acknowledge other drivers for allowing a vehicle to merge or pass, commonly referred to as “thank you hazard”. Analysis of stops with hazard light when picking up and dropping off shows that the minimum stop time is 20 seconds. In this step, short stop greater than 20 seconds with hazard light more than 10 seconds is used as a cutting point for trip end.

(f) Step 6: U-turn

The last cleansing step looks at the shape of the trajectory that resembles a loop or a u-turn. A u-turn is often a point close to a trip end for example after dropping off a passenger; the taxi may make a u-turn to go back where it came from. Some u-turns are sharp turns (e.g. 3 point turn) and others are more gradual. It is also important to note that the geometric configuration of some road networks is shaped like a loop such as clover interchange, and on and off ramps. Firstly, an exception list of all loops in the road network is created. The list is used to ignore loops detected in the excluded area. Secondly, loops are ignored in the CBD area because there are one-way streets. Excluding the exception list and CBD area, the u-turn algorithm checks the turning angle of all the trajectories. If the turning angle of its current position with respect to the last 10 ST trajectories of length more than 20 meters exceeds 170 degree, it is considered as a u-turn.

Finally, after the data are cleansed, all the cut points become trip ends. The cleansing process also generates some very short trip ends due to gaps in the data and also due to imprecision in the search for trip ends. It is decided that trip ends less than 500 meters are eliminated, as almost all trips are longer than that.

3.6.3. What is the reference data?

(a) Comparison of estimated (instantaneous) route speeds and measured route speeds on single routes

An important practical objective of quality evaluation of travel time measurements is generating a reference data set, which can be used for quality evaluation of other travel time data sources. The required accuracy quality levels of the reference travel times are at least as high or higher than the evaluated data sources. If target quality levels for travel speeds on a road link are an allowable error of 5 km/h and a confidence level of 95 %, the reference data set has to fulfil at least the same quality level or even a higher one.

Reference data sets have a longer time for data collection, and more time and effort can be invested in data handling and data cleaning.

If possible, single route speed measurements should be chosen for comparison and evaluation, as they allow a better description of the frequently irregular speed or travel time distribution (see Torday, 2005).

In most previous studies on travel time quality in urban areas, main urban corridors were chosen as test routes, on which typical characteristics of urban traffic (mainly unsignalised and signalised intersections, public transport lines) can be observed. The measurement setup is usually dictated by budget constraints, which restrict the measurement campaign to a single route.

The selection of these test routes is therefore an essential part of the overall evaluation methodology. Local knowledge is invaluable in this selection process, and it is usually local experts, who make an expert decision on these routes based on several criteria.

(i) Route layout and length

In order to calculate a reliable indicator for traffic data quality for the whole road network it is recommended that test routes consist of a good mix between main traffic arteries and smaller roads. Circular routes composed of coherent parts are good candidates (e.g. one part of the route could follow a major city arterial road, while the next part focuses on secondary roads).

An optimal route length should represent typical average trips lengths in a city (5 to 7 km). Longer routes are fine, as they can easily be split into smaller parts in a post-processing phase. However, it is recommended that a route should not take longer than 30 minutes to complete. Combined with the recommendation to use circular routes, these constraints allow one probe vehicle to perform at least 2 measuring runs per hour.

(ii) Time frame and covered traffic states

To allow a reliable statement on the quality of the provided travel times, all traffic states typical for the pilot city, i.e. at least both unstable traffic conditions (rush hours) and stable traffic conditions, have to be covered. Road types and timeframes have to be selected accordingly.

(iii) Obstacles and unusual events

Roads with unusual obstacles (like blocked roads due to construction work) need to be avoided when selecting routes and test timeframe. The time windows should be chosen in such a way that extreme weather conditions are unlikely to occur.

(iv) Sampling frequency / Number of probe vehicles

As the frequency of measurements has a great influence on the map matching process and therefore the possible overall accuracy of evaluation, an appropriate sampling frequency is desirable. The time delay between consecutive measurements of the proposed GPS trackers should be in the interval of 20 to 30 sec in order to ensure accurate map matching. Since the map matching quality is dependent on other factors like denseness of road network, this reporting interval is a recommended value.

On the investigated routes, (pairwise) speed differences between estimated speed values from the RTTI information system and speed measured by probe vehicles are compared.

The minimum number of vehicles to be sampled depends on the underlying speed distribution of route speeds. In general, route mean speeds on a road link have been shown to follow a normal distribution in probe-based monitoring systems (due to the central limit theorem).

Subsequent trips of probe vehicles should be scheduled at 5/6 min intervals, in order to guarantee independence of measurements.

Based on these requirements and conditions, a minimum measurement setup consists of 2 days with 3 measurement hours on unstable traffic conditions (with 5/6 min intervals between trips) and 2 days with 3 measurement hours on stable traffic conditions (with 5/6 min intervals between trips).

The expected maximum travel-time (in minutes) is the time required to complete the test route on adverse traffic conditions. Furthermore, we recommend a minimum number of 10 probe vehicles, to compensate for driver and vehicle peculiarities.

(b) Comparison of estimated route speeds and measured route speeds of a vehicle subgroup on randomly selected routes

An increasing number of floating car data are registered on a regular basis, e.g. for fleet management purposes or in the context of travel information. These floating car data constitute an important data source for quality evaluation of travel times, especially in urban areas (Kuhns, et al. 2011).

For the purpose of travel time evaluation, a subgroup of vehicle trips in the investigated traffic zone is selected as reference data set. The required number of trips depends on the target accuracy quality levels for the routes in the road network under investigation. As route speed variance is usually unknown before an investigation, the link speed variance is used to estimate the route speed variance according to the methodology for travel speed estimation (see section 4.3.2). The link speed variance is usually larger than the route speed variance and can be regarded as an upper limit of the route speed variance for the purpose of sample size estimation.

After map-matching, the actual routes of this subgroup are calculated or retrieved from an existing database. The route length of the chosen reference trips should be at least 2 to 3 km, as travel speeds on shorter routes in urban areas usually exhibit high variance. An optimal route length should represent typical average trips lengths in a city (5 to 7 km). For these routes, which are expected to be randomly distributed in the road network, (reference) route speeds are calculated.

In a next step, (instantaneous) route speeds from the data source under evaluation are calculated for all routes covered by the vehicle subgroup. Evaluated route speeds are compared to reference route on these routes pairwise. The result of the accuracy evaluation is e.g. a mean error or a correlation coefficient of evaluated and reference route speeds.

The advantage of this approach is a random selection of routes in the whole investigated road network, circumventing the frequently arbitrary choice of reference routes.

A disadvantage of this approach is that reference route speeds are measured by the same measurement method as estimated route speeds. A possibly present bias of the measurement method (FCD travel times) cannot be detected, as it affects both speed measurements. If available, alternative methods for route speed measurements (e.g. based on Automatic Vehicle Identification) can be used to check for a possible systematic error in the reference data set.

3.6.4. Map-matching algorithm

Map-matching is the process of aligning a sequence of observed user positions with the road network on a digital map. This method is required since on one hand the GPS-coordinates needs to be connected with the map data and on the other the accuracy of the Global Positioning System is not satisfactory to meet the demands of our purpose. Thus, even if the GPS-coordinate lies exactly on one link before matching, a lane-element needs to be assigned to that point, which includes amongst others a direction. The traditional map-matching algorithms mainly use two methods: the incremental method and the global method.

The incremental method is usually to search the roads in the vicinity of the GPS point from the road network, and calculates the distance between the GPS point and its nearby roads in order to choose the road, which is closest to the GPS point as the map-matching result.

On the contrary, the global method is to match a curve to the road graph and the similar curve. It connects the GPS points to form a curve, matches the curve to a path using Fréchet distance and then searches the road network with the goal to a curve, which is as close as possible to the vehicle trajectory.

Map-matching is the most vulnerable method since the algorithm is relatively primitive, which is implemented in the software for matching the above mentioned input vectors to the digital map if the status is appropriate. Vulnerable on one hand in the sense that due to this method some measurements need to be thrown away since they cannot be appropriately matched which is a pity from the point of statistics and the reliability of estimators (reducing the sample size) and on the other hand in the sense that some GPS points are matched to the wrong lane-element thus causing a wrong routing and in the end obtaining wrong travel times.

Algorithms of the map matching have been developed continuously and they can be classified into two categories roughly. First, map-matching algorithms, which consider only geometric relationships between GPS data and a digital map. Secondly, map matching algorithms, which consider not only geometric relationships but also the topology of the road network and the history of GPS data. It has been reported that the latter worked better most of the time.

The first map matching algorithms can be classified again into the map-matching algorithm using the distance of point-to-curve, one using the distance of curve-to-curve and one using the angle of curve-to-curve. Some past studies used the distance of point-to-point. But these vertex-based map-matching algorithms are appropriate when one pursues simplicity rather than accuracy.

The second map matching algorithms use the result of map matching at time t-1 for the map matching of GPS data at time t. And for the selection of candidate segments which GPS data will be matched, the topology of the road network is inputted as a constraint. But these algorithms should be used under particular prudence. For example, if the result of map matching at time t-1 is wrong then the result of map matching after that time will be wrong also. Thus, it should be guaranteed that the result of map matching at time t-1 is exact to use these algorithms. Besides, if the vehicles with a GPS receiver follow abnormal routes (e.g. the left turn on the left turn restricted intersection) we cannot expect the right result of map matching because the normal topology respects traffic regulations.

The shorter the polling time interval is, the better the performance of the map matching algorithm is, because the availability of the GPS data history will be increased. But in practice, various problems restrict the shortening of the polling time interval. For example, there should be some telecommunication method to collect the GPS data of many persons on real time. If the telecommunication is accomplished by the third telecommunication company, very short polling time will inevitably accompany with a high cost.

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V. Example Applications

1. Japan: Energy ITS project (Development of Energy-saving ITS Technologies project)

As approximately 20% of all carbon dioxide emissions in Japan emanate from vehicles, energy conservation measures related to vehicles and traffic are essential. Because ITS can be an effective energy/environmental measure to reduce energy consumption in the transport sector, the Energy ITS project was conducted in Japan from FY2008 to FY2012 to develop technology for autonomous driving and platooning and to establish reliable international evaluation methods.

Under the theme of establishment of reliable international evaluation methods, hybrid traffic flow simulations that encompass traffic networks from metropolitan to rural areas and an emission model to estimate CO_2 emission emanating from vehicles using output from the traffic simulation were developed. In this theme, technology to monitor CO_2 emission using probes and a traffic database to share traffic related data internationally were also developed and comprehensive technology to estimate CO_2 emission was examined. The following case study is a part of the results of the project.

1.1. Modelling

1.1.1. Target ITS application

For the Japanese case study, an evaluation of the effect of introduction of Eco-driving in Tokyo's 23 wards was conducted following the steps of this report. According to Chapter I.2, Eco-driving belongs to the ITS category 1: 'Improving driving behaviour'. Therefore, evaluation tools for Eco-driving have to take into consideration driving behaviour changes such as decrease of unnecessary acceleration / deceleration behaviour.

1.1.2. Definition of Eco-driving

In Japan, ten items are mentioned as Eco-driving. Three of them are shown in Fig. V.1 and cause driving dynamics to change: moderate start, maintain a steady speed, and slow down by releasing the accelerator. In this project, we only focused on "moderate start" (e-Start). Here, moderate start is defined as acceleration from 0km/h to 20km/h in 5 seconds which is the value generally recommended in Japan. Fig. V.2 shows a comparison between normal start and moderate start.

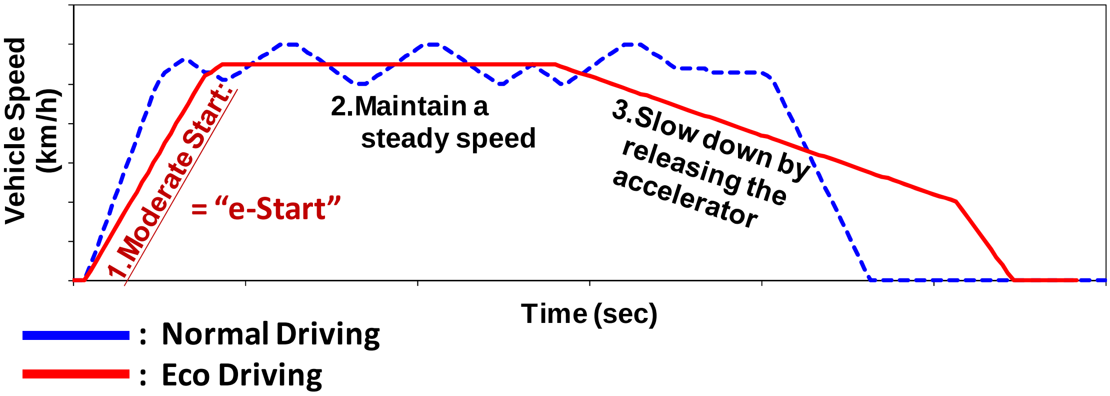


Fig. V.1 Eco-driving by changing driving behaviour

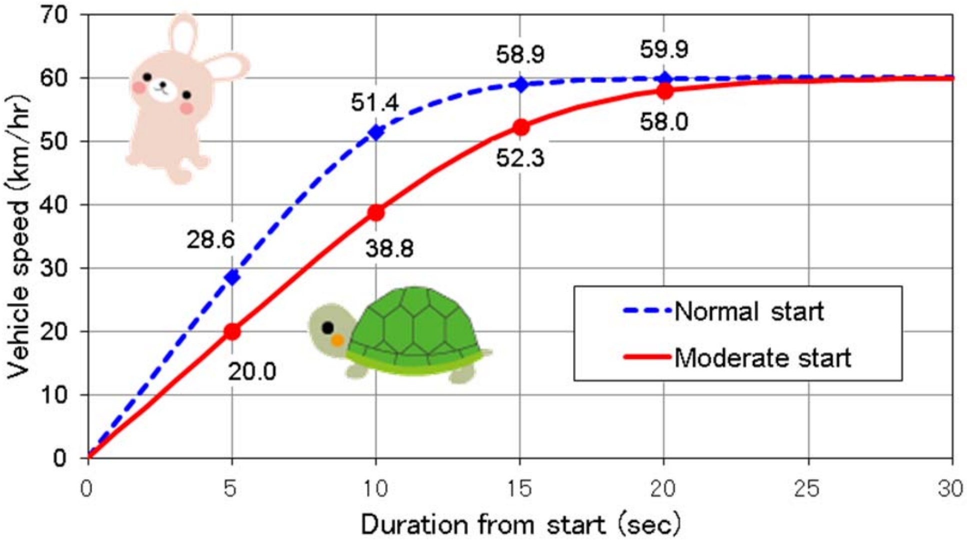


Fig. V.2 "e-Start" support concept

1.1.3. Scope of modelling by using a reference model

According to Chapter 2, our scope of modelling for evaluation was defined by using a reference model. In this study, we supposed that the driver of an e-Start vehicle just follows the e-Start instruction at the starting scene. So as shown in Fig. V.3, we did not consider the behaviour of the 'driver' and the influence by the 'ICT system'. We focused on the effect of direct reduction on the CO_2 emissions from the Eco-driving vehicles and the indirect changes from other vehicles which will be influenced by the e-Start vehicle.

Fig. V.4 shows the instance model for the case study on e-Start. Moderate acceleration of the e-Start vehicle and of the following vehicles have the positive effect of reducing CO_2 emission. However, it also has a negative effect because start-up loss at an intersection will be increased by e-Start and it will cause a drop in the capacity of the signalized intersection. Our subject of the evaluation is these two effects.

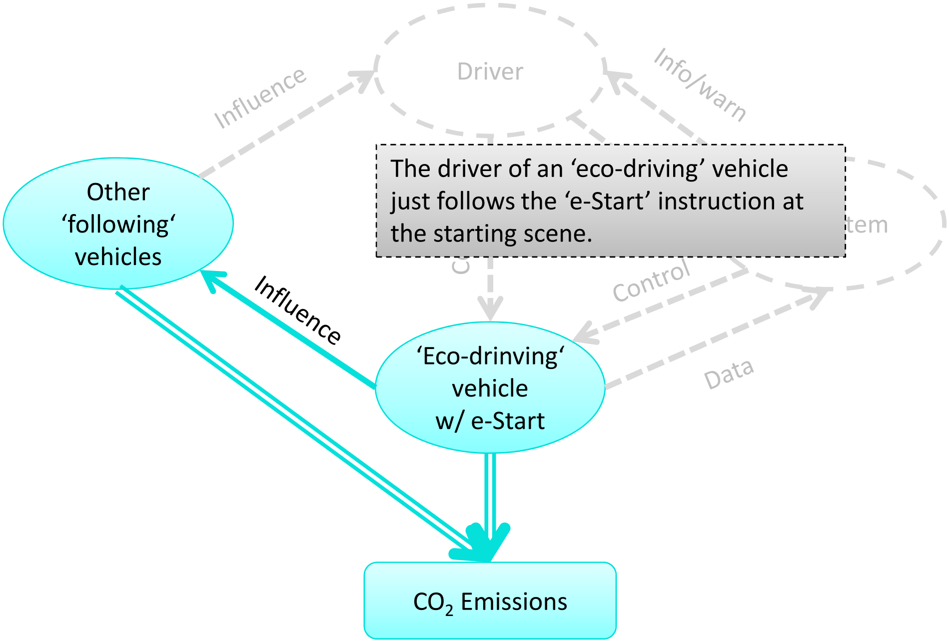


Fig. V.3 The Delimited Category Model for the Japanese Case Study on e-Start

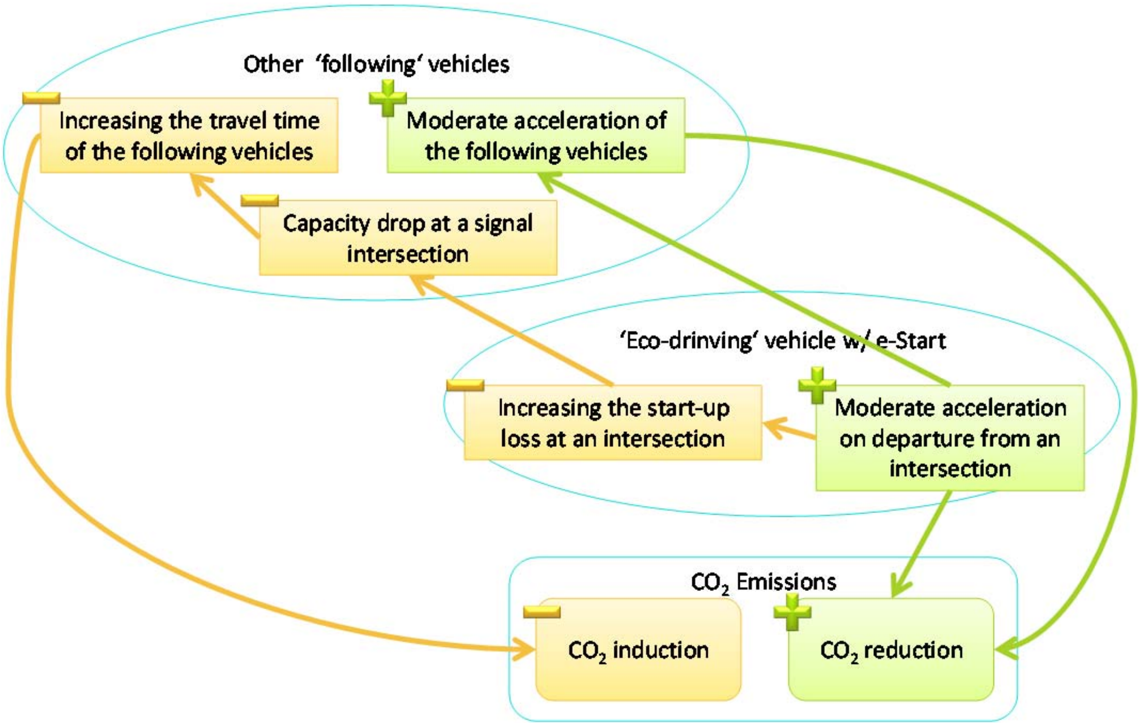


Fig. V.4 The Instance Model for the Japanese Case Study on e-Start

1.1.4. Concept of evaluation tool

For the purpose of evaluating various kinds of ITS applications in a large area, such as the 23 wards of Tokyo, an evaluation tool which consists of mesoscopic model cooperation between a traffic simulation model and CO_2 emission model was developed in this project. A mesoscopic traffic simulator which deals with a vehicle's condition as two modes (running mode or stopping mode) can simulate traffic conditions in a large area with low computational complexity. However, it cannot reproduce the acceleration and deceleration behaviour of each vehicle. As mentioned in V.1.1.1, acceleration and deceleration behaviour is one of the important factors in the evaluation of Eco-driving. To solve this issue, we developed a mesoscopic CO_2 emission model which can estimate CO_2 emission of each vehicle from the mesoscopic traffic state and verified that the mesoscopic model has enough accuracy for practical use.

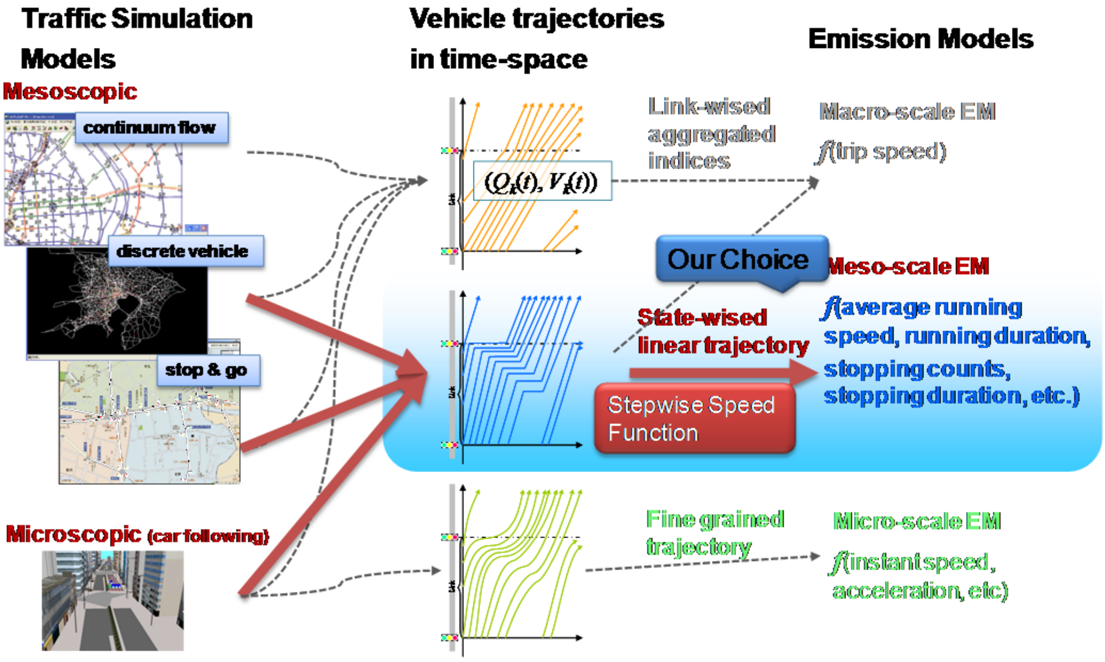


Fig. V.5 Concept of the evaluation tool

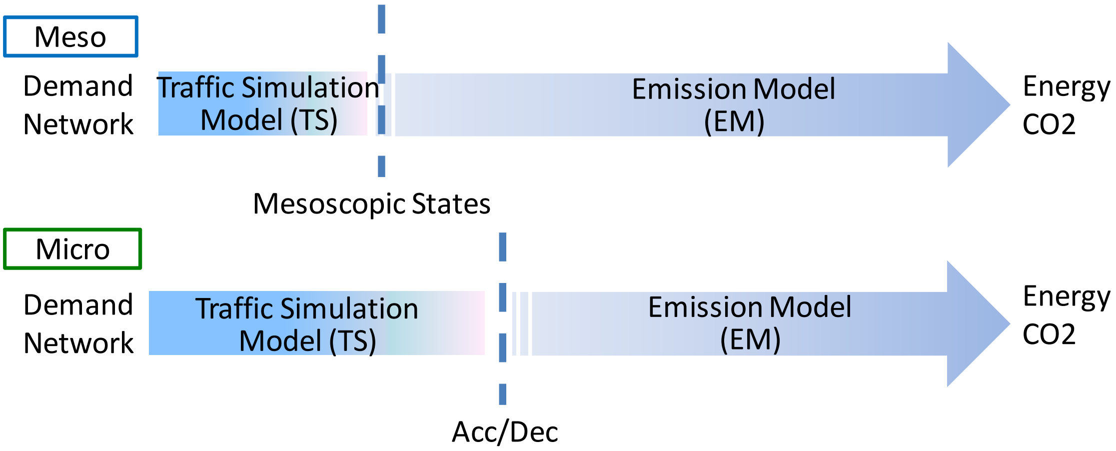


Fig. V.6 Difference between mesoscopic approach and microscopic approach

1.1.5. Modelling of traffic simulation model

(a) Mesoscopic traffic simulation model: SOUND

SOUND (Simulation On Urban road Network with Dynamic route guidance) is a mesoscopic traffic flow model which was developed by the Institute of Industrial Science, the University of Tokyo. It can deal with physical queuing phenomenon by implementing Newell's "Simplified Kinematic-wave Theory" to reproduce shockwave propagation and dynamic stochastic assignment of traffic flow with Dial's assignment algorithm.

SOUND consists of a route choice model and a vehicle movement model as shown in Fig. V.7. Each vehicle moves on a network within the vehicle movement model, and the direction at a diverging section is determined in the route choice model based on traffic conditions, such as travel time.

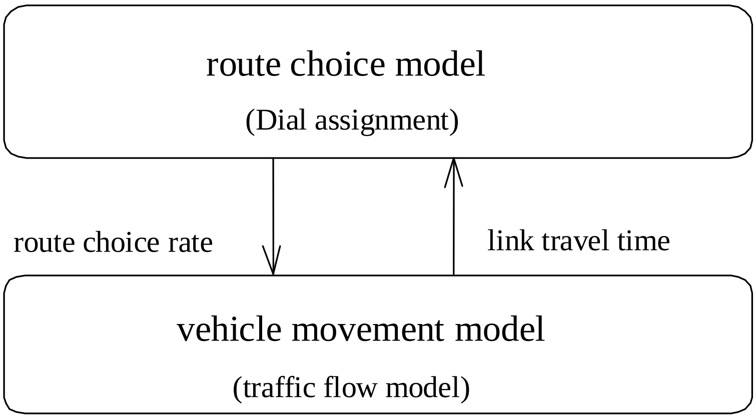


Fig. V.7 Structure of SOUND

In SOUND, vehicles move in a packet, putting similar vehicles together (same attributes, destination, etc.). In addition, each link is divided into two vehicle lists, a list of moving vehicles and a list of dischargeable vehicles, as shown in Fig. V.8. Packets in the list of moving vehicles obey the FIFO (First In First Out) principle; that is, packets exit the list in the same order they entered. Each packet is switched over to the list of dischargeable vehicles after the free travel time of the link T_F passes. Each link has a capacity which indicates the maximum value of traffic flow to the next link according to its road class, road grade, and so on. In SOUND, the traffic signal lighting was modelled and it is able to evaluate the travel times, even taking into consideration unsaturated delays caused by traffic signal controls.

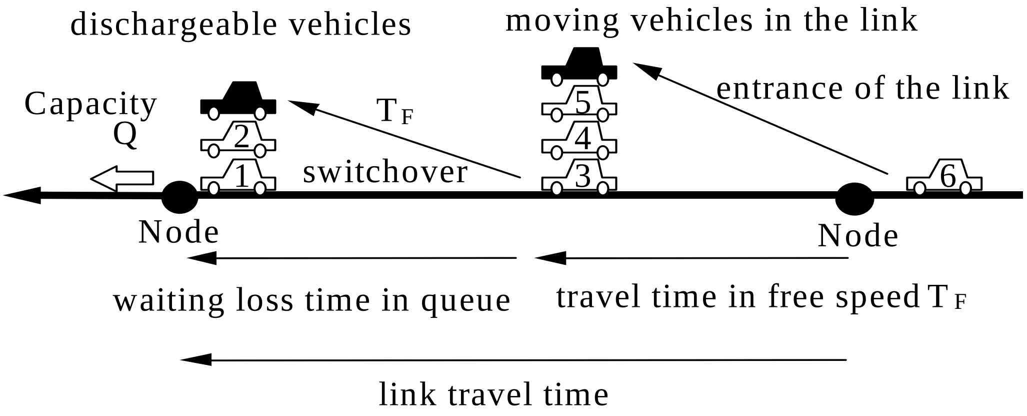


Fig. V.8 Vehicle moving logic of SOUND

To reproduce traffic flow in SOUND, each link has a cumulative curve of in-flow demand to the link from the upstream link. The list of dischargeable vehicles shows queues in front of intersections and the packet in the list moves to the next link in accordance with the capacity of the intersection. Also, right and left turning vehicles can move to the next link depending on the extent of the number of vehicles existing in the exclusive right and left turn lanes in spite of the FIFO principle, even in the case that vehicles moving through are blocked at the intersection. The link keeps the history of the cumulative curve of out-flow to the downstream link and compares it with the in-flow demand curve. The cumulative curve of in-flow of the link is given by the lower bound of these two curves. In the case the in-flow to the link exceeds the out-flow of the link, a traffic jam occurs on the link and waiting loss time in the queue of the link becomes longer. The timing of extension of the jam is calculated by the shockwave theory.

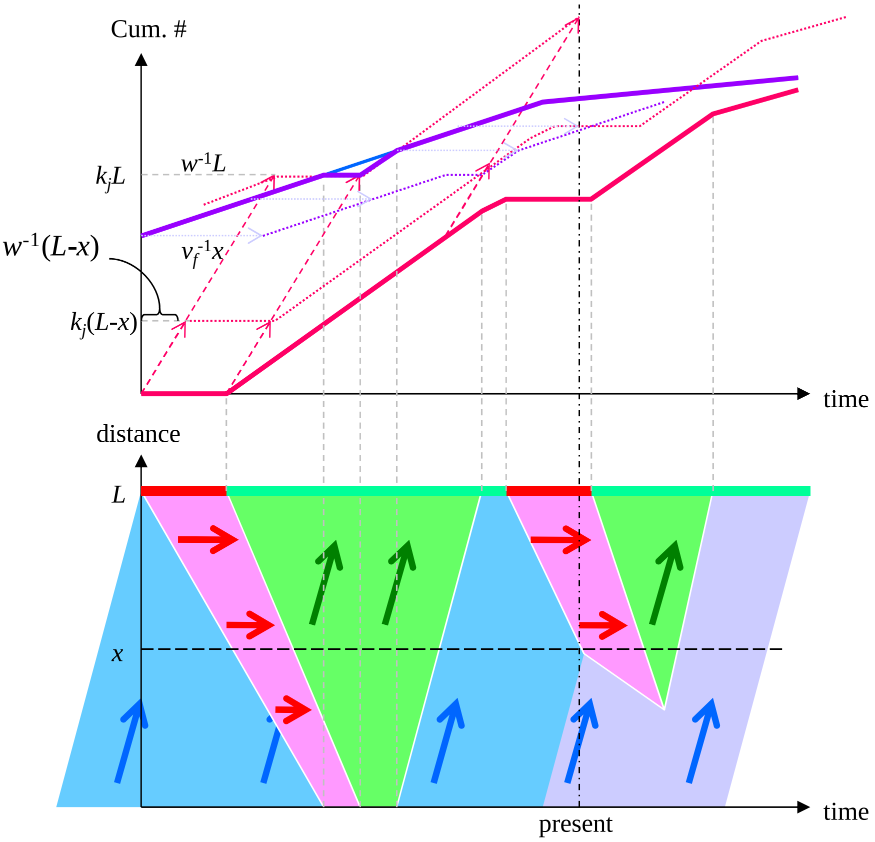


Fig. V.9 Flow model of SOUND

(b) Methodology for cooperation with CO_2 emission model

As mentioned before, the concept of our evaluation tool is mesoscopic model cooperation between the traffic simulation model and emission model. In the mesoscopic traffic simulation model, a vehicle's state is described in mesoscopic states, running and stopping. For the purpose of passing the result from the traffic simulation model to the CO_2 emission model, Stepwise Speed Function (SSF) was developed (Fig. V.10 and Fig. V.11). SSF defines two types of a vehicle's state. One is the vehicle in a stopping condition starts and after running over 3km/h for more than 3 seconds, stops again (short trip). The other is the vehicle stops (less than 3km/h) for more than 3 seconds (short stop). SSF is a speed profile which has the same running distance and running time of actual speed running. It also has the number of accelerations and decelerations, and road grade, etc. In addition, when the accumulated mileage from the start of the SSF exceeds 500m, the SSF must be divided as shown by the second and third SSFs in Fig. V.11.

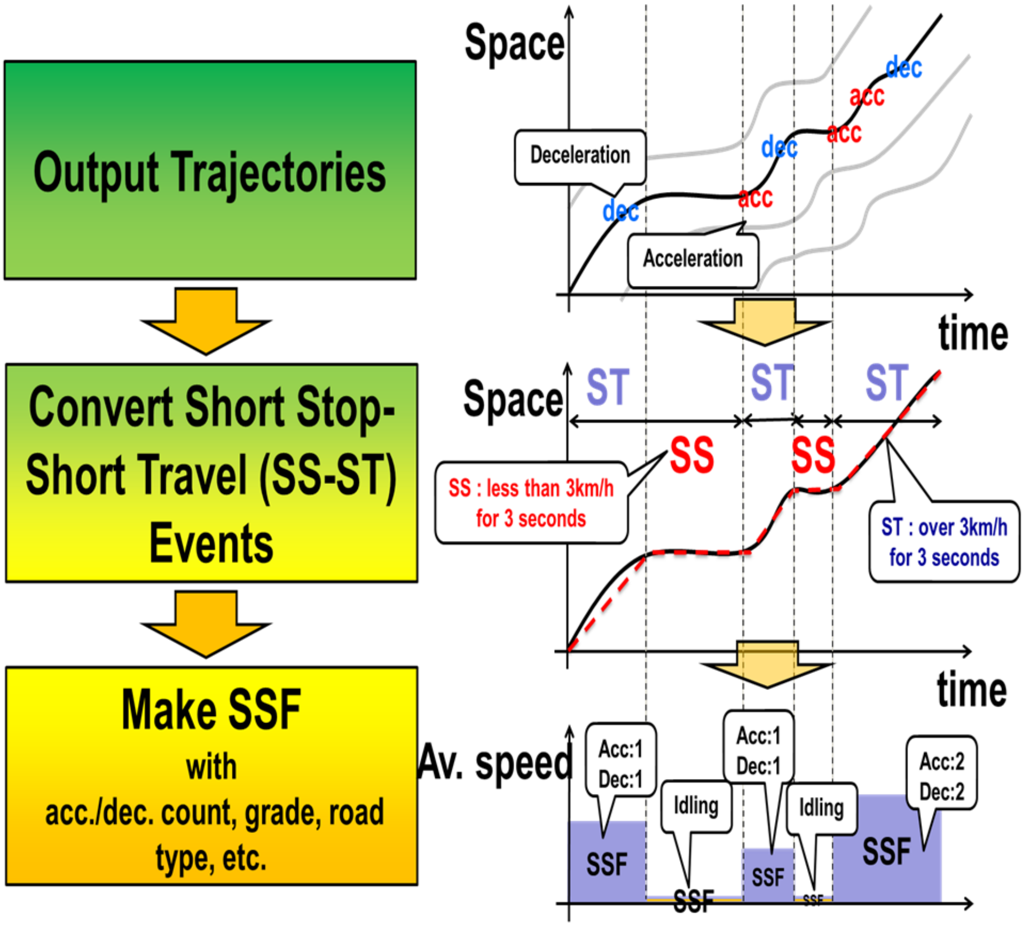


Fig. V.10 SSF from traffic simulation

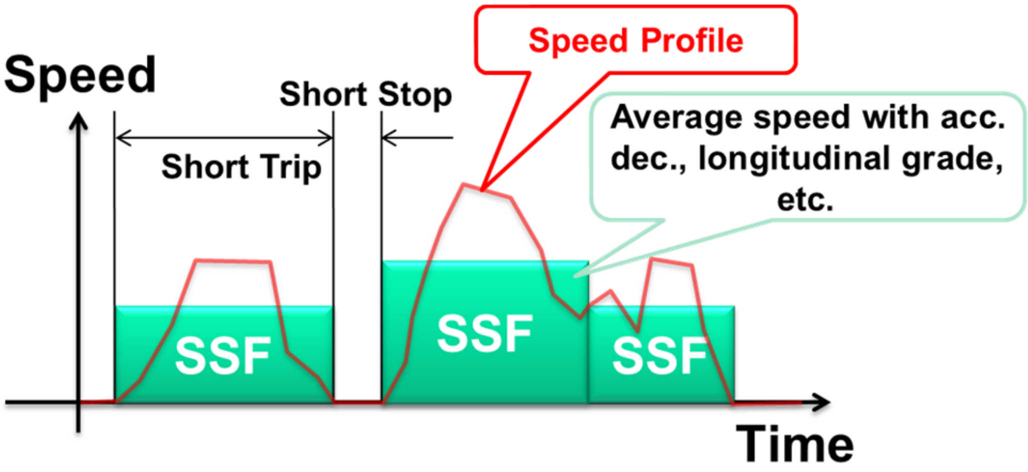


Fig. V.11 Schematic of SSF

1.1.6. Modelling of CO_2 emission model

(a) Concept of mesoscopic CO_2 emission model

CO_2 emission from each vehicle's travel is calculated by the mesoscopic CO_2 emission model which uses SSF from the traffic simulation model as its input data. In order to estimate the CO_2 emission with each SSF, it is important to predict the fuel consumption for the CO_2 estimation because the CO_2 emission is proportional to the fuel consumption. Additionally, it is known that vehicle drive energy is one of the most important factors to predict fuel consumption. Thus, predictions of the drive energy are important processes for the estimation of CO_2 emission.

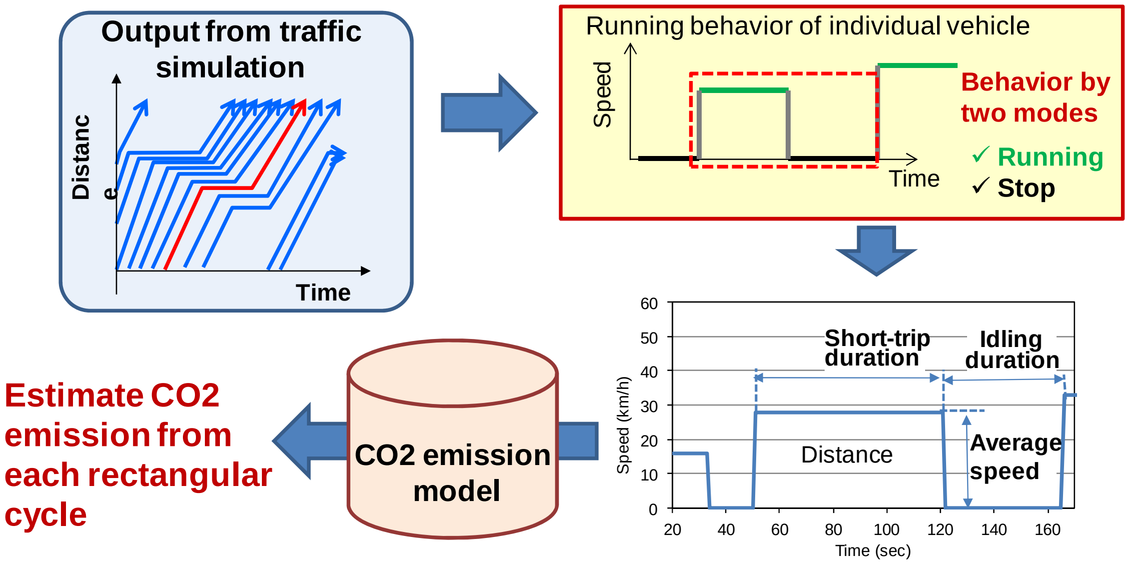


Fig. V.12 Concept of estimating CO_2 emission

(b) Methodology of estimating vehicle drive energy by SSF

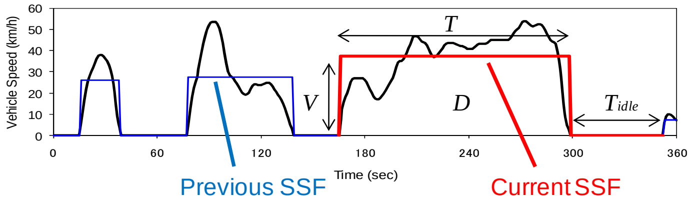
Fig. V.13 shows the definition of vehicle drive energy. The drive energy consists of an acc./dec. term, aerodynamic drag term, rolling resistance term and road grade term. Delta_acc. is a special sign function. Delta_acc. equals 1 when the vehicle accelerates and delta_acc. equals 0 when the vehicle decelerates. The acceleration term expresses the supply of energy from engine to wheel. This energy supply is carried out during an acceleration duration. Therefore, it is understood that delta_acc. is the function to express the effect of acc./dec.. The aerodynamic drag term, rolling resistance term and road grade term can be directly calculated with information included in SSF, which are mean vehicle speed (V) and running distance (D). However the acc./dec. term cannot be directly calculated and it is necessary to model this term.

Vehicle drive energy: *E*

$$E = \underbrace{m\int_0^T \left\{\delta_{acc.}\left(v\frac{dv}{dt}\right)\right\}dt}_{\text{Acceleration term}} + \underbrace{c_D a V^2 D}_{\text{Aerodynamic drag term}} + \underbrace{c_R mgD}_{\text{Rolling resistance term}} + \underbrace{mgD\sin\theta}_{\text{Road grade term}}$$

Statistical modeling

$$\begin{cases} \delta_{acc.} = 1, & when \quad dv/dt \geq 0 \\ \delta_{acc.} = 0, & when \quad dv/dt < 0 \end{cases}$$



Short trip (ST)
v : Vehicle speed
t : Time
V : Vehicle mean speed
D : Running distance
T : Running duration
θ : Mean road grade
Short stop (SS)
T_{idle} : Idling duration
Constants
m : Vehicle mass
g : Gravity acceleration
c_D : Aerodynamic drag coefficient
a : Vehicle frontal area
c_R : Rolling resistance coefficient

Fig. V.13 Vehicle drive energy definition

In this project, the acceleration energy is modelled with a statistical method, which is the multiple regression analysis of results of field operation tests. To get data for the analysis, we conducted field operation tests on various vehicle types in various roads. Fig. V.14 is one example of the field operation tests which is for modelling the acceleration energy of a passenger car. A CO_2 emission database for the CO_2 emission model was built by this field operation test's data.

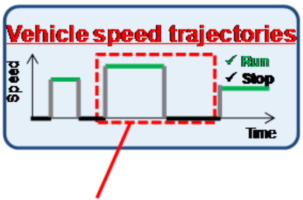
Vehicle

Vehicle	**Passenger car: TOYOTA Vitz (Yaris) 1.0 liter engine**
Fuel	**Gasoline**
Number of drivers	**6**

TOYOTA Vitz (Yaris)

Area

Drive areas	**Tokyo (city area), Tsukuba (rural area)**
Roads	**General roads**



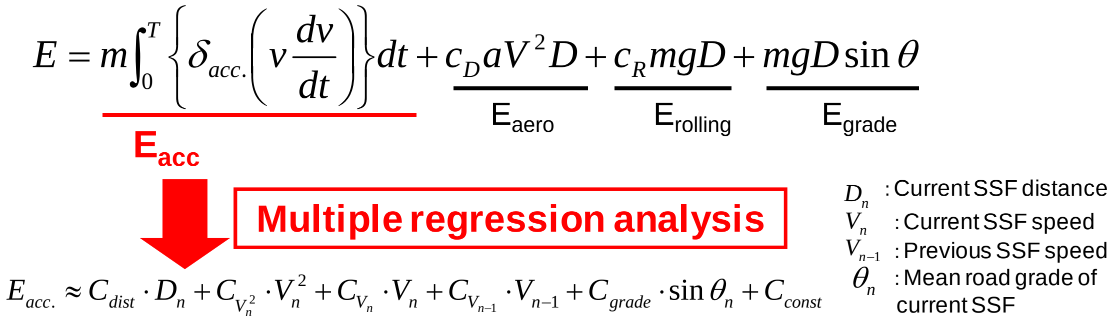
Stepwise Speed Function (SSF)

Analysed data

No. SSF (obtained by exp.)	**440**
SSF distance	**smaller than 500m**
Total running distance	**80.8km**

Fig. V.14 Experimental conditions

The formula for the model of acceleration energy of the passenger car is obtained as shown in Fig. V.15 by the experiment. This formula has five variables which are the term of current SSF distance, current SSF speed squared, current SSF speed, previous SSF speed and mean road grade of the current SSF. The table in Fig. V.15 shows the result of multiple regression analysis of the acceleration energy. Additionally, it shows that the current SSF distance is the largest contribution's term, followed by current SSF speed squared, current SSF speed, previous SSF speed and mean road grade of current SSF.



$$E = \underbrace{m\int_0^T \left\{\delta_{acc.}\left(v\frac{dv}{dt}\right)\right\}dt}_{E_{acc}} + \underbrace{c_D a V^2 D}_{E_{aero}} + \underbrace{c_R mgD}_{E_{rolling}} + \underbrace{mgD\sin\theta}_{E_{grade}}$$

$$E_{acc.} \approx C_{dist}\cdot D_n + C_{V_n^2}\cdot V_n^2 + C_{V_n}\cdot V_n + C_{V_{n-1}}\cdot V_{n-1} + C_{grade}\cdot \sin\theta_n + C_{const}$$

D_n : Current SSF distance
V_n : Current SSF speed
V_{n-1} : Previous SSF speed
θ_n : Mean road grade of current SSF

Constants	C_{dist}	Cv_n^2	Cv_n	Cv_{n-1}	C_{grade}	C_{const}
Variables	Current SSF distance (m)	Current SSF speed squared (km2/h2)	Current SSF speed (km/h)	Previous SSF speed (km/h)	Mean road grade of current SSF (deg.)	Constant
Contribution	Large				Small	—
Standardized coefficients	0.462	0.269	0.251	0.049	-0.044	—

Fig. V.15 Acceleration term modelling

(c) Adaptation for the changes in driving dynamics

As described above, in the mesoscopic model, CO_2 emission is modelled with multiple regression analysis of a CO_2 emission dataset which has driving behaviour and CO_2 emission data. This dataset is created with results of a field operation test under normal conditions. However, to evaluate the ITS measures with driving behaviour change, it is mandatory to create a new CO_2 emission dataset under the ITS measures.

We prepared the following three options to create the new CO_2 emission dataset, as explained in Chapter 2.

- Option 1: Real field operation test

  A new CO_2 emission dataset under the ITS measures is collected by a field operation test.

- Option 2: Microscopic traffic simulation model and microscopic CO_2 emission model
  The new driving behaviour under the ITS measures is estimated by a microscopic traffic simulation. Corresponding CO_2 emission is estimated by a microscopic emission model.

- Option 3: Designed driving behaviour and microscopic CO_2 emission model
  The new driving behaviour under the ITS measures is estimated by a designed driving behaviour. Corresponding CO_2 emission is estimated by a microscopic emission model.

We must create a multiple regression formula such as Fig. V.15 using one of the above-mentioned options, in the case of evaluation of the ITS measures with driving behaviour change.

As examples of application of Option1 and Option 3, we describe the estimation result of driving with e-Start. "e-Start" is defined as acceleration from 0km/h to 20km/h in 5seconds, as shown in Fig. V.2.

In Option 1, the driving behaviour and CO_2 emission dataset is measured by a field operation test in which test drivers drive with e-Start.

In Option 3, to obtain the new driving behaviour with e-Start, the speed patterns from a start to peak speed is transposed to the theoretical speed patterns which reach peak speed with reduced acceleration. Corresponding CO_2 emission is estimated by a microscopic emission model.

Fig. V.16 shows an example of an e-Start speed pattern in Option 3. The speed pattern of e-Start is created with weighted averaging of two acceleration patterns. One is a straight line which passes the point of 5sec-20km/h, and the other is a first order lag curve which approaches asymptotically to peak speed, and passes the point of 5sec-20km/h. In both options, the multiple regression formula, such as Fig. V.15 with the above-mentioned speed pattern and CO_2 emission dataset, is created by the statistical method described in (b).

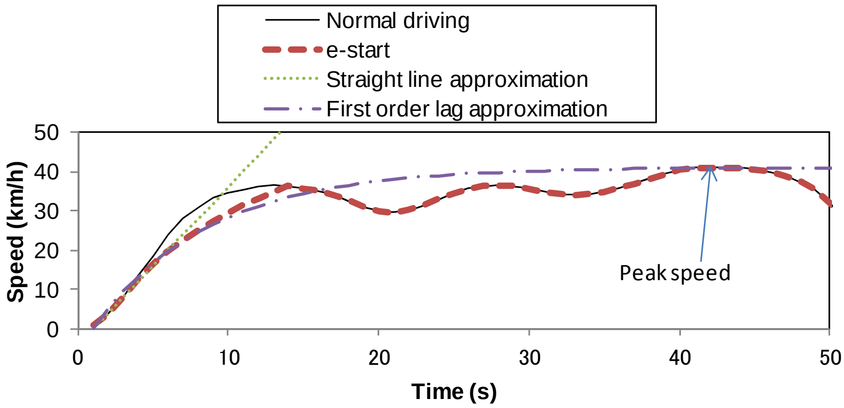


Fig. V.16 Speed pattern with e-Start in Option 3

The results of the field operation test are shown in the right of Fig. V.17. This figure shows the difference of the CO_2 emissions of normal driving and e-Start driving. The results of Option 1 and Option 3 are shown in the left of Fig. V.17. This figure expresses that Option 1 and Option 3 have lower CO_2 emissions similar to field operation test results compared with normal driving. Furthermore, it is shown that the CO_2 emissions of Option 1 and Option 3 are comparable.

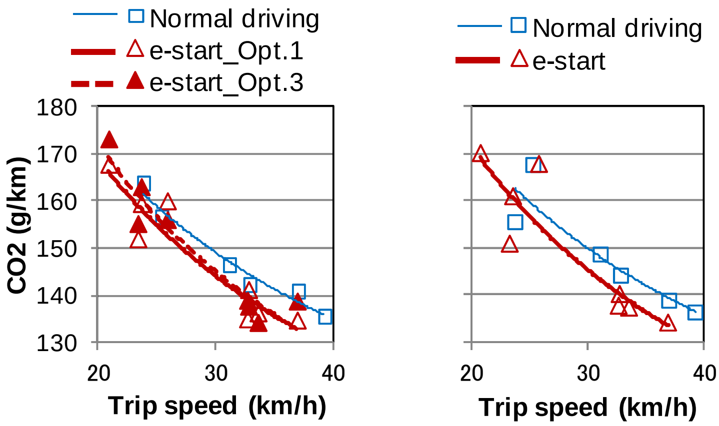
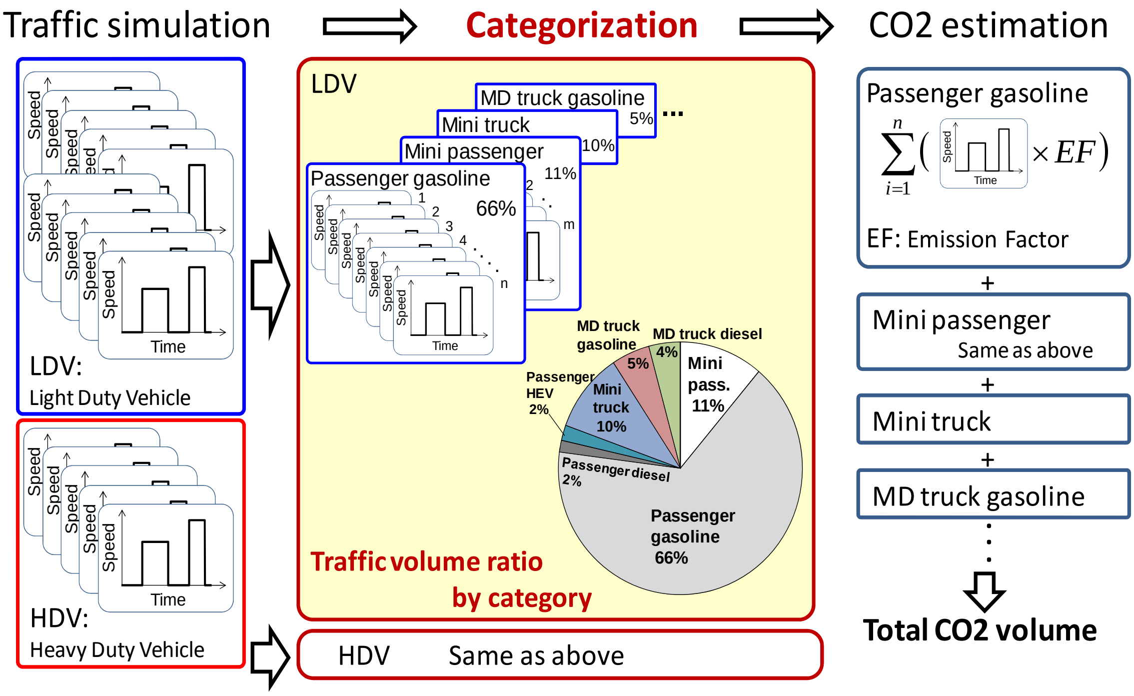


Fig. V.17 Results of CO_2 estimation of Option 1 and Option 3

(d) Vehicle type classification in the model

The CO_2 emission model can estimate CO_2 emission based on output data of the mesoscopic traffic simulation model. In the traffic simulation model, each vehicle is classified according to its running behaviour. However, in the CO_2 emission model, characteristics of CO_2 emission of vehicles which have the same driving behaviour differ with vehicle type, i.e., passenger car or truck or fuel type, i.e., gasoline or diesel. Thus, more detailed vehicle type classification should be used in the CO_2 emission model. This vehicle classification was defined based on running volume ratio calculated from the number of each type of vehicle and its running volume. Fig. V.18 shows the concept of vehicle type classification in the traffic simulation model and emission model.



			Traffic simulation	
	Motor	Categories	Small	Large
CO2 emission model	Gasoline	Minicar	✓	
		Passenger Car	✓	
		HEV (Hybrid Electric Vehicle)	✓	
		Mini Truck	✓	
		Light and Medium Truck	✓	
		Heavy Truck		✓
	Diesel	Passenger Car	✓	
		Light and Medium Truck: GVW=<3.5t	✓	
		Heavy Truck: 3.5t<GVW=<5t		✓
		Heavy Truck: 5t<GVW=<8t		✓
		Heavy Truck: 8t=<GVW		✓
	Electricity	BEV (Battery Electric Vehicle)	✓	

Fig. V.18 Concept of vehicle type classification in traffic simulation and emission model

1.2. Verification of traffic simulation model

Verification of the traffic simulation model is done according to the verification and validation processes given in Chapter 3 and the results are shown here.

1.2.1. Verification

(a) Vehicle generation

To verify vehicle generation of SOUND, a simple case study shown in Fig. V.19 was run. Fig. V.20 is the cumulative traffic volume at upstream of the link calculated by SOUND. Scan interval is every one second and one packet has one vehicle here. The figure indicates that the same traffic volume as given traffic demand is generated in every cases Furthermore, vehicle is generated in constant ratio even the traffic demand is given in hours.

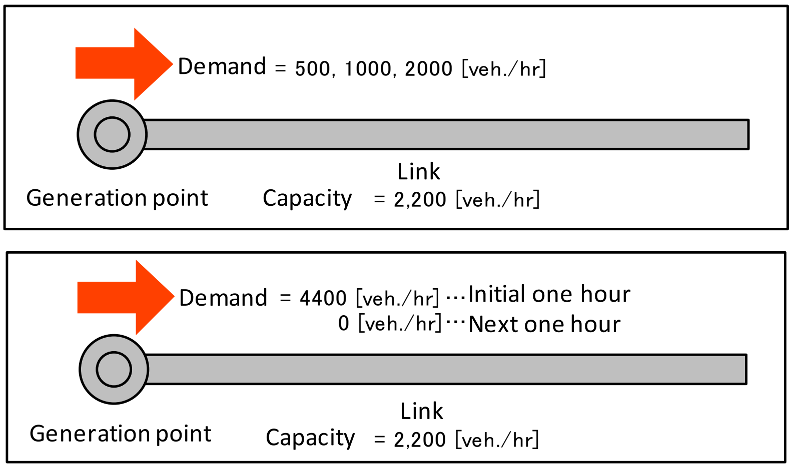


Fig. V.19 Setting for verification of vehicle generation

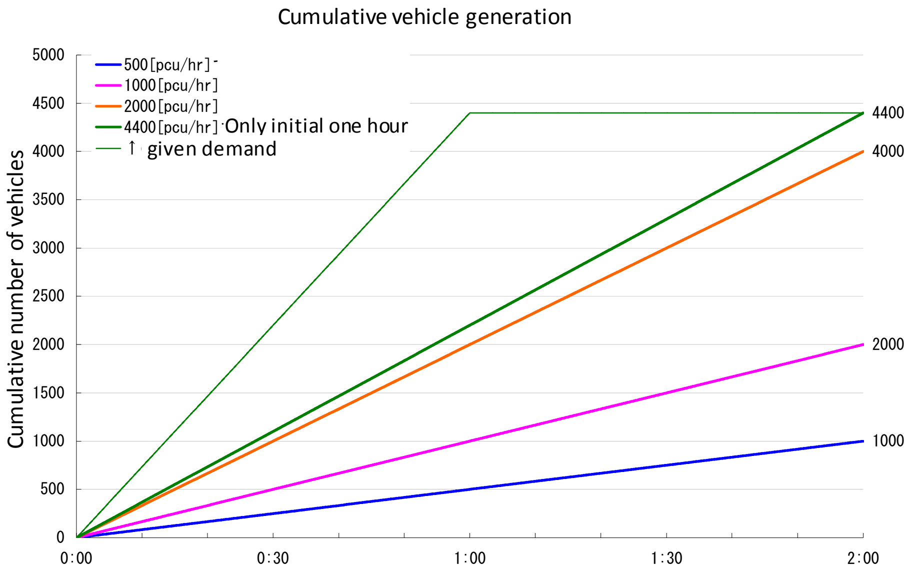
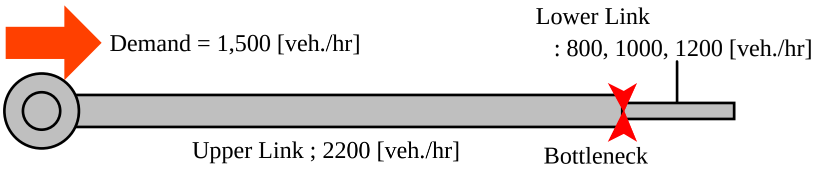


Fig. V.20 Cumulative traffic volume by SOUND

(b) Bottleneck capacity

To verify reproducibility of bottleneck capacity by SOUND, as shown in Fig. V.21, a simple simulation study of a single road link which has a bottleneck on downstream of the link was run. The bottleneck capacity was set with three patterns, 800, 1,000, 1,200 [pcu/hr]. Fig. V.22 is cumulative traffic volume calculated by SOUND. The figure shows that the each cumulative traffic volume reproduced the given bottleneck capacity clearly.



Parameter	Upper link	Lower link
Length[m]	100	100
Number of lanes	1	1
Capacity[pcu/hr]	2200	800～1200
Jam density[pcu/km]	120	120
Free flow speed[km/hr]	36	36
Saturation flow rate[pcu/G1hr]	1800	1800

Fig. V.21 Setting for verification of bottleneck capacity

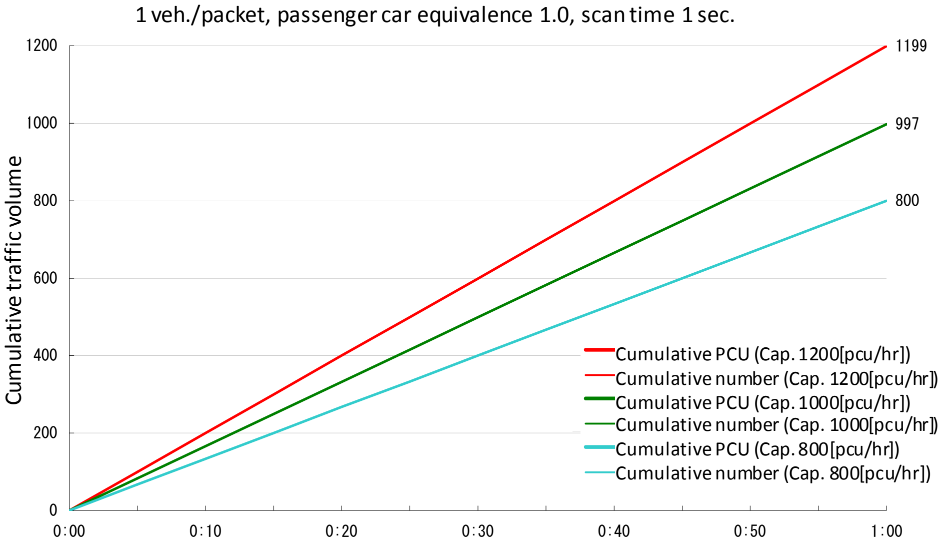


Fig. V.22 Cumulative traffic volume by SOUND

(c) Shockwave propagation

To verify the shockwave propagation of SOUND, a simple case study shown in Fig. V.23 was run. Fig. V.24, Fig. V.26 and Fig. V.28 are propagation speed of the shockwave which is derived theoretically for each setting bottleneck capacity and Fig. V.25, Fig. V.27 and Fig. V.29 are the cumulative traffic flow of each link calculated by SOUND. The time that the shockwave reaches the top of each link is marked with a pink circle in the figures of the result. The figures indicate that the inclination of the cumulative curve changes at the time that the shockwave reaches the link. Therefore, it is confirmed that SOUND can reproduce shockwave propagation according to the shockwave theory.

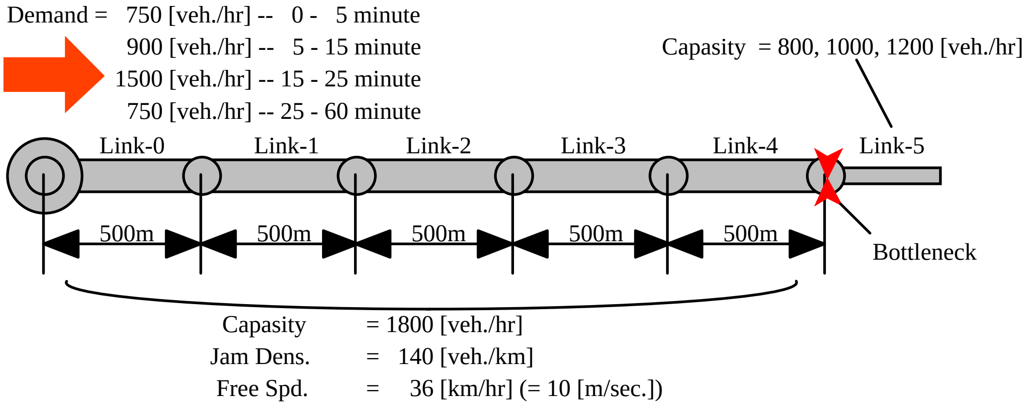


Fig. V.23 Setting for verification of shockwave propagation

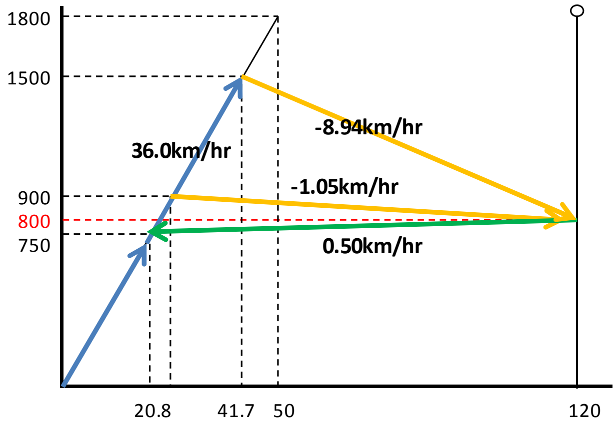


Fig. V.24 Propagation speed of shockwave (cap=800veh/h)

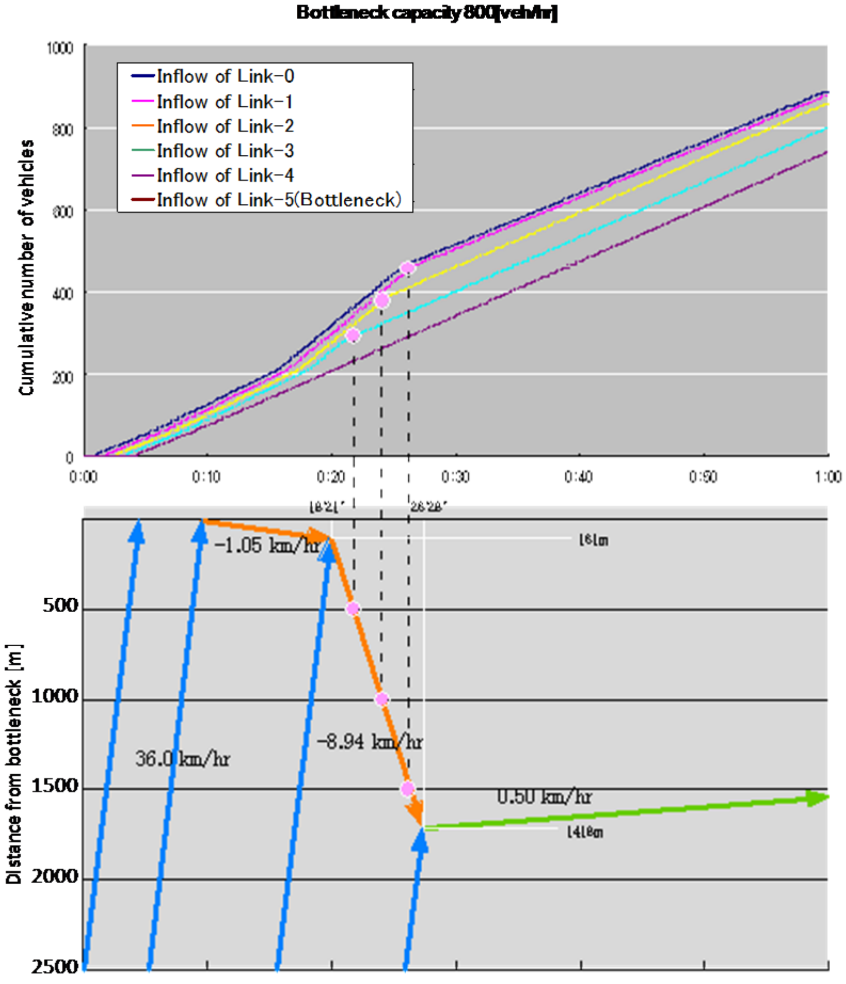


Fig. V.25 Cumulative traffic volume of each link (cap=800veh/h)

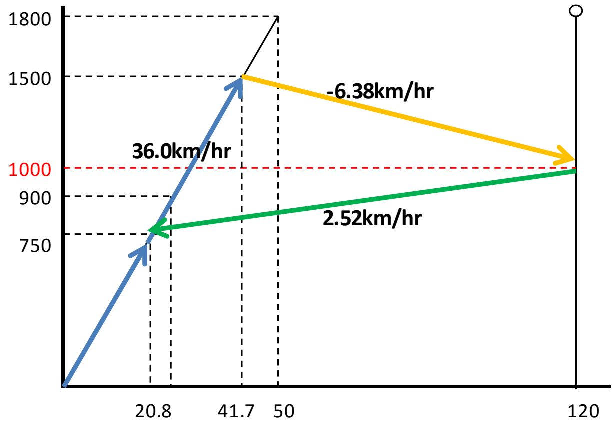


Fig. V.26 Propagation speed of shockwave (cap=1000veh/h)

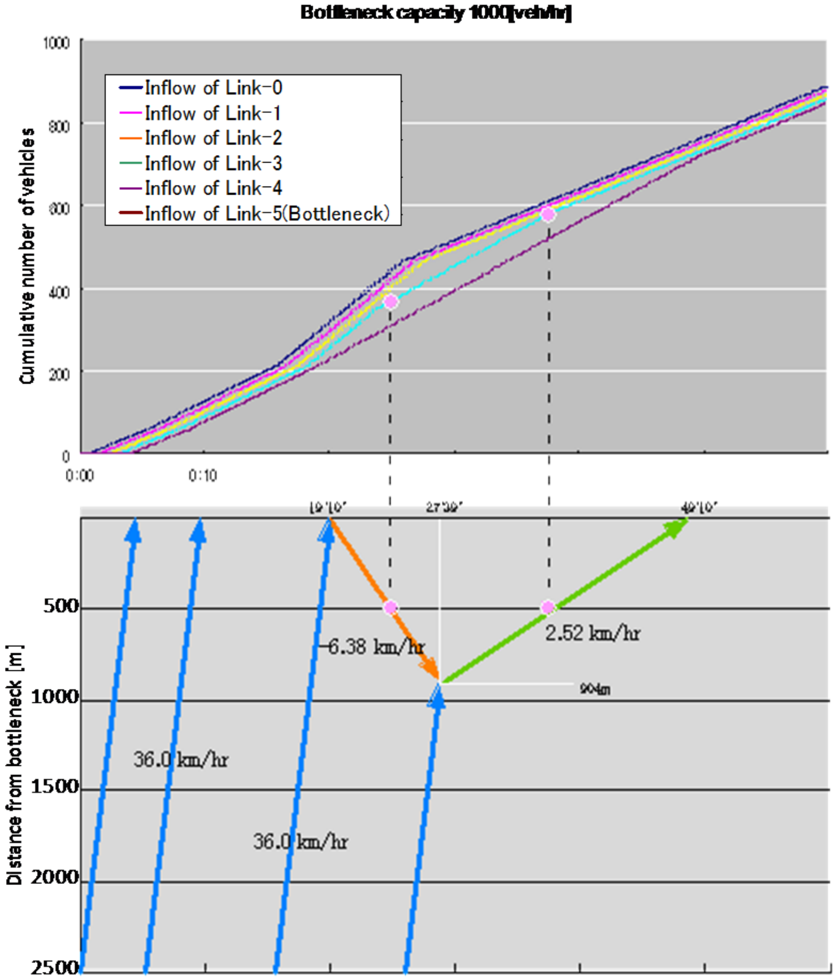


Fig. V.27 Cumulative traffic volume of each link (cap=1000veh/h)

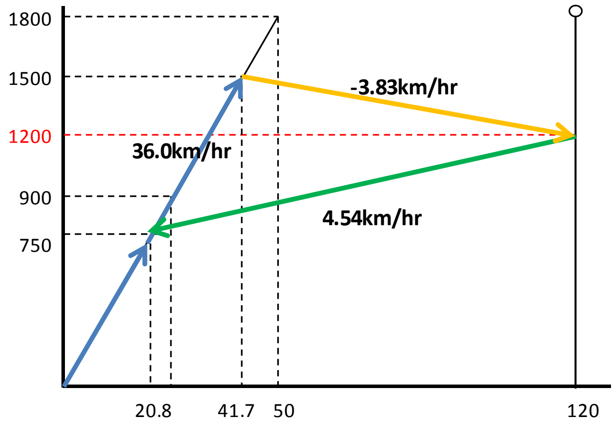


Fig. V.28 Propagation speed of shockwave (cap=1200veh/h)

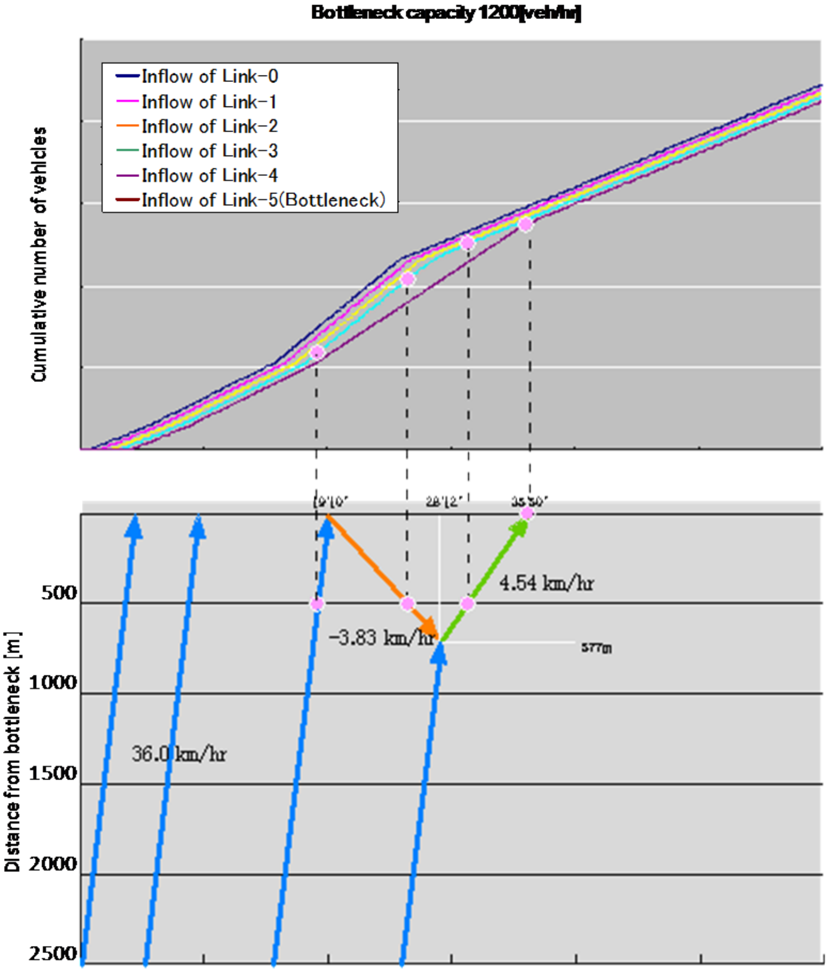


Fig. V.29 Cumulative traffic volume of each link (cap=1200veh/h)

(d) e-Start behaviour

To verify the ability of SOUND to reproduce vehicles' behaviour using e-Start, we checked trajectories and speeds of individual vehicles at the acceleration point (at the

240-meter mark in Fig. V.30) with/without an e-Start vehicle. The green trajectories show e-Start vehicles. From the figure, we can see that the first two e-Start vehicles which stop at the traffic signal moderate their acceleration behaviour at the acceleration point. On the other hand, the last two e-Start vehicles which don't stop at the traffic signal don't change their acceleration behaviour. Therefore, SOUND has capability to represent e-Start behaviour.

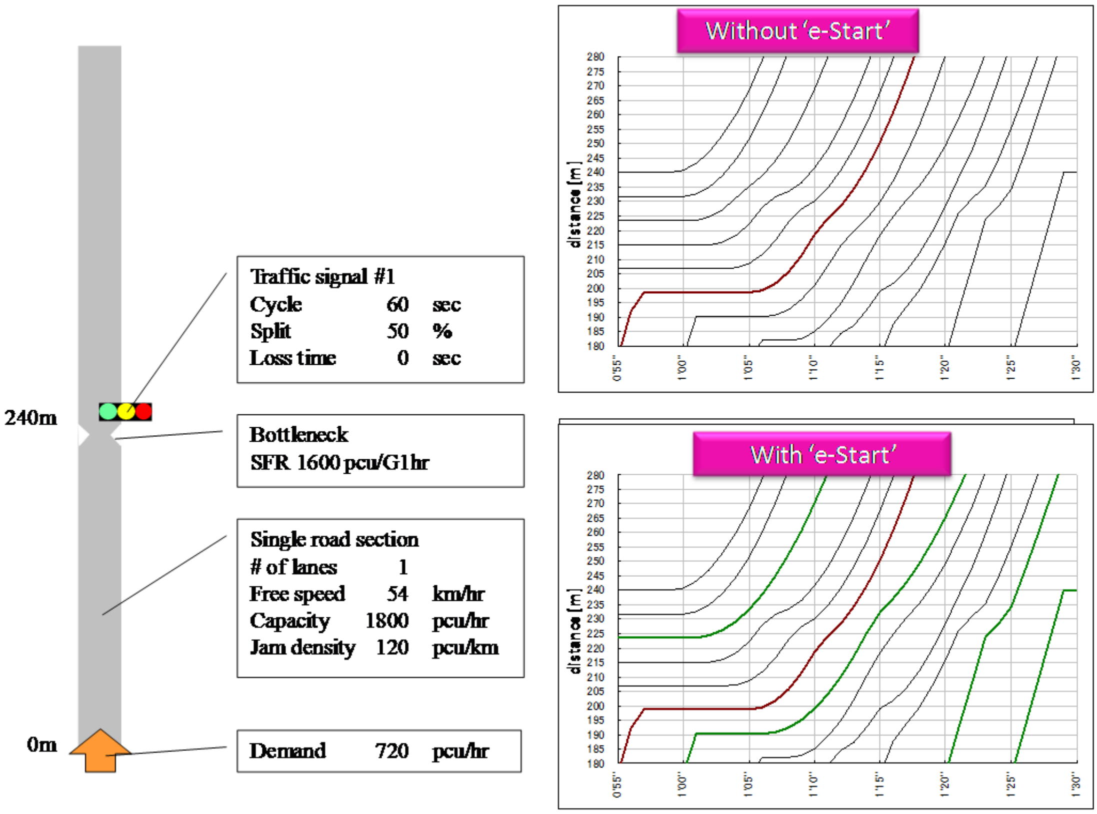


Fig. V.30 "e-Start" behaviour in SOUND

1.2.2. Validation

To validate the traffic simulation model, the results of the comparison between the calculation result from the traffic simulation model using the Komazawa benchmark dataset and actual measured data are given here.

(a) Traffic flow

Fig. V.31 shows the comparison results of traffic flow for all streams in each intersection on Komazawa-dori (Street). The coefficient of determination is near 0.90.

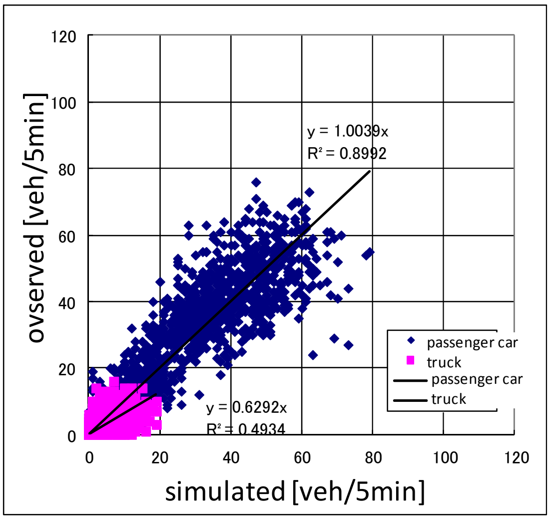


Fig. V.31 Validation results of traffic flow

(b) Travel time

Simulated travel time of both directions (inbound traffic to central Tokyo and outbound traffic from central Tokyo) is well in accord with observed travel time.

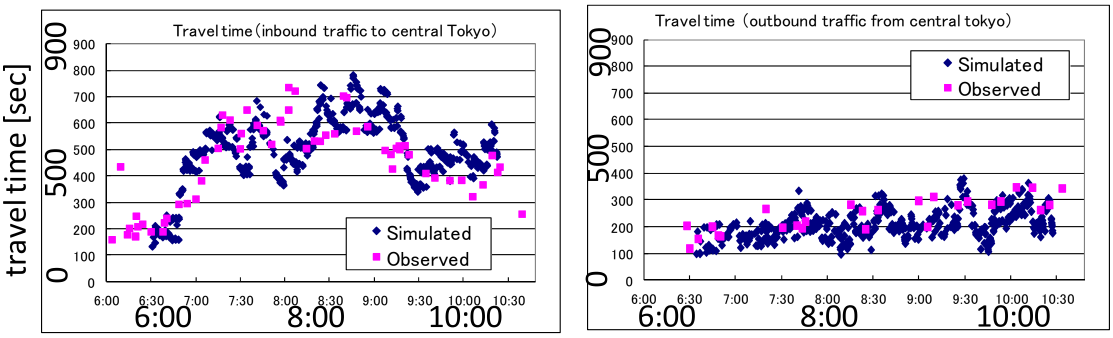


Fig. V.32 Validation results of travel time

(c) Average travel speed

Simulated average travel speed agrees well with observed average travel speed. From the results shown from (a) to (c), it is said that the overall traffic situation is represented by SOUND.

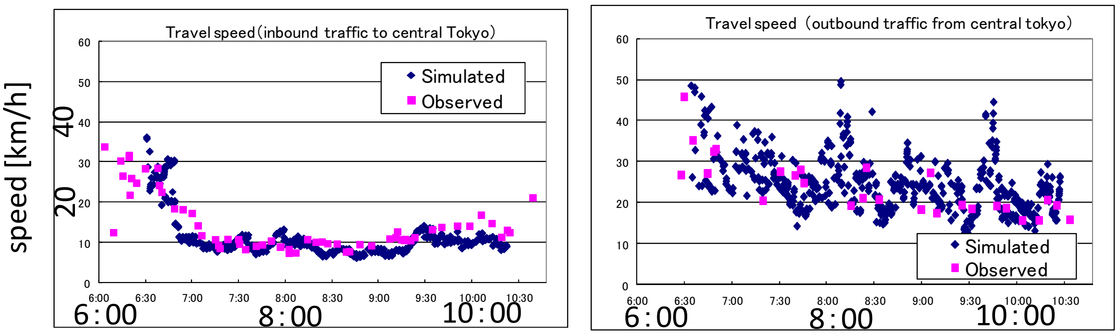


Fig. V.33 Validation results of travel speed

(d) SSF

Distribution of SSF calculated from the simulation result of SOUND is clearly in accord with SSF calculated from the probe data.

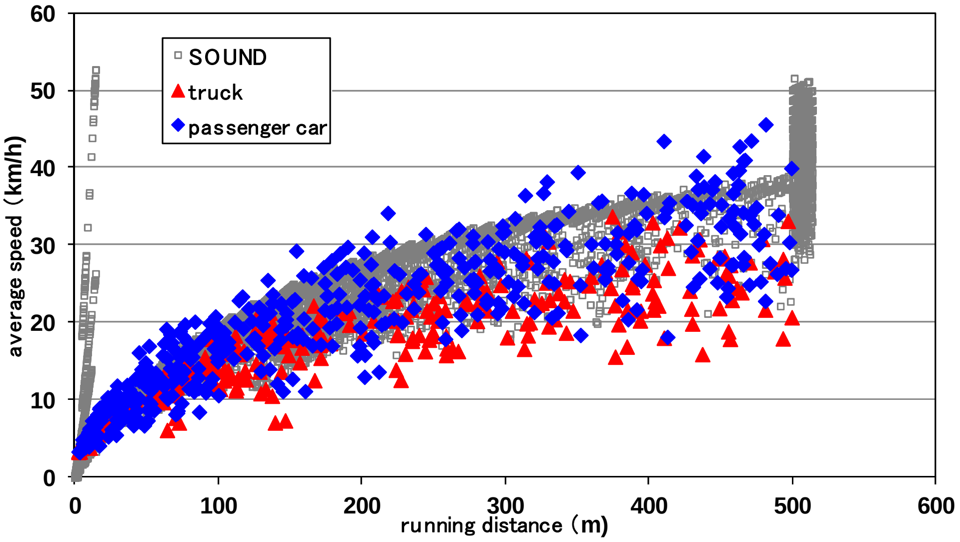


Fig. V.34 Validation results of SSF

1.3. Verification of CO_2 emission model

1.3.1. Verification

(a) Model structure

As mentioned in the section of "Modelling of CO_2 emission model ", it is important to predict the fuel consumption for CO_2 estimation, and vehicle drive energy is one of the most important factors to predict fuel consumption.

In this project, the acceleration energy is modelled with a statistical method (See

1.1.6). Fig. V.35 shows the correlation between measured and predicted acceleration energy. Although the result of prediction has some dispersion, this acceleration model can be predicted with accuracy of $R^2=0.91$ (R^2 is the coefficient of determination).

$$E = \underbrace{m\int_0^T \left\{\delta_{acc.}\left(v\frac{dv}{dt}\right)\right\}dt}_{\boxed{E_{acc}}} + \underbrace{c_D a V^2 D}_{E_{aero}} + \underbrace{c_R mgD}_{E_{rolling}} + \underbrace{mgD\sin\theta}_{E_{grade}}$$

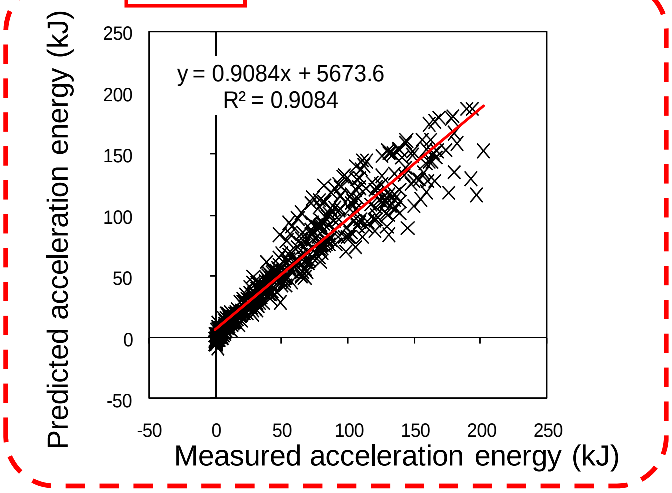
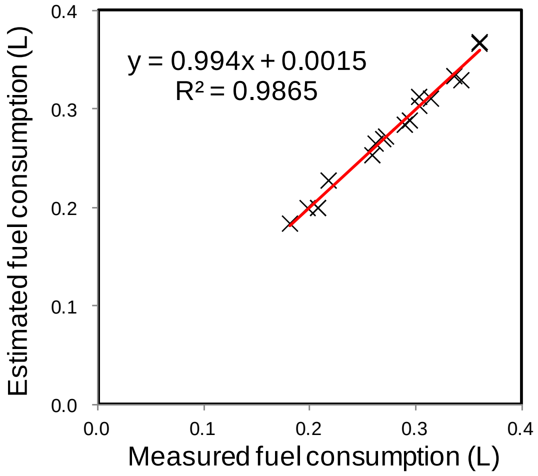


Fig. V.35 Measured vs. predicted energy of E_{acc}

Fig. V.36 shows the correlation of fuel consumption between measurements and estimations in actual SSF series of five kilometers. When the dispersion becomes smaller, the fuel consumption is predicted with high accuracy of R2=0.99.

$$E = \underbrace{m\int_0^T \left\{\delta_{acc.}\left(v\frac{dv}{dt}\right)\right\}dt}_{\mathrm{E_{acc}}} + \underbrace{c_D a V^2 D}_{\mathrm{E_{aero}}} + \underbrace{c_R mgD}_{\mathrm{E_{rolling}}} + \underbrace{mgD\sin\theta}_{\mathrm{E_{grade}}}$$



Note: SSF summed in actual SSF series of 5 km)

Fig. V.36 Measured vs. predicted fuel consumption

1.3.2. Validation

To validate the CO_2 emission model, the results of the comparison between the calculation result from the emission model using the Komazawa benchmark dataset and actual measured data are given here.

(a) CO_2 from emission model and from probe

CO_2 emission per kilometre estimated by our emission model is clearly in accord with measured CO_2 emission ($R^2 = 0.986$).

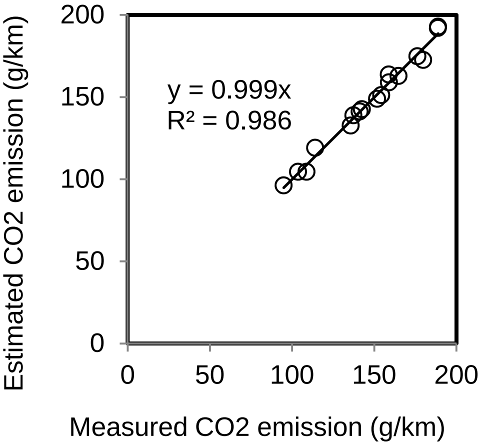


Fig. V.37 CO_2 emission comparison

(b) CO_2 by one vehicle

The emission model can estimate CO_2 emission corresponding to the fluctuation of the vehicle speed calculated by a traffic simulation model.

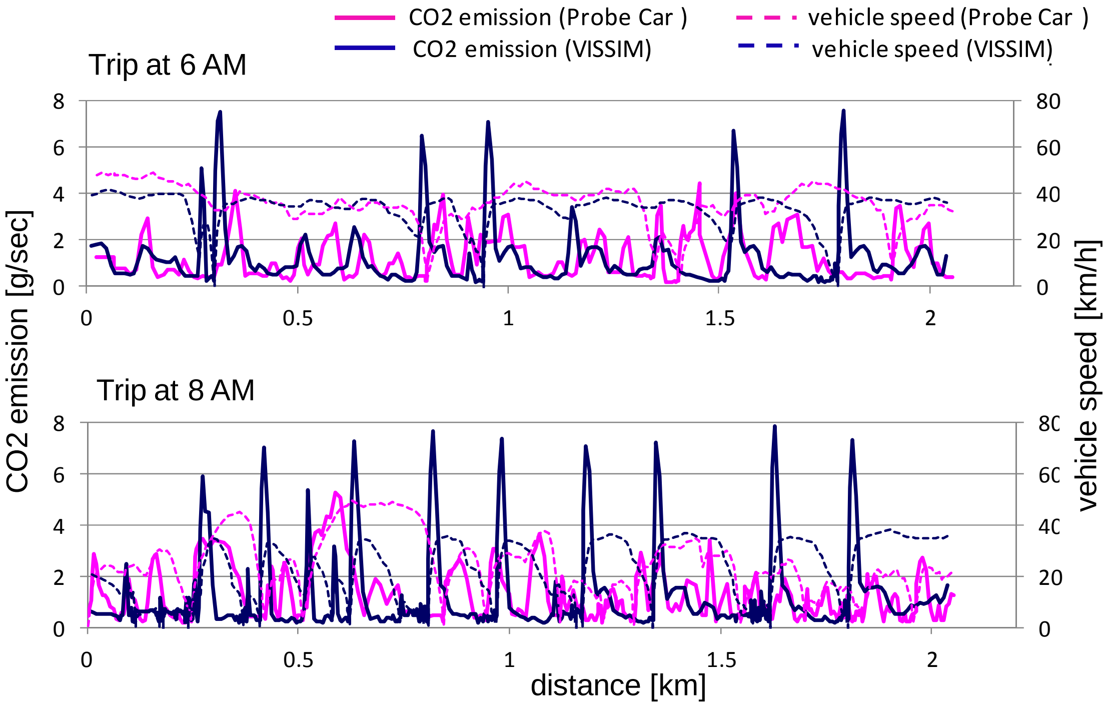


Fig. V.38 Time series CO_2 emission by one vehicle

1.4. Validation of combination between traffic simulation model and CO_2 emission model

Fig. V.39 is CO_2 emission comparison between observed by probe vehicle and calculated by our evaluation tool using the Komazawa benchmark dataset. This figure shows that the tool can reproduce CO_2 emission and it's change with time with enough precision.

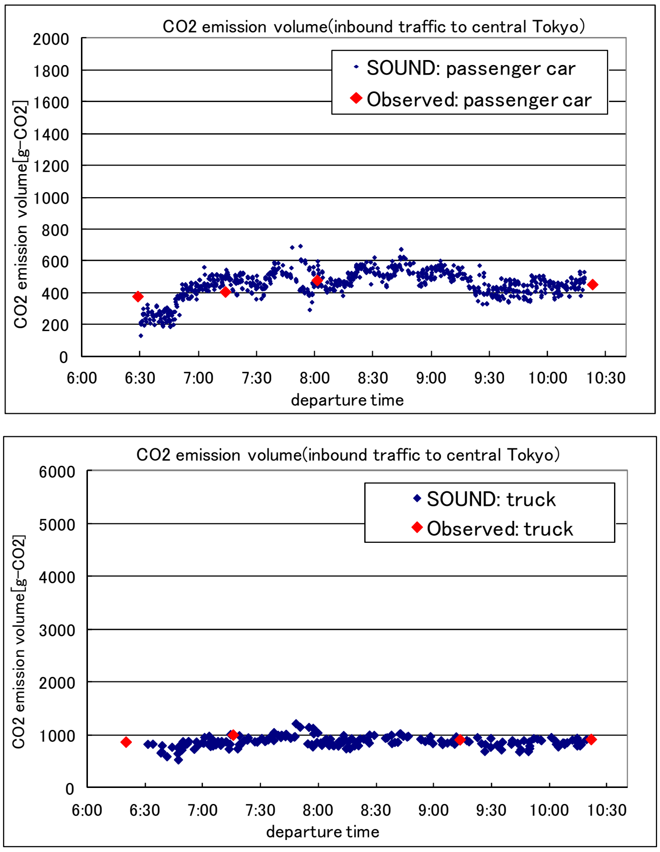


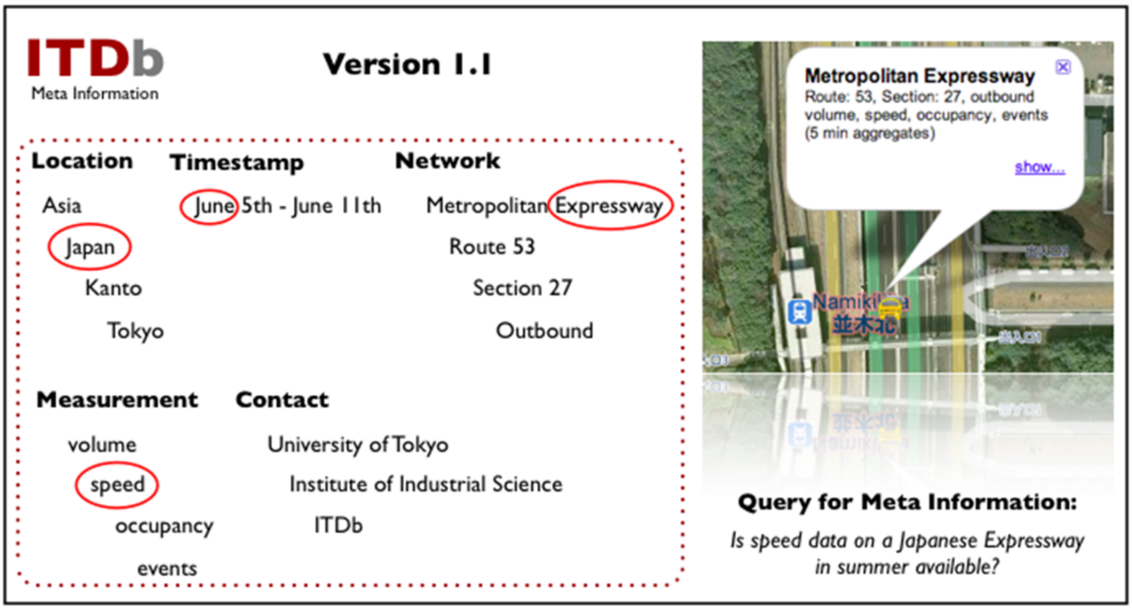
Fig. V.39 CO_2 emission comparison between observed and simulated

1.5. Establishment of traffic database

Traffic-related data has a wide variety of data such as data related to traffic flow, traffic demand, population, land use, meteorology, and so on. However, such a wide variety of data is scattered not only in Japan but also worldwide, and it has not been utilized yet. Furthermore, in the case an international discussion about global problems such as environmental problems, it should be discussed based on common dataset. From these viewpoints, we developed a traffic database that can be used for sharing the data throughout the world.

1.5.1. Proposal of versatile data structure

According to the standard structure of meta-information mentioned in the chapter 4, we proposed the simplest standard which is given in Fig. V.40. The information is composed of measurement, location, timestamp, data provider, etc. The format of standard meta-information is used in the meta-information search engine of the International Traffic Database (ITDb).



ITDb
Meta Information

Version 1.1

Location
Asia
Japan
Kanto
Tokyo

Timestamp
June 5th - June 11th

Network
Metropolitan Expressway
Route 53
Section 27
Outbound

Measurement
volume
speed
occupancy
events

Contact
University of Tokyo
Institute of Industrial Science
ITDb

Metropolitan Expressway
Route: 53, Section: 27, outbound
volume, speed, occupancy, events
(5 min aggregates)
show...

Query for Meta Information:
Is speed data on a Japanese Expressway in summer available?

Fig. V.40 Meta-information example

Fig. V.41 shows the overall structure of the database. In Fig. V.41, the red frame indicates users. First, a user can take a general view of what data is stored by the map on ITDb. Second, a user can request ITDb to specifically find what data they want. Then ITDb extracts the requested data from data storage (or outside data which is linked with ITDb) according to the requested format and provides it to the user. We developed the meta-information structure which is shown in

Users cannot access the data storage directly because there is a firewall between the user (within the red frame) and ITDb, but a user can obtain the desired data by requesting data-items and data-format to ITDb.

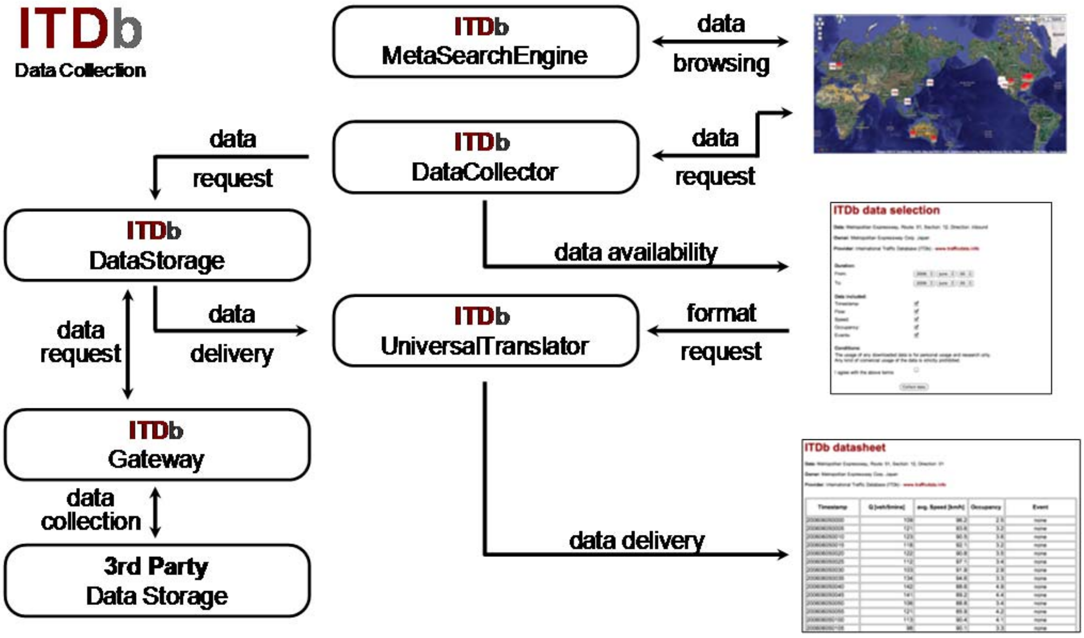
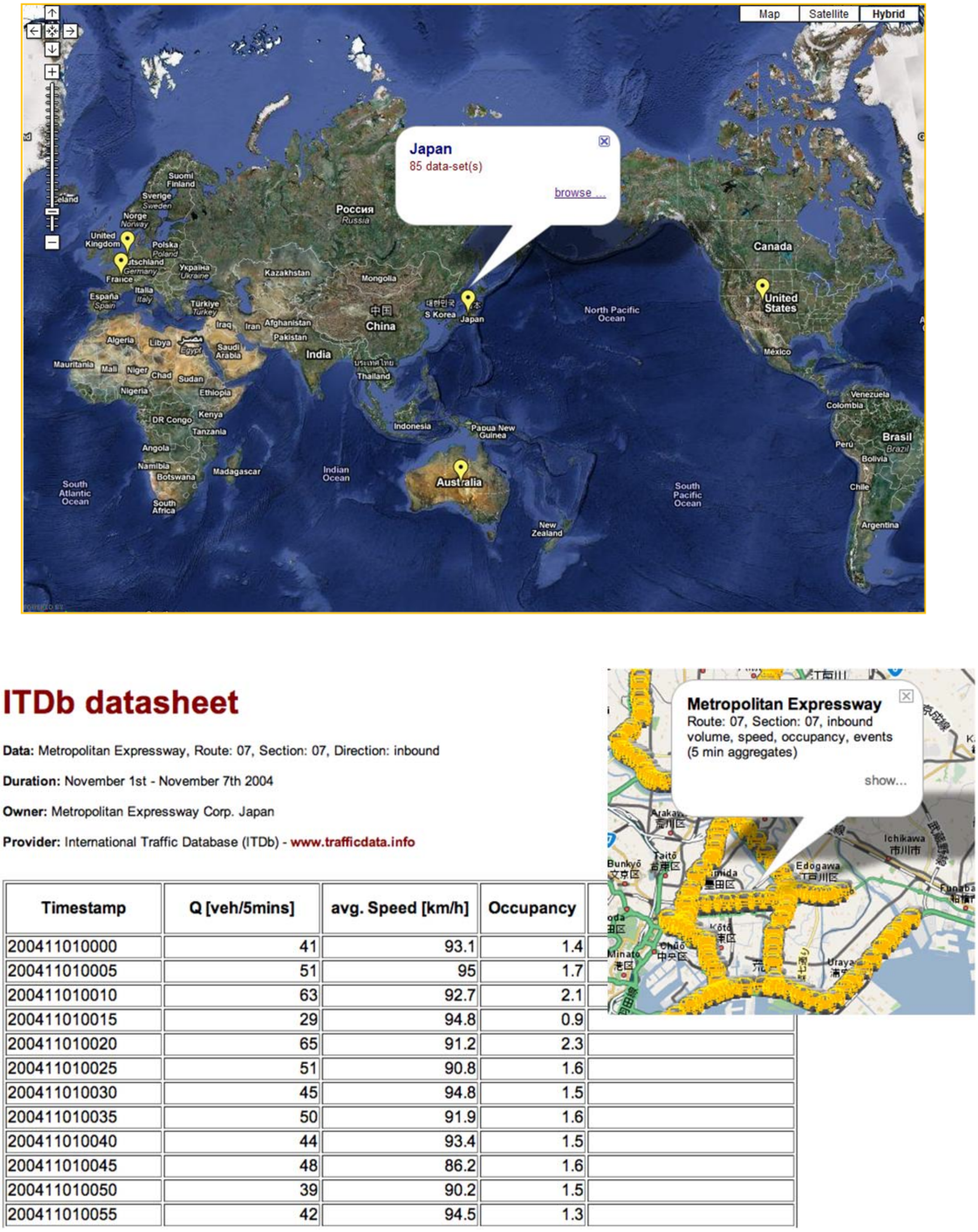


Fig. V.41 Database structure

1.5.2. Building the data warehouse

According to the proposed meta-information and database structure, the International Traffic Database (ITDb) was built using XML and its test site was opened on the Web (http://www.trafficdata.info/). Fig. V.42 shows a screen shot of ITDb.



ITDb datasheet

Data: Metropolitan Expressway, Route: 07, Section: 07, Direction: inbound

Duration: November 1st - November 7th 2004

Owner: Metropolitan Expressway Corp. Japan

Provider: International Traffic Database (ITDb) - www.trafficdata.info

Timestamp	Q [veh/5mins]	avg. Speed [km/h]	Occupancy	
200411010000	41	93.1	1.4	
200411010005	51	95	1.7	
200411010010	63	92.7	2.1	
200411010015	29	94.8	0.9	
200411010020	65	91.2	2.3	
200411010025	51	90.8	1.6	
200411010030	45	94.8	1.5	
200411010035	50	91.9	1.6	
200411010040	44	93.4	1.5	
200411010045	48	86.2	1.6	
200411010050	39	90.2	1.5	
200411010055	42	94.5	1.3	

Metropolitan Expressway
Route: 07, Section: 07, inbound
volume, speed, occupancy, events
(5 min aggregates)
show...

Fig. V.42 Screen shot of International Traffic database (ITDb)

To promote usage of ITDb, myITDb which can share data between specific registered people was developed.

Fig. V.43 Screen shot of myITDb

1.6. Case study (Eco-driving (e-Start))

1.6.1. Model calibration

To evaluate the effect of introduction of e-Start to the 23 wards of Tokyo, reproduction of the traffic conditions in Tokyo by the traffic simulation model is conducted as model calibration. Parameters of the model are set to agree with traffic volume of the census. Fig. V.44 shows a correlation between 24-hour traffic volume of the census and 24-hour traffic volume calculated by the traffic simulation model.

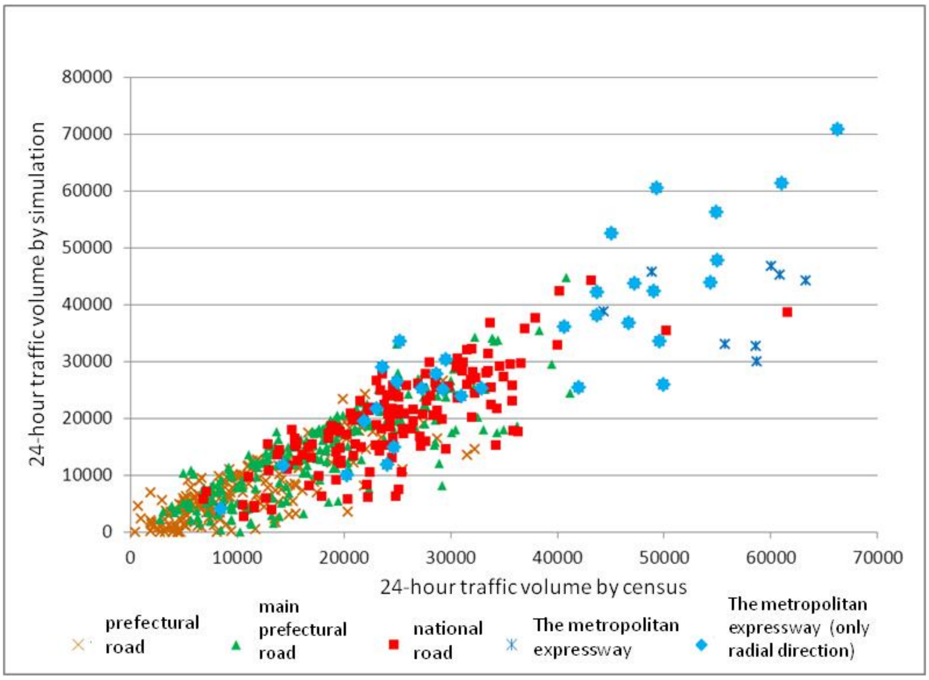


Fig. V.44 Scatter diagram of 24-hour traffic volume

In addition, to check the reproducibility of average speed by the model, average speed measured by probe vehicles and average speed calculated by the simulation are compared around some major bottleneck intersections in Tokyo. Fig. V.45 shows the subject bottleneck intersections. Fig. V.46 indicates that the model can reproduce average speed changes over time and average speed at a peak period in every area. (Variation of observed data on the first two figures are caused by a small number of probe vehicle.)

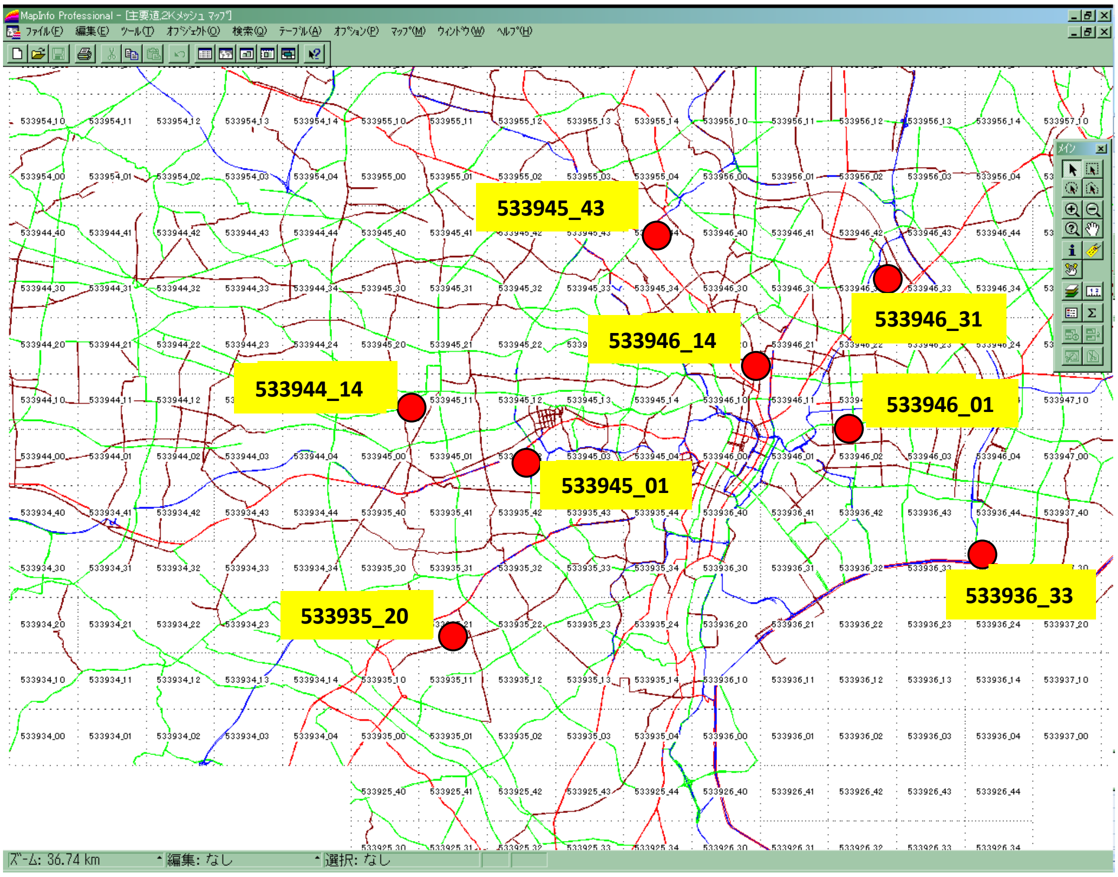


Fig. V.45 Subject bottleneck intersections for model calibration

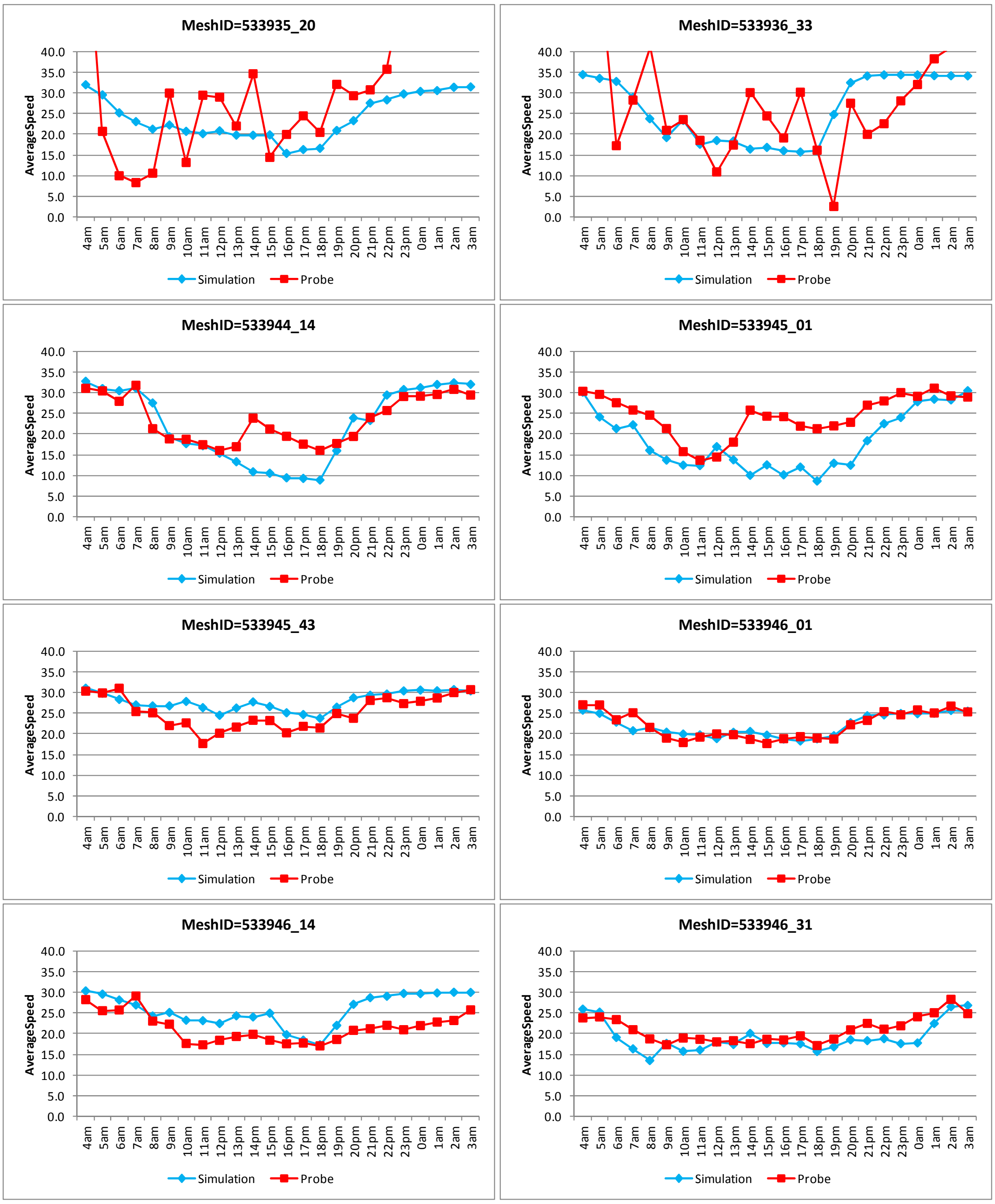


Fig. V.46 Comparison of average speed around bottleneck intersection

1.6.2. Study scenario and evaluation result

The CO_2 reduction effect by introducing e-Start in Tokyo's 23 wards was evaluated. Analyzed duration was from 6:00 AM to 4:00 AM on the next day. Six scenarios of e-Start ratio were conducted and compared, with estimated CO_2 emission of each scenario with a baseline set at a 0% e-Start ratio scenario. The study area and calculation conditions are described in Fig. V.47.

Area	Tokyo's 23 wards
Date	Weekdays 6:00 ～ 4:00 on the next day
e-Start Ratio	0%(Base),10%,30% 50%,70%,90%

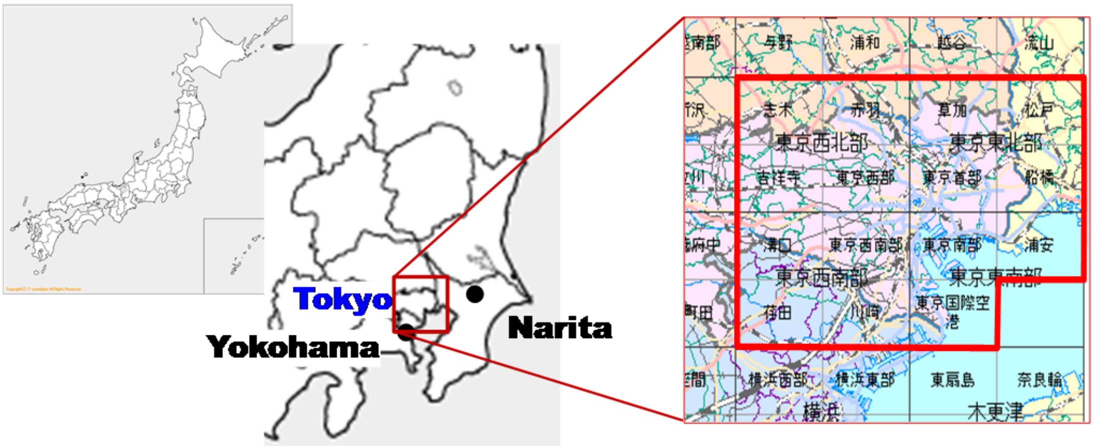


Fig. V.47 Study area and calculation condition

Fig. V.48 shows each e-Start ratio scenario's estimated CO_2 emission volume and the ratio of CO_2 emission to the base case (e-Start ratio is 0%). It can be seen in Fig. V.48 that the maximum effect of CO_2 emission reduction appears when the e-Start ratio is 50%. On the other hand, in the case that e-Start ratio is more than 50%, the CO_2 emission reduction is less than the 50% case. These results indicate that the e-Start ratio has optimal value from the viewpoint of the effect of CO_2 emission reduction for a city area. It can be considered that e-Start has both a positive effect by improving fuel consumption and a negative effect by reducing traffic flow at an intersection, as shown in Fig. V.49. Thus, when the e-Start ratio is less than 50%, the effect of CO_2 emission reduction becomes larger as the e-Start ratio increases, because the positive effect of improving fuel consumption exceeds the negative effect of reducing traffic flow. On the other hand, when the e-Start ratio is larger than 50%, the negative effect exceeds the positive effect, therefore, the effect of CO_2 emission reduction becomes smaller as the e-Start ratio decreases.

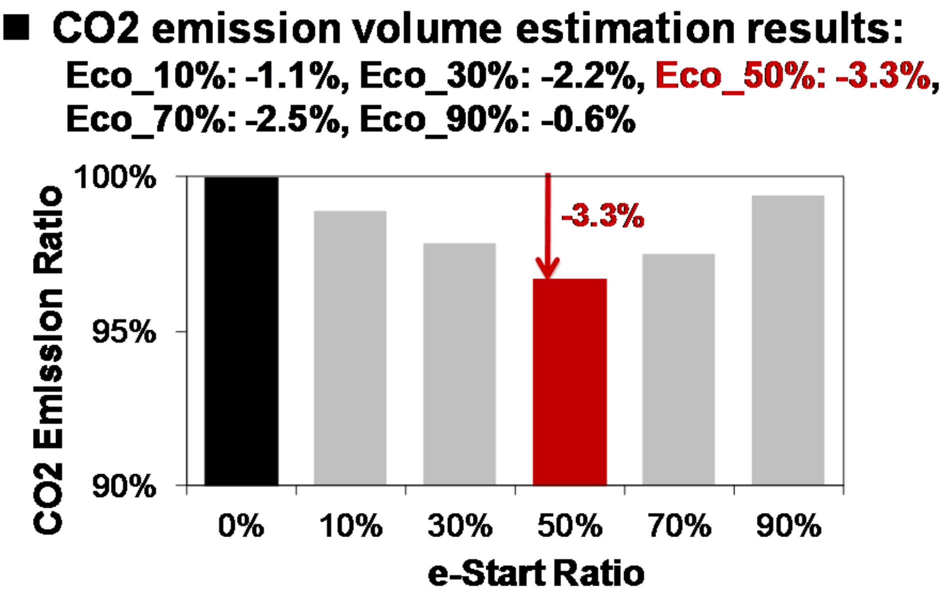


Fig. V.48 Estimated CO_2 emission with Eco-driving

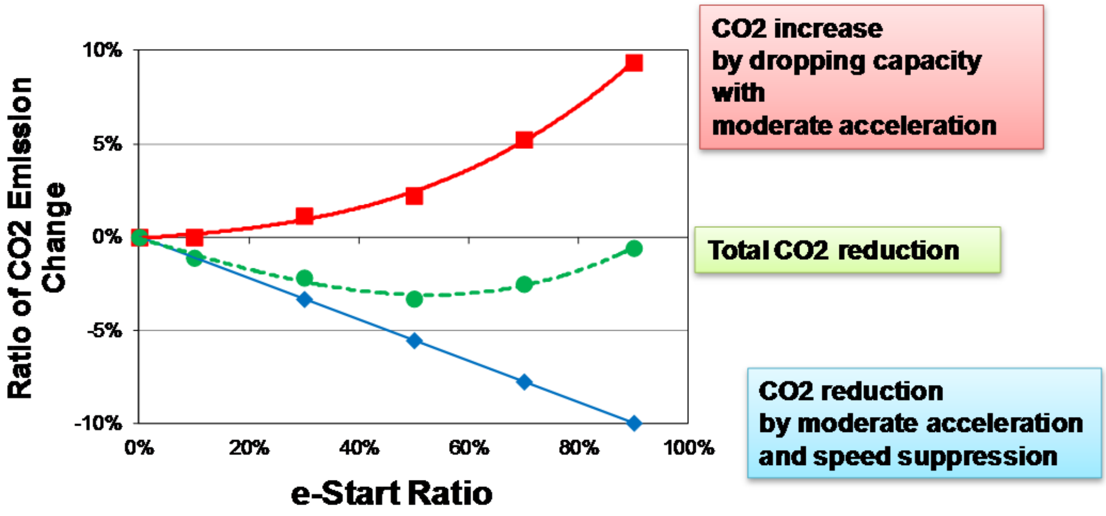


Fig. V.49 Hypothesis about estimation result

1.7. Conclusion

This case study was conducted as part of the Energy ITS project. From the case study, we showed the effectiveness of the approach, which is cooperation between a mesoscopic traffic simulation model and mesoscopic CO_2 emission model in evaluation of ITS applications in a large area. The mesoscopic traffic simulation model cannot reproduce each vehicle's detailed behaviour such as acceleration and deceleration. To consider the impact of driving dynamics change by ITS in the mesoscopic model, we developed a methodology that makes it possible for the mesoscopic emission model to estimate CO_2

emission from the output of the mesoscopic traffic simulation model and verified that it has enough precision for the evaluation.

2. EU examples

In this chapter different European examples are shown for which impact assessments with respect to CO_2 impacts are an important part of the research being performed. The projects show a mix of R&D and demonstration projects all with a focus on increasing energy efficiency and/or reducing CO_2 emissions.

All projects have used (as can be seen in the different figures in the chapter) the V-model commonly used in the EU for performing impact assessments. For some projects the assessment has already been finished, in that case the results of the projects are published. For the other projects the evaluation principle are shortly explained. The chapter starts with a short introduction to all the different projects. Secondly the evaluation principles are discussed for the different project and lastly the projects that ran simulations and have results are presented.

The projects that are explained here are:

- EcoMove
- FreiLot
- COSMO
- In-time

Secondly a French case study has been added which focuses on the discussion regarding probe data and trajectories and how this can be used within the different types of analysis.

2.1. Introduction to the projects

2.1.1. EcoMove[13]

The eCoMove project's core concept (illustrated in Fig. V.50) is that there is a theoretical minimum energy consumption achievable with the 'perfect eco-driver' travelling through the 'perfectly eco-managed' road network. eCoMove is an R&D project. Its objective is to develop a combination of cooperative systems and tools using V2V and V2I communication to help:

- drivers sustainably eliminate unnecessary fuel consumption,
- fleet managers manage their vehicles more economically and promote eco-driving through feedback & incentives,

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[13] The description below is an adaptation of [Themann et al., 2012].

- road operators balance traffic flows in the most energy efficient way,

with the aim to reduce up to 20% fuel consumption and therefore CO_2 emissions.

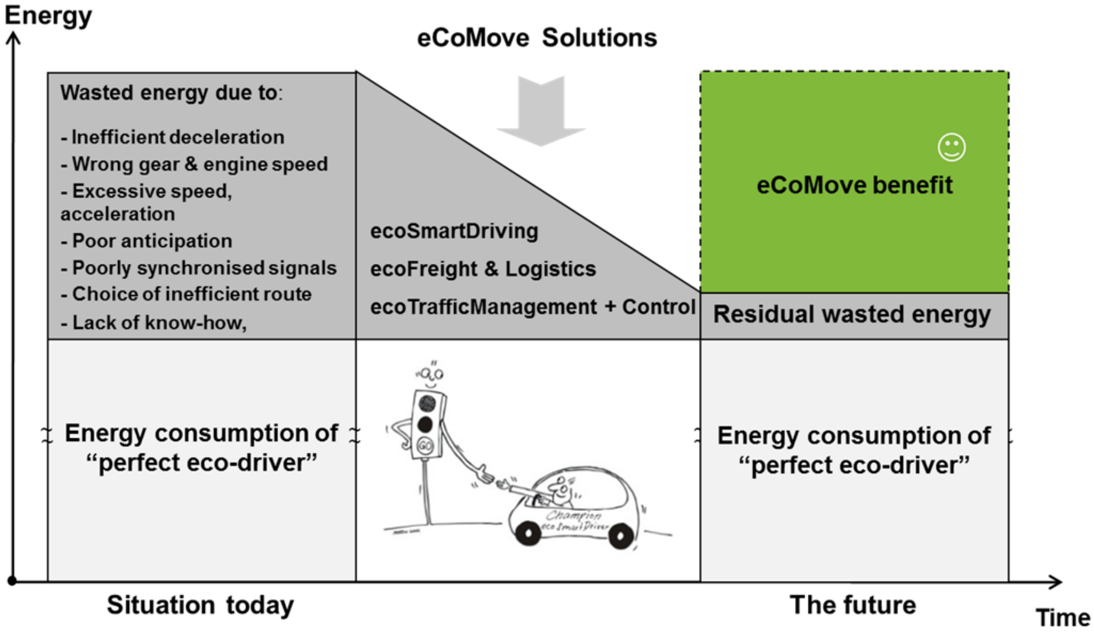

Fig. V.50 eCoMove core concept

The eCoMove system provides drivers with recommendations on how to improve efficiency depending on the driving context, by facilitating a more economical and fuel efficient driving style and by encouraging the use of the most efficient routes. The applications providing these recommendations consider the current as well as the predicted traffic situation and driving style, to determine the optimal driving strategy for the actual trip. The eCoMove system is using state of the art vehicle-to-vehicle and vehicle-to-infrastructure communication technologies based on results of earlier EC funded projects such as CVIS, SAFESPOT and COOPERS (see http://www.ecomove-project.eu/links/ for references). Some examples of applications are: eco-friendly navigation, driving support (in-vehicle – cars and trucks), traffic control, ramp metering, speed and headway management and parking guidance. The applications are supported by several core technologies, such as ecoMonitoring, an ecoMap, ecoMessages and ecoModels (providing the state of traffic and the environment, at the vehicle and network level).

2.1.2. Freilot

The FREILOT project ran from 2009 until 2012 and had as its main aim to evaluate the extent to which a set of applications for heavy goods vehicles could reduce carbon dioxide production. The applications were: Acceleration limiter, adaptive speed limiter, delivery space booking, eco driving support and energy efficient intersection control. The applications were evaluated in four cities: Bilbao, Helmond, Krakow and Lyon. No all applications ran in all cities, moreover, in a number of cases there were different versions of applications running on different sites.

The acceleration limiter, adaptive speed limiter and the eco driving support applications are vehicle centred applications with limited info from the infrastructure (e.g. speed limits). The delivery space booking application has a central loading/unloading space allocation algorithm and 3G communication to the vehicles. The energy efficient intersection control application is a true cooperative application with local interaction between traffic light controllers and drivers. The on-board units request priority at intersections and the traffic light controller answers with an intersection approach advice.

2.1.3. In-Time

In-Time (Intelligent and Efficient Travel management for European Cities) focuses on Multimodal Real Time Traffic and Travel Information (RTTI) services with the goal to reduce the energy consumption in urban areas across the different modes of transport by changing the mobility behaviour (modal shift) of the single traveller. This aspect contributes to the reduction of the environmental impact of traffic without the necessity of dedicated measures and additional costs to the stakeholders. The In-Time is mainly a Business-to-Business oriented service, which provides benefits to the large number of users served by dedicated travel information service providers.

The In-Time project makes regionally existing services and data sources more easily accessible to super-regional service and information providers by implementing a set of standardised interfaces (the so called Commonly Agreed Interface – CAI) based on standard technology including DATEX 2, TPEG, WMS and WFS, to name just a view examples.

The idea behind this approach is, that super-regional information providers can easily take up the data and services offered in a region and either provide their services locally or merge these information sets and services with other (In-Time) regional sources to generate a super-regional service.

Based on the project´s expectation, that any modal shift towards public transport reduces the trip number of passenger cars (which have a considerable environmental impact in urban areas) accordingly, the possible effect of Real Time Traffic and Travel

Information (MRTTTI) or Advanced Traveller Information Systems (ATIS) on mode choice is of particular importance. The expected modal shift depends on many factors, e.g. provision of information (see e.g. [PROVET 2010], [Polydoropoulou and Ben-Akiva, 1998]).

This means, that the access of the travellers and haulers to sophisticated information services, especially co-modal online services, would generate a shift of trips from motorised individual transport to public transport leading to energy and emission savings.

The In-Time solution with the commonly agreed standardised interface has been set up in six European pilot sites while additionally LED based traffic signals and a modern traffic management system were introduced in the test site Bucharest to understand their contribution to CO_2 savings in terms of lower energy consumption compared to traditional lighting and traffic management options.

2.1.4. COSMO

The aim of the COSMO project is to demonstrate the impact of the new generation of ITS systems quantifying their advantages by looking at energy savings, traffic efficiency and reduction of CO_2 emissions. In particular COSMO has therefore set up a range of cooperative ITS applications in three pilot sites (Gothenburg, Salerno and Vienna). The pilot sites in Italy, Austria and Sweden, were carefully selected to produce complementary results; they include, for example, urban and motorway scenarios and involve public transport as well as private cars. The demonstrations will help to provide concrete evidence of new opportunities for more sustainable transport.

For example in the Austrian pilot site a “Mobile Road Works Kit”, designed to be set up for the duration of the construction work, then dismantled and used again when and where required, has been installed. It consist on: high luminosity LED streetlights, wireless sensor network for traffic detection, mobile trailer displaying variable messages and a smart phone application with real-time information and advice for drivers. The objective of this pilot site is to reduce congestion by smoothing the traffic flow and to increase safety by improving the visibility of the lane deviation zone.

Moreover, in the Italian pilot site a bundle of cooperative applications for eco-driving, multimodal guidance and traffic adaptive street-lighting has been installed and a smart phone application suggests to a sample of end-users the “greenest” solution for mobility and parking options. Finally, in the Gothenburg pilot site, the impact of eco-driving for public transport has been considered. In this case eco-driving application are integrated with existing traffic control system in order to give, to the bus-driver, suggestions for reaching green light at intersections and avoiding traffic queues.

2.2. Evaluation principles

2.2.1. eCoMove validation and assessment concept

Validation of the different applications developed within eCoMove has to take into account the particular characteristics of these cooperative in-vehicle and traffic management applications. The validation methodology applied in eCoMove integrates the results from several validation methods. Validation methodologies such as FESTA [FESTA, 2008] were used as a basis and extended for the specific eCoMove needs, in terms of the inefficiencies addressed in the project. All applications developed are targeting vehicle and traffic inefficiencies identified at the very beginning of the project. These inefficiencies, along with the use cases defined for the applications, are the main basis for establishing the validation criteria. Fig. V.51 below summarizes the assessment concept. The validation and assessment is still on-going at the time of writing of this document. Results from the validation and assessment can therefore not yet be given.

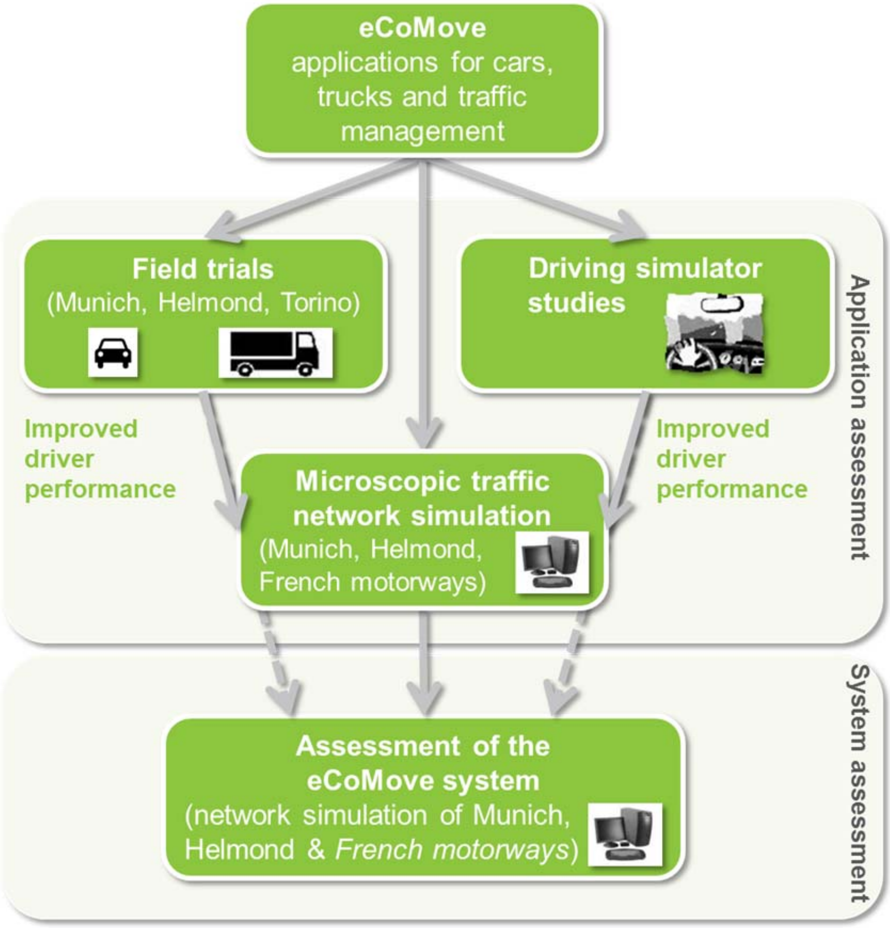

Fig. V.51 eCoMove assessment concept for applications and the complete system

Three types of test methods are used:

1. Real-world field trials with passenger cars and commercial vehicles.
2. Driving simulator studies.
3. Microscopic traffic simulations of traffic management applications and combinations of different applications in traffic networks.

To ensure consistency between the test methods, the performance indicators as well as the test scenarios were harmonized wherever possible. The results of the validation tests of individual and combined applications will be integrated for a subsequent full eCoMove system assessment, which is described in more detail in the following sections.

2.2.2. Research questions and harmonization of validation scenarios

The main research questions the eCoMove project wants to answer are the following:

1. In the environment category: to what extent can eCoMove solutions decrease the fuel consumption and also CO_2 emissions of a vehicle/fleet/network?
2. In the mobility category: what impact have eCoMove solutions in a cooperative environment for the traffic system of a city/region/network (smoothing of speeds, congestion avoidance, changes in travel distances and travel times)?
3. In the driver behaviour category: how can eCoMove sustainably change the behaviour of private and professional drivers into a more eco-friendly driving style?

The developers of eCoMove applications had to decide which methods were suitable for validating their application. However, at the end of the project, all results need to be integrated in order to assess whether a 20% reduction of fuel consumption and CO_2 emissions is feasible. A harmonized approach was needed to avoid misinterpretation of results found under specific circumstances (as encountered in the tests). All developers used the same format to describe their test set-ups and chose their performance indicators from a predefined list. The set-ups described the validation tests in detail and included information on use cases, inefficiencies addressed by the applications tested, as well as control and situational variables. This enabled clustering of the test set-ups in a smaller numbers of test cases. These in turn were clustered in nine validation scenarios: Trip/Tour Planning, Traffic Signal Control, Network Usage, Driving Behaviour, Park Guidance, Route Guidance, Urban Traffic Management, Motorway Management and Driver Feedback. This structured way of describing the validation tests will make it much easier to also structure the results. The circumstances under which the results were achieved are clear, and that will enable the next step: translating the results into adjustments of simulation model parameters, which will be applied in the full system (impact) assessment (see the paragraph on microscopic traffic simulation and full system assessment).

(a) Real-world field trials

For the field trials passenger cars and trucks are being equipped with several cooperative applications. These will be validated in a cooperative environment in different European cities such as Munich, Helmond and Turin as well as on French motorways. Different test setups in motorway, rural and urban conditions will used. In each real-world field trial a set of applications will be assessed as several applications need input from other applications to come up with well suited recommendations to drivers. Test runs will be driven by various drivers to assess the impact of the eCoMove system on different driver types (along with the assessment of impacts on fuel consumption and travel time). However, this is not the main focus of field trials, as driving simulator studies cover this in more detail.

Different vehicle types are being equipped with tailor made configurations of the eCoMove system. The field trials will evaluate the impact of the systems on two trucks and five passenger cars, thus covering a variety of vehicle classes. The cooperative aspect of the eCoMove system is the same in all vehicles and communication interfaces have been standardized. Components such as the human machine interface (HMI) have been adapted to the specific vehicle in order to guarantee optimal functionality and user acceptance. A logging bundle has been implemented in Java OSGI and has access to CAN-bus data, GPS signals, cooperative messages, but also outputs of applications such as provided driving recommendations to drivers. This setup allows to synchronously log all relevant data (for validation) into a database for each trip. Besides event based or periodic signals, the database will contain general information about trip, route, driver and vehicle. Once the test runs have been done, all databases can be examined using Matlab in order to deduce relevant performance indicators such as the fuel consumption per distance.

In a real-world scenario for instance, an eCoMove equipped vehicle approaches an intersection that sends its signal states and traffic management advices to the applications in the vehicle. These applications derive recommendations that are provided to the driver via the HMI (e.g. haptic pedal or displays) in order to minimize fuel consumption and emissions. In the tests, indicators such as the fuel consumption are determined for a variety of set-ups with different vehicles, drivers and traffic management advices under real world disturbances.

(b) Driving simulator studies

In order to validate and to be able to assess the impact on the behaviour of the professional or private driver of the eCoMove human-machine interface (HMI) recommendations on efficient routes and eco-friendly driving style, driving simulator studies are a suitable method, without the need to execute a field operational test. High-fidelity simulators offer a realistic driving environment, complete with realistic components and layout, a coloured, textured, visual scene with roadside objects such as trees and signposts, and often have a motion base. Within the eCoMove project, five high-fidelity driving simulators were available for testing eCoMove applications.

Driving simulators can be an important tool for driver behaviour validation, as they allow for a number of driving performance measures, - such as speed control and lateral position on the road - to be examined in a relatively realistic environment, providing a safe environment to conduct research that is potentially too dangerous to be conducted on the road. In addition, greater experimental control can also be applied in driving simulators compared to on-road studies, because driving simulators allow the type and difficulty of driving tasks to be precisely specified. Also, situational variables, such as weather conditions can be eliminated. Other advantages over field test studies are: the cost of modifying the cockpit of a simulator to address different research questions may be significantly less than modifying an actual vehicle and an expensive installation of vehicle dynamic sensors is not necessary; or the possibility to repeat the exact test scenario under the same traffic conditions with a representative sample of different driver profiles. Driving simulators therefore allowed the eCoMove partners to evaluate aspects of the eCoMove applications that are relatively difficult to evaluate in the field. However, the use of driving simulators as research tools has a number of disadvantages as well. For instance, data collected from a driving simulator includes the effects of learning to use the simulator and any in-vehicle devices and may also include the effects of being monitored by the experiment. Simulator sickness is another problem encountered with simulators, particularly common among older drivers.

The driving simulator studies makem it possible to assess the acceptance, driver performance, safety and driver compliance (sub-categories of the main assessment category driver behaviour). It is also possible to assess the effect of the eCoMove applications on fuel consumption through analysing the modification of drivers' behaviour. For this purpose, within each driving simulator study different test scenarios were carried out, in several simulation environments such as urban, interurban, motorway or long-hauls. Some other indicators used to assess the stated subcategories are usefulness or perceived ease of use (acceptance), critical time to collision or DALI score (safety), frequency of gear usage or acceleration profile (driver performance) and percentage of followed recommendations (compliance).

In addition, to cover as many validation scenarios and the driver behaviour sub-categories to be validated as possible, and to make the most of eCoMove partner's facilities, the tests have been coordinated, i.e. the approach to calculate the success criteria and thresholds was pre-defined in early stages of the eCoMove project, and has been the same for all driving simulator studies. Also, the methods to obtain the self-reported data, i.e. questionnaires used to assess the user acceptance, were equal for all driving simulator studies, or at least with only minor differences (between private and truck drivers). The number of tests participants is higher than approximately 140 subjects, considering the total amount of the five studies (around 30 participants per study).

As stated above, the main result of the driving simulator studies is validation of the eCoMove system from the driver behaviour perspective. Additionally, several speed profiles were obtained for various situations, such as entering to a motorway or approaching to traffic lights with different speed limits and eco-recommendations. These provide an important input for another test method: microscopic traffic network simulations.

(c) Microscopic traffic simulation and full system assessment

The impact of several eCoMove applications focussing on traffic management will be assessed mainly in VISSIM traffic simulation environments. Simulations are furthermore used to assess the impact of several combinations of eCoMove applications. The main interest in these studies is to identify synergies and counter-productive combinations to come to integrated traffic management strategies. Using microscopic traffic simulation allows the analysis of the influence of varying equipment ratios, which is important, as to visualize the impact of many of the applications. A high penetration rate of eCoMove equipped vehicles and road side units (RSUs) is necessary. This was not feasible in eCoMove, given the limited number of real-world test vehicles available. To carry out the assessment of the eCoMove system traffic network models of parts of Munich, Helmond and the French motorways will be used. The approach for the validation and impact assessment is to collect data from the real-world test drives and the driving simulator studies, for single applications or combinations of applications and to use these results in the traffic simulations. This requires that validation conclusions derived from vehicle data and changes in driver performance found in field trials and driving simulator studies will be translated into changes in parameters of the driver models within the different VISSIM simulation environments. Several parameters, such as desired speed, desired acceleration and desired deceleration, describe the driver performance in the VISSIM driver model. Relevant, for instance, is to know drivers response (e.g. compliance) to the different signals provided by eCoMove applications in the vehicle (truck and passenger car). Therefore, the test scenarios of field trials and driving simulator studies were designed to cover specific situations which promise a significant fuel reduction and are common in everyday driving, such as approaching a red traffic light or entering a highway. They are derived from the use cases described early in the project lifetime. Also, the compliance rate to eCoMove recommendations can be derived from test results and integrated.

2.2.3. Freilot evaluation principles

During more than twelve months the trucks using FREILOT applications collected in the different pilot sites. When the different pilots were finished, the data analysis processes start. Depending on the applications and the data loggers used, different processes were applied. For example, in the case of delivery space booking, the data was collected from four different sources: the truck (using a GPS data logger), the reservations system, the drivers and fleet operators (questionnaires) and observations in the street. The data from the GPS had to be cleaned to provide the indicators needed. Added to this, this real data was the input for the models used in the calculation of fuel consumption and emissions. To calculate the emissions and fuel use from the GPS traces the CMEM (Comprehensive Modal Emission Model) model was used. CMEM does not use an engine model, but relies on calibration with average vehicle characteristics of the fleets involved.

In the case of the energy efficient intersection control, the different sources of information being treated and processed were the data from the trucks (using a GPS logger different from the delivery space booking), the data collected in the intersections and the information provided by the drivers and fleet operators. The data provided by the traffic light control equipment had to be synchronised with the data from the trucks. For the in-vehicle applications the data processing was totally different. In this case, the data logger provided direct information about consumption, therefore the model was not needed and only data provided by the data logger and by the drivers and fleet operators were analysed.

For all applications, questionnaires were presented to the drivers and fleet operators. Once the information was collected, the results were codified and analysed.
Due to the difference nature of the applications, the data analysis performed for each one is different. In particular the geographical area over which the results are produced differ from application to application. For example, the analysis for delivery space booking is done for the area of the delivery areas, the analysis for the energy efficient intersection control is done per intersection area and per route crossing a number of intersections. For the in-vehicle applications, in some cases the analysis is performed per zone in which the functionality is activated (acceleration limiter and adaptive speed limiter) and in others for the complete route (eco driving support).

2.2.4. In-Time evaluation principles

The In-Time project pursued a twofold approach to assess the potential impact of the project´s results on the energy consumption and emission generation in the concerned test sites.

On the one hand side, a methodology common to all test sites was developed. As the ancillary conditions in terms of socio-economic conditions, number of inhabitants, data availability, software and hardware equipment, service environment and other aspects are significantly different from site to site, this methodology is based on the utilization of statistical data, the results of the project´s end user survey and a commonly accepted practice to compute these inputs [IPCC 2006].

On the other hand side, several test sites also executed site-specific validation and assessment schemes which are tailored to their specific capabilities and cannot be easily compared.

Both methodologies are briefly described in the following chapters.

(a) Common assessment methodology

On an aggregated level, a mode shift towards public transport can be expressed as a reduction of individual transport demand, i.e. a reduction of mileage driven with passenger cars and other vehicles. As In-Time (and especially the end-user survey) has its focus on passenger transport and information of passengers, only passenger trips are taken into account.

The expected emission reduction, which can be attributed to information provision, is the car mileage reduction in the group of information users times a specific emission factor for each greenhouse gas. This emission factor for each greenhouse gas should be specific for the vehicle fleet in each investigated site or city.

There are three important greenhouse gases emitted by road transport, namely carbon dioxide (CO_2), di-nitrogen-oxide (N_2O) and methane (CH_4). Carbon dioxide, di-nitrogen-oxide and methane typically contribute 97, 2 to 3 and 1 % of CO_2-equivalent emissions of road transport. Official national greenhouse gas inventories have been based on fuel consumption (see [IPCC 2006], a report prepared by the Task Force on National Greenhouse Gas Inventories (TFI) of the IPCC, the International Panel on Climate Change). When fuel sales data are used, distinction between on-road and off-road transport has to be made.

In order to estimate the contribution of each greenhouse gas, the following steps have to be executed [IPCC 2006].

Step 1: Determining the amount of fuel consumed by fuel type for road transportation using local data or, as a fallback option, national data sources. One has to consider corrections for e.g. on-road and off-road transport and fuel tourism. As In-Time has its focus on passenger transport and information of passengers, only the passenger car fleet (fuelled with petrol, diesel and other fuels as e.g. Compressed Natural Gas (CNG)) is investigated.

Step 2: For each fuel type, multiplying the amount of fuel consumed by the appropriate standard emission factors for each fuel type. As the influence of vehicle type and emission control technology on the specific emission factor of CO_2 is negligible, the amount of CO_2 emitted can be calculated directly from the amount of fuel consumed.

The specific emission factors of N_2O and CH_4 depend on vehicle type and emission control technology to a large extent, but their overall contribution to CO_2-equivalent emissions of road transport is low. Therefore their contribution to the overall CO_2-equivalent emissions of road transport (error propagation) is neglected in this estimation.

Step 3: Aggregation of each pollutant for all types of fuels (for all respective vehicle types).

Specific data sets are required to satisfy the needs of the described methodology. On the one hand side, these constitute data from the project´s end user survey which lasted several months to understand the gradual shift between mode choices due to the use of the In-Time services.

In detail, the required end-user survey data consist of:

a) Socio-economic data of demonstration participants:

Gender, income, car availability / PT availability, number of trips per day / mileage per day with each transport mode.

b) Survey of trips on a predefined day before start of the demonstration phase:

Trip length, transport mode, travel time or departure and arrival time.

c) Survey of trips on a predefined day in the mid and at the end of the demonstration phase:

Trip length, transport mode, travel time or departure and arrival time, number of information service users in pilot site or city.

On the other hand side, site specific statistical data are required for the emissions model to understand the impact of the modal shift registered in the end user survey on the emissions produced in a site.

These are in detail:

a) Fuel consumption: per fuel type in [l/day] or [TJ/day]

Possible corrections have to be made regarding on-road / off-road traffic, fuel tourism and any other difference regarding the amount of fuel sold (in the pilot site or city) and consumed (in the pilot site or city) and passenger car fraction.

b) Emission factors: per fuel type in [g/l] or [kg/TJ]

In case there are no pilot site specific values available, the standard values defined in [IPCC 2006] can be used

c) Total mileage: per fuel type in [km]

possible corrections have to be made regarding the passenger car fraction

Optionally, additional data can be used to support the environmental impact assessment which comprise the composition of the current vehicle fleet for passenger cars divided into categories with different propulsion systems (gasoline / diesel engine) and the difference in total mileage travelled based on the end user survey.

(b) Site specific assessment methodology

The test sites Bucharest, Florence, Munich, Oslo and Vienna each investigated the specific impact of the In-Time services reflecting on different core aspects.

The analyses carried out in Bucharest concerned the impact of the In-Time services on the traffic condition, travel times, fuel and energy consumption and emission levels as well as the effect of the employment of LED signalling combined with a harmonised traffic management.

For the evaluation of the traffic-related environmental impact, a two steps approach was followed: the environmental impact of private traffic is based on manually and automatically collected data for the specific test-route in downtown Bucharest. The environmental impact assessment of the public transport separately considered fuel-driven (gasoline/diesel) public transport vehicles (buses) and the electrically driven public transport vehicles (trams and trolleybuses) and on test routes in Bucharest.

The evaluation of the energy consumption impact of LED the road signalling (LED-driven traffic heads) based on three scenarios: the former state, where the whole Bucharest‘s traffic signalling network has been equipped with incandescence bulb lamps; the present situation, where a considerable part of the network have been renewed with modern traffic controllers and LED traffic signals‘ heads; and a future case, when it is expected that the whole network will be fully equipped with LED technology and traffic management systems cover the whole city. The life-cycle costs and reliability of the systems have been considered and the for all these scenarios the equivalent emissions have been computed. These emissions were also converted into virtual road vehicles “removed” from the traffic environment.

The test site Florence focused its assessment on the energy required for emissions generated by the operation of the public transport vehicles additionally required (compared to the status without In-Time services) to cover the trips shifted from motorized private to public transport. The methodology is based on the investigation of the free capacity of public transport vehicles depending on the origin and destination of a trip and the additional capacity required under the assumption that one and three percent of the trips would be shifted from private motorized to public transport.

Munich, as the third test site executing a site specific assessment, utilized the existing traffic model for the conurbation area and simulated the shift from individual private to public transport means by reducing traffic demand on the private motorized transport side. Based on PTV´s VISUM software, the methodology described in the Handbook of Emission Factors (HBEFA) used in Germany, Austria and Switzerland which is readily integrated into the software was used to calculate the emission levels for a estimated one, three and five percent reduction in private motorized traffic. Due to the complexity of modelling and lacking data e.g. concerning the public transport fleet compositions, the energy required to operate additional public transport vehicles potentially required to provide the capacity to cover the trips shifted from private motorised to public transport could not be considered. The results from Florence can provide some very general indication but, in detail, are very site specific to Florence.

The test site Vienna compared the estimation of total CO_2 emissions based on fuel consumption and mileage of passenger cars from other sources to those values calculated on basis of the results of a sophisticated regional traffic simulation model. For the calculation of the emission factor, the estimated average travel speed resulting from the traffic model is used to determine the traffic state. Based on the Handbook of Emission Factors‘ database (HBEFA), an average emission factor for the Austrian passenger car fleet in the investigated year is calculated for each road link for the calculated traffic states.

2.2.5. COSMO validation principles

For the validation of the impacts of the ITS application developed in the project a V-model has been used where three stages have been considered:

- Definition stage: at this level all the required information for carrying out the validation are defines. The result of this stage is the Validation Matrix where Target Criteria are associated to Performance Indicator and necessary Measurements. To the Validation matrix test cases are linked, supporting successive stages.

- Operational stage: during this stage measurements required for the Performance Indicator evaluation are acquired, logged and processed according to a plan developed for each Pilot Sites. In order to have an effective assessment of the pilot application, should be necessary to have an accurate plan of measurements for the Performance Indicators. In particular should be necessary to distinguish between reference applications and trial applications with the aim of comparing the COSMO application performance with a baseline scenario.

- Impact assessment: the last stage of the validation will give a final evaluation of the impact of installed application following two steps:

  - The evaluation of the Target Criteria: this means that a matching should be done between established criteria (during the definition stage) and collected results (during Operational stage).

  - The Impact Appraisal: consisting on the preparation of evidence for the policy-decision makers and/or stakeholders on the advantages/disadvantages of COSMO services by assessing their potential impacts, with particular emphasis on energy-efficiency and environmental impact.

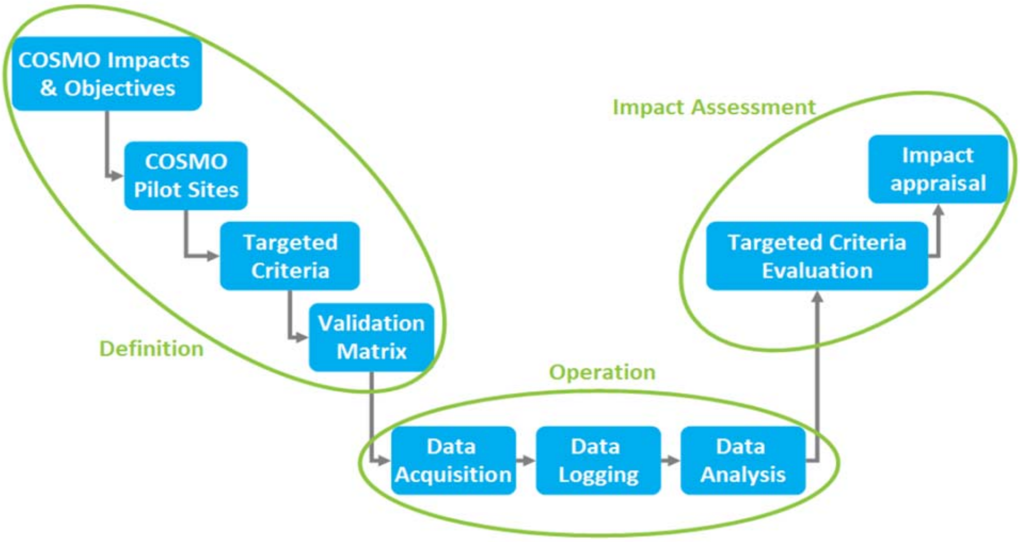

Fig. V.52 V-Model used in COSMO validation plan

For example in the Austrian Pilot site, the following validation matrix has been obtained:

Table. V.1 Austrian pilot site Definition of the Performance Indicator

CATEGORY	STATED OBJECTIVE	HYPOTESIS	TARGET CRITERIA	PERFORMANCE INDICATOR
ENVIRONMENTAL	Reduce fuel consumption	The applications will contribute to a fuel reduction	The fuel consumption reduction due to driving recommendation is estimated >10%	Fuel consumption [l/km]
	Reduce CO_2 emission	The applications will contribute to $C0_2$ emission reduction	The CO_2 emission reduction is estimated to be >10%	CO_2 emissions [g/km]
MOBILITY	Traffic efficiency (reduce stop & go)	The applications will contribute to a smooth traffic flow.	The traffic flow with the applications is estimated to be higher than without applications	Traffic flow [veh/hour]
DRIVER BEHAVIOUR	Driver behaviour change	The on-board application will modify the driver behaviour.	The increase on the number of recommendations followed is estimated to be >30%	Rate of use = number of instructions followed [absolute percentage]
USER ACCEPATNCE		The application is accepted by the driver .	The system is not switched off	System is switched off [bool]
		The applications are accepted by the driver.	High user acceptance score in questionnaire	Mean value satisfaction/usefulness scale

2.3. Results

2.3.1. Freilot: Results

After all the data processing work, briefly described above, the indicators were available and it was possible to perform the statistical analyses. In accordance with the principal objective of the project the fuel consumption saving was significant in systems and pilot sites such as the energy efficient intersection control where the difference between the baseline and pilot periods is -13% in Helmond and -8% in Lyon. Krakow obtained local improvements of the efficiency in two intersections (-62 and -22%).

Since the fuel consumption is strongly linked to gas emissions, the energy efficient intersection control in Helmond reduces the CO_2 and NO_x emissions by 13% with comparable results in Lyon. Intersection 2EW in Krakow reduces the emissions by 65%. These scores were achieved by the system mainly due to the drastic reduction in the number of stops.

Though the evaluation of the delivery space booking application does not show a significant result in terms of fuel consumption/emissions reduction, it highlights its considerable impact on overall traffic, especially in illegal parking. In this case the system led to a remarkable increase in the number of deliveries. Many drivers thought that the application improved the image of freight transport in urban areas; they liked the application and found it is easy to use. Moreover, drivers believed that the delivery space booking application increases the efficacy of their work, facilitates their delivery operations and it increases the delivery efficiency.

In the case of acceleration limiter the results found under the experimental conditions, are not significant; between -2% and 2% fuel consumption change. In the case of the adaptive speed limiter there is a small reduction in fuel use. The scope of this limiter is more safety-related than efficiency related. Added to this, the driver has a fundamental role in the success of this system since he can accept or reject the limitation. The data analysed shows that most of the times the drivers were rejecting the limitation.

The impact on fuel consumption of the eco driving support application is also very much dependent on the drivers. In this case, the data analysed shows a maximum fuel reduction of 6,6% in the 0-100 km/h speed range and 15,3% in the 0-50 km/h speed range (in urban/suburban use). In long haul uae, the maximum fuel reduction achieved was 6,3% in the 0-100 km/h speed range and 11,6% in the 0-50 km/h speed range.

2.3.2. In-Time: Results

The common assessment methodology showed, that the average CO_2 emission per driving inhabitant varies between 330 and 6690 g CO_2 per person and day depending on the specific test site. From this figure, a reduction potential of 3.3 to 66.9 g of CO_2 per person and day for every percent of mileage reduction can be calculated. However, it was found the statistical data available in each region are not fully harmonised meaning that specific figures on fuel consumption originate from different sources and computational methods and are available in different granularities (local, regional, national etc.) thus limiting comparability.

The site specific results are, by nature, not applicable on general level but might provide some insight on general expectations and are sketched below.

The test site Bucharest found that only a large scale usage of In-Time services supported by additional measures such as the utilization of alternative engine concepts in public transport vehicles would be suitable to support a significant decrease of emissions in the highly loaded city centre. On the other hand, the LED technology clearly lead to decreased energy consumption and lower requirements towards maintenance thus reducing costs and emissions from energy production.

Florence found, that the current public transport system should be largely sufficient to cover the anticipated numbers of additional passengers and would require between two and six electrically driven public transport vehicles to be employed in addition to the existing fleet. The additional CO_2 emissions originating from these public transport vehicles is significantly lower than the reduction achieved by reducing the related number of trips in the individual motorized segment.

In Munich, the simulation results indicated that the reduction in CO_2 emissions is quite proportional to the reduction of mileage in the private motorized segment (see figure below).

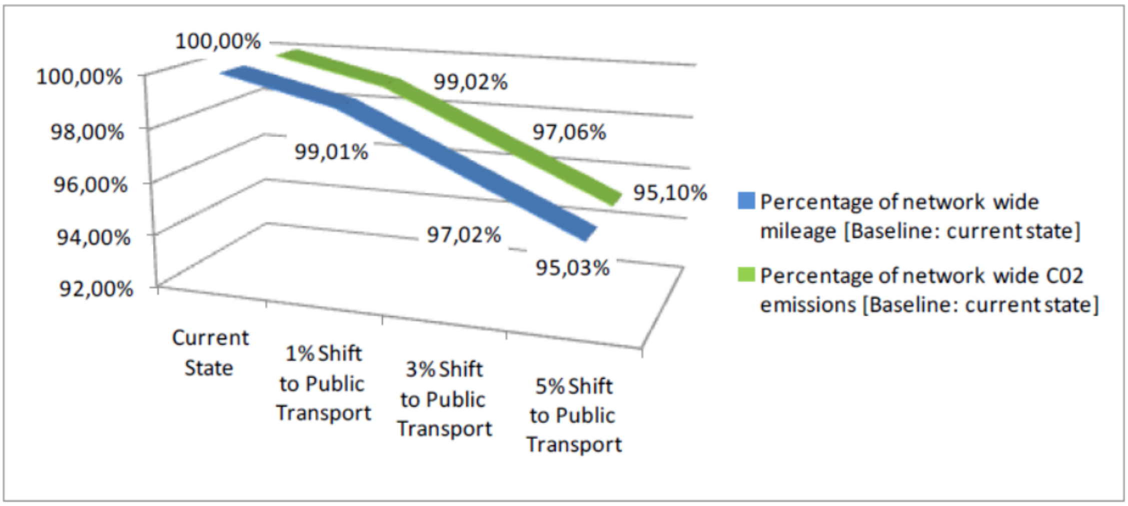

Fig. V.53. Results of site specific assessment in Munich – In-Time project.

The assessment in Vienna resulted in the understanding, that the total sum of CO_2 emissions estimated from the traffic model (approx. 3200 t CO_2/d) is significantly lower than the estimated CO_2 emissions based on fuel consumption (approx. 4600 t CO_2/d). As there are known uncertainties associated with the approach utilising fuel consumption (mainly the export of fuel from Austria to surrounding countries in the order of 25 %), the overestimation can be explained by these factors to a large extent.

It should be noted, however, that the beta-testers involved in the project´s end-user survey which provided core input factors for the assessments were willing to test and evaluate subjectively innovative systems in an R&D environment. It was found, however, to be very difficult to attract test users to test a system which seems, from an end-user perspective, similar to existing systems. This is applicable to areas where a wide range of traffic information services is already in place. In these cases, alternative methods for test-user attraction need to be considered e.g. by considering to give incentives either within the project or within a separate project where a more detailed diary-based survey can be performed similar to the U.S.

2.4. Assessment: Further discussion

2.4.1. Ecomove: Scaling up of results and cost-benefit analysis

Some scaling up will be done for the two urban test sites, to obtain impacts at the level of the whole city (each of the test sites only covers part of the city network). Munich and Helmond are very different in terms of size, traffic network length, amount of traffic and share of different road types. Assessing the impact of the eCoMove system for two cities will not only demonstrate potential CO_2 savings for each of the cities, but also outline differences caused by varying city types. Variables such as road network length, number of signalised intersections, the share of motorised individual traffic or the traffic volume per day are different for both cities. As stated above, the traffic models used will not be able to simulate the entire network of Munich and Helmond (the same is true for the French motorways test site: this is only a small part of the total motorway network). The reason for this is that the preparation of such a network in a simulation environment is a time consuming task. Every intersection within the urban networks has to be programmed as it works in reality to represent the base case (or base line). For impact assessment, these have to be configured and fine-tuned again to represent the eCoMove traffic management applications. Therefore it was preferred to use a representative segment of each network in the traffic simulation environment. These segments cover most of the situations which can be found in both cities and will be fully "equipped" with eCoMove solutions. The approach described above will give insight into the impacts for segments of two typical, relatively well managed European traffic networks from a traffic management perspective. In order to gain more insight into what this would mean on the level of an entire city, data about the rest of the networks of Munich and Helmond will be collected and the impacts for the whole city will be estimated (quantitatively).

The results from the scaling up (benefits at the city level) will be used in a limited cost-benefit analysis. For this, an estimate of the costs of the eCoMove system will also be needed.

2.4.2. eCoMove: Baseline of the eCoMove system assessment

For the assessment of the eCoMove system using the traffic network simulations of Munich, Helmond and the French motorways, the real traffic situation as currently found on these networks will be the baseline. Necessary data (e.g. traffic volume, fleet composition, driver performance, driver compliance, traffic management & control etc.) will be used for calibration during the development of these models, so that they are valid for the area they represent, in the current situation. eCoMove aims to show the environmental impact on traffic networks with today's state of the art traffic management. It is the opinion of the consortium that the chosen cities and motorway networks are relatively well equipped and managed, thus providing a good baseline for the eCoMove impact assessment. N.B. using state-of the-art networks ensures that the impacts are not overestimated. The baseline calculations will reflect the real world fleet composition as well as driver performance. The simulations will include different traffic network situations such as the peak, off-peak and night periods (some applications may be effective only for heavily loaded networks; or in quiet periods).

2.5. Conclusions and outlook

2.5.1. eCoMove: Conclusion and outlook

eCoMove is a large and complex project, with a large number of core technologies, applications and components being developed, tested and evaluated. The validation approach for eCoMove needed to be flexible yet structured to ensure that at the end of the validation phase, the results are transparent and interpretable. The FESTA handbook offers a structured approach. Terminology used in the handbook was adopted in the eCoMove project, which helped to resolve many inevitable moments of confusion among the partners working together. At the moment of writing, the validation tests are about to be started, in the field, in driving simulators and in simulations. The network simulations for the impact assessment will take place after that. The impact assessment provides input for a cost-benefit analysis, which is accompanied by an analysis of barriers to implementation (some of which will be identified in the validation tests) and an eCoMove road map.

2.5.2. Freilot: Lessons learned

These are two of the main lessons learned (quoted from D.FL.4.2 Final Evaluation Report):

(a) Methodology

When the methodology definition started, no methodology specially defined for pilots was available. In this case, and for similitude with a Field Operation Test, FESTA was adopted as reference methodology for FREILOT. From this project, the use of this reference methodology is suggested as it fits really well with the different phases of the pilot. Added to this, it is really important in the different steps of the definition (identification of research questions, hypothesis, indicators and measurements) to collaborate with the partners in charge of business models. In this case, it is interesting to take into account to the analyses of the potential benefits defined for the services and contribute with the real data collected to analyse the business cases in terms of benefits obtained from the pilot for each site.

(b) Data measurement

From the evaluation point of view is really important to provide the list of measures to be collected during the pilot and the requirements of this data collection to the implementation WP as soon as possible. In this way all the requirements regarding data collection can be taken into account during the implementation of the services and, in case any problem appears, it will be possible to look for a solution in order to get similar data or data that can help in order to perform the analyses of the services.

2.6. Case study: Driving cycles for passengers cars

Optimizing traffic management systems requires the development of dynamic traffic models capable of estimating environmental externalities. However, such models only produce simplified trajectories. Therefore they cannot be directly coupled with traditional emission models based on real trajectories, i.e. observed experimentally. The aim of this case study is to evaluate the impacts of using simplified instead of real trajectories as an input for a fuel consumption model.

In this case study, extract from the work of Thamara and al.(Thamara Vieira da Rocha, Bruno Jeanneret, Rochdi Trigui, Ludovic Leclercq, How Simplifying Urban Driving Cycles Influence Fuel Consumption Estimation?, Procedia - Social and Behavioral Sciences, Volume 48, 2012, Pages 1000-1009), driving cycles are selected from 37 ARTEMIS urban driving cycles and processed. The resulting driving cycles are then simplified to make them correspond to the classical outputs of microscopic traffic flow models, i.e. piecewise linear speed profiles. The simplification method used is based on a genetic algorithm with a given number of break points. Reducing the number of such points leads to several levels of simplification. The fuel consumption is then estimated for each simplified driving cycle and its original. The differences of these consumptions are first study for the whole sub-cycle set, for several levels of simplification. Then, several sub-cycles are individually studied to figure out which kinds of simplification have the main influence on the fuel consumption.

The selected cycles from ARTEMIS project are divided in 249 sub-cycles by identifying stops that last at least 6 seconds. 25 homogeneous groups has been defined by a cluster analysis (based on travel time, distance travelled, stop duration, maximum and average speed and acceleration) in order to reduce the database size. In the end, 39 sub-cycles are selected providing a statistically representative description of the possible encountered traffic situations.

A genetic algorithm is used to transform one sub-cycle into a piecewise linear function with a fixed number of action points. Reducing this number provides several simplification levels. The simplification level is defined by the ratio between the number of considered AP and the total number of time points in the original sub-cycles. Note that original sub-cycles are defined with a time step of one second. Thus, the total number of time point is equal to the duration of the sub-cycle. The genetic algorithm tries to minimize the RMSE between the original and the simplified sub-cycle.

The algorithm is defined by the parameters described hereafter. The population size is adapted to the considered number of actions points (AP). A sample of this population is defined by the list of the positions in time of the action points. During the reproduction step two crossovers are considered. They are defined by the number of AP before the crossover positions. The minimal considered number for action points is six. The positions of crossovers depend on the number of AP, see Table. V.2.

Table. V.2 Population size and crossover positions with respect to the number of AP.

Parameter	AP ≥30	10 ≤ AP < 30	10 < AP ≤ 6
Population size	12	8	4
Crossover position 1	4	3	2
Crossover position 2	8	6	4

Two kinds of mutations are possible: minor mutation corresponds to the incrementation of AP position of ±1. Major mutation corresponds to a random change of an action point position. The probability of minor mutation is 0.09% and 0.005% for major mutation. An elitist selecting method is applied, i.e. only the best samples are kept to define the new population after the reproduction and the mutation steps. The algorithm stops either when a maximum number of iterations is reached (N=1500) or when the RMSE has been stabilized for at least 150 iterations.

2.6.1. Macro analysis

The average duration for the 39 original sub-cycles is equal to 83s. It varies from 20 to 193s. The average speed is 21.2km/h and the maximum one is 73.5km/h. After simplifying, 1367 simplified sub-cycles are obtained with the genetic algorithm and different levels for the number of action points. The following parameters are calculated for each sub-cycle:

- The standard relative error on the fuel consumption estimation [FC error] (%): it corresponds to the relative difference between fuel consumption on the original and the simplified sub-cycles.

- The reduction in the number of action points [AP reduction] (%): it corresponds to the relative positive difference between the action points' number in the simplified sub-cycle and the total time points in the original one.
- The RMSE: the root mean square error between both sub-cycle. This error defined the root mean squared difference in speed every second on the speed profile.

The AP reduction varies between 24.1% and 96.9%. Three levels of simplification are then distinguished by analyzing the sub-cycles profiles ans the RMSE with respect to the AP reduction (Fig. 48). These levels are: fine, intermediary and coarse. Moreover, the figure presents the FC error with respect to the AP reduction. The mean curve of this function and the boundaries including 80% of data are also provided.

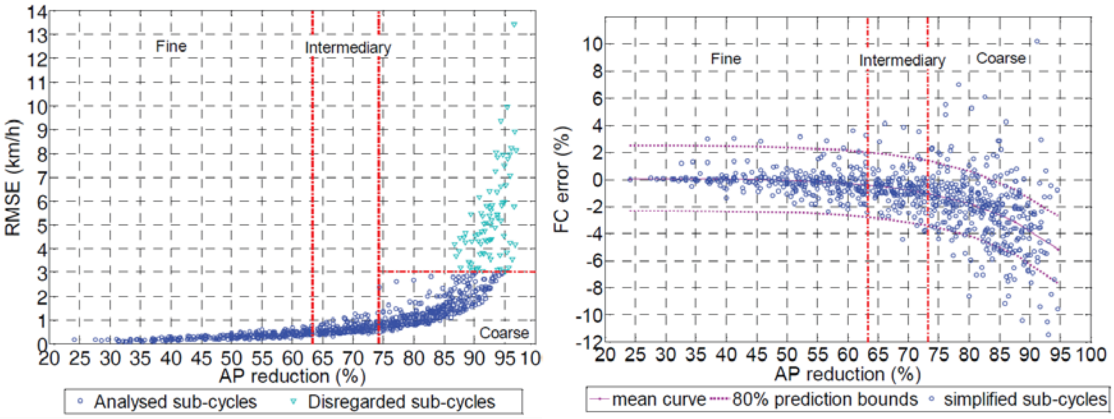

Fig. V.54 (left) Evolution of the RMSE with respect to the AP reduction (right) Evolution of the FC error with respect to the AP reduction.

The fine level corresponds to RMSE values lower than 0.75km/h. It corresponds to AP reduction lower than 63.3%. The average RMSE is equal to 0.33km/h (the RMSE increases between 0.09 and 0.75km/h). At this level, only the high frequency but low amplitude noise is eliminated. The intermediary level is bounded by RMSE values lower than 2.37km/h. It corresponds to AP reduction between 63.3% and 74.3%. The average RMSE is equal to 0.66km/h (the RMSE increases between 0.33 and 2.37km/h). The variations of accelerations are more smoothed than at the fine level. The coarse level corresponds to AP reduction higher than 74.3% and RMSE lower than 3.0km/h. The average RMSE is equal to 1.46km/h (the RMSE increases between 0.50 and 3.0km/h). The simplified cycles have longer phases of constant acceleration than both previous levels. 31.2% of data corresponds to the fine level, 19.3% to the intermediary level and 39.3% to the coarse level.

From the data set, the increase of AP reduction results in an exponential increase of the RMSE (the average RMSE is equal to 0.90km/h). High values of RMSE (the RMSE higher than 3km/h) lead to simplified sub-cycles that are far away from the originals. These kinds of simplification are not relevant for our study and the corresponding sub-cycles have been disregarded. It corresponds to 10.2% of simplified sub-cycles.

As the AP reduction increases, the FC error also tends to increase negatively. The average error is equal to -1.27% for sub-cycles set. According to the simplification level the average FC error is equal to -0.13% at fine level (the FC errors varies between -2.47% and 3.57%), -0.77% at intermediary level (the FC errors varies between -4.47% and 4.13%) and -2.42% at coarse level (the FC errors varies between -11.46% and 10.20%).

The main result here is that FC error is not very sensitive to the AP reduction. It appears that we can significantly simplify the real sub-cycle without introducing crippling bias in fuel consumption estimation. This first result should be confirmed with a refine analysis.

2.6.2. Micro analysis

We now study some particular sub-cycles and investigate the evolution of fuel consumption with respect to time. To emphasize the difference in fuel consumption, we will focus on the cumulative consumption with respect to time for simplified and original patterns. When these two curves diverge, it means that the kinematic simplifications imply a significant error. This error may (i) never be compensated and then play a significant part of the total FC error, (ii) be quickly compensated in the same driving phase (acceleration, deceleration or cruising) or (iii) be compensated but latter in sub-cycle. We will mainly focus on error types (i) and (ii) because the third one result from hazard and cannot drive any simplification guidance.

The cumulative consumption curves are compared with the respective speed profiles to determinate the kinds of simplification that most influence the fuel consumption. Only three sub-cycles (ID = 39, 32, 25) are selected for this micro analysis (but several level of simplifications are investigated). These sub-cycles highlight different cases:

Sub-cycle 39 has simplified sub-cycles with FC error always inside the error bounds for all sub-cycles. The FC error is very low for low values of AP reduction. It tends to increase with the increase of the AP reduction, especially from coarse level (AP reduction equal to 89.6%). This sub-cycle lasts 173s and has average speed equal to

37.3km/h.

Sub-cycle 32 corresponds to a case where FC errors are high even for low AP reduction values. The simplified sub-cycles have high FC error until AP reduction equal to 80.4%. Sub-cycle 32 is a short sub-cycle that lasts 46s and has low average speed equal to 5.5km/h.

Sub-cycle 25 was studied to best identify the kinds of simplification in coarse level (high RMSE) that lead to high FC error (fuel consumption underestimated). The simplified sub-cycles start with low FC error (-0.33%) and then increase discontinuously with the increase of the AP reduction. This sub-cycle lasts 96s and has average speed equal to 39.9km/h.

Fig. V.55 presents the evolution of the FC error and the RMSE with respect to the AP reduction for these sub-cycles. The mean FC error values and bound encompassing 80% of the studied sub-cycles are also represented in this figure.

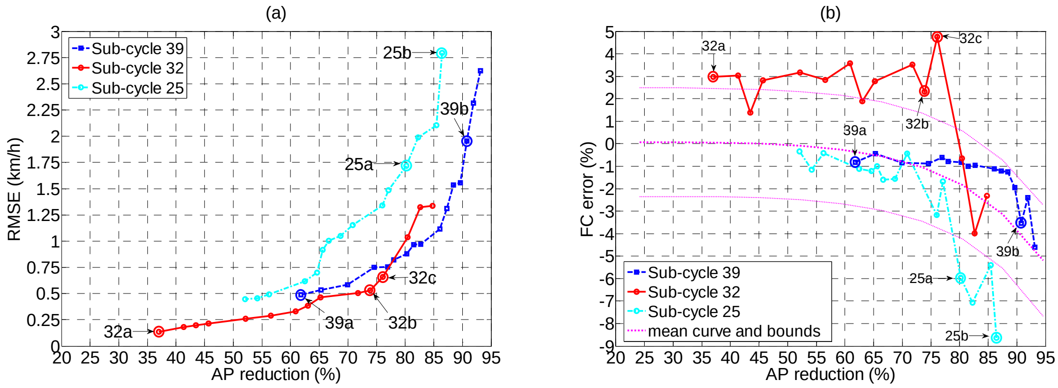

Fig. V.55. Evolution of (a) the FC error and (b) the RMSE with respect to the AP reduction.

The Fig. V.56 presents the cumulative consumption curve and the speed profile for the three selected sub-cycles and the most representative levels of simplification see Fig. V.55.

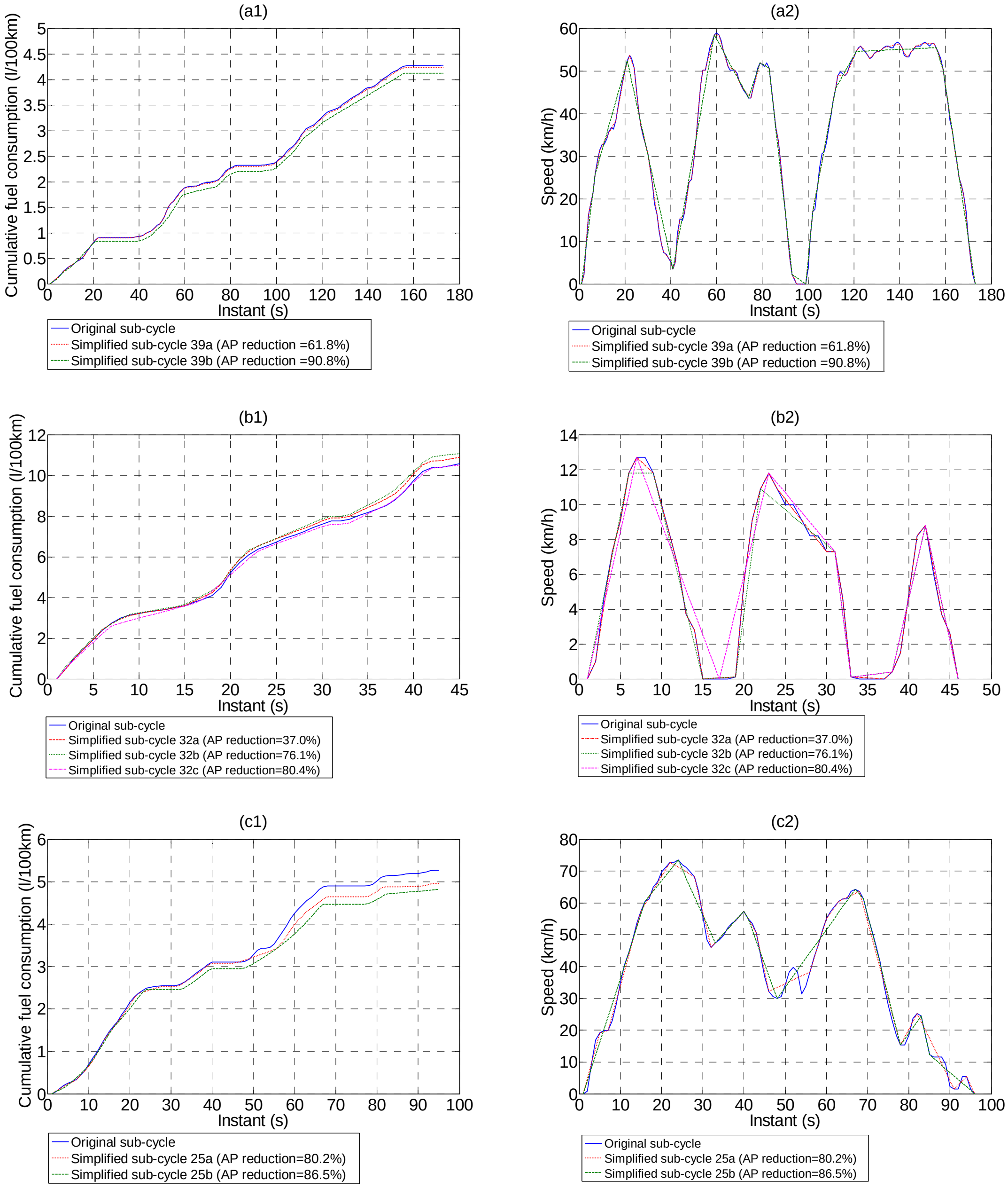

Fig. V.56. (a) Sub-cycle 39, (b) sub-cycle 32, (c) sub-cycle 25. (1) Cumulative fuel consumption with respect to time, (2) Speed profile.

The accelerations phases are responsible for higher fuel consumption than the deceleration phases. An significant difference is seen when the deceleration phase occurs at high speed (e.g. sub-cycle 39 and 25) or at low speeds (e.g. sub-cycle 32). In the first case, the Electronic Control Unit of the engine pilots an injection cut-off and the fuel consumption is equal to zero, i.e. the cumulative curve remains constant. In the second case, the fuel consumption continues to increases with lower values than in acceleration phase. Additionally, the phases with zero speeds also contribute to fuel consumption.

We now deal with the impacts of different levels of simplification. The levels are denoted with lower use letter after the sub-cycle ID, see Fig. V.56. Sub-cycle 39a corresponds to a fine simplification with a cumulative consumption curve close to the original. The resulting FC error is low (-0.82%). For sub-cycle 39b, the maximal speed is not reached at time 22s in the simplified sub-cycle. The cumulative fuel consumption at the end of the acceleration phase is then underestimated. This corresponds to a type (i) error, i.e. the contribution of this error on the total error is equal to 22.8%. Moreover, the simplification between 122 and 156s replaces the original speed profile by a phase on constant and low acceleration. The initial speed is 54.6km/h and increases until 55.5km/h. This simplification has low impact on fuel consumption.

The different levels of simplification for sub-cycle 32 show that kinematic errors during phase with zero speed induces significant errors on fuel consumption, see time 34 to 37s and time 15 to 18s. As result, these simplifications overestimate the fuel consumption for sub-cycles 32a and 32b. The simplifications of this first phase are the same for sub-cycles 32a and 32b. However, as this simplification does not cause a local error in sub-cycle 32b, we can conclude that it is corrected by another simplification. After the end of this phase in zero speed (instant equal to 18s), the simplifications cause local errors that cumulate until the FC error of sub-cycle 32b. Additionally, the reduction of the maximal speed at instant equal to 6s does not cause an error on fuel consumption estimation. As the maximal speed reached is low (11.8km/h), the fuel consumption continues to increase close to the original. In sub-cycle 32c, the combination of the simplifications (including the simplification of the second phase on zero speed) results in a low FC error (-0.66%). The simplification of the discontinuous deceleration phase between 23 and 31s in sub-cycles 32a and 32c does not impact the cumulative consumption curve.

In sub-cycle 25a, the deceleration phase that starts at instant 40s has same maximal speed that the original but reaches higher minimum speed. This last point is anticipated in time (instant equal to 46s instead of 48s) and the fuel consumption for the next acceleration phase increases earlier. During this deceleration phase the consumption curve remains close to the original because maximal speeds are the same.

Additionally, the simplified sub-cycles 25a and 25b have error coming from the simplification of the oscillation between 48 and 54s in original sub-cycle. The oscillation corresponds to an acceleration followed by a deceleration phase. In sub-cycle 25b, it is replaced by a constant acceleration phase between 46 and 56s. In sub-cycle 25b, it is also replaced by a constant acceleration phase but longer, from time 48s to 67s. Both simplifications contribute to the FC error, higher in sub-cycle 25b than in sub-cycle 25a. Reducing the maximal speed at 67s in sub-cycle 25b also has great impact on FC error. The simplifications made from the instant 68s have low impact on fuel consumption in both simplifications.

2.6.3. Discussion

First, the impacts of simplifications have been evaluated at a macro level. All sub-cycles have been simplified with different values of the AP reduction. Results show that an increase in AP reduction negatively increases the FC errors especially for the coarse level, i.e. the simplification tends to underestimate the fuel consumption. The FC error is equal to -1.27%. It is equal to -0.13% for the fine level (AP reduction <63.3%), -0.77% for the intermediary level (AP reduction between 63.3% and 74.3%) and -2.42% for the coarse level (AP reduction >74.3% and RMSE <3.0km/h).

A complementary analysis has determined which kinds of simplification have the main influence on the fuel consumption. This is achieved by studying the evolution of fuel consumption over time (cumulative fuel consumption with respect to time). The time when the cumulative consumption curve of the simplified sub-cycle moves away from the original represents a local error on fuel consumption estimation. The localization of these specific errors can then be investigated on the speed profile.

This study shows that, by reducing the number of action from the original cycle, the genetic algorithm first eliminates high frequency but lowers amplitude noise. Indeed variations in acceleration are smoothed. The acceleration phases are then reproduced with only a few successive values of constant acceleration. The deceleration phases are treated the same way. Such kinds of simplifications seem to have no or a relatively low impact on fuel consumption.

Going on in reducing the number of action points eliminates noise with low frequency and/or higher amplitude. From here, the position of the action point and the speed value seems more important. However, some action points are more important for fuel consumption estimation than others. These actions points correspond to signal changes in acceleration and more precisely the points when the speed reaches its maximum value before a deceleration phase. Introducing errors on the maximum (respectively minimum) speed value at the end of an acceleration (respectively deceleration) phase leads to significant errors on fuel consumption. Furthermore, higher the maximum speed higher the fuel consumption is.

Additionally, an acceleration phase with one or more significant change on acceleration value can be replaced by a phase with different successive values of acceleration. If this kind of speed profile is replaced by another with only one acceleration value, the FC error tends to be higher. The deceleration phases are treated the same way.

The minimum speed at the end of a deceleration phase is less important than the maximum speed at the end of an acceleration phase. Moreover, vehicle standstill can highly influence the fuel consumption even at fine level. This kind of simplification overestimates the fuel consumption.

The conclusions taken from this work try to give a first answer to the impacts of using simplified instead of real trajectories as an input for a fuel consumption model. The major observation is that simplified driving cycles can still maintain good fuel consumption estimation.

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3. Modelling energy and emissions for Intelligent Transportation Systems:An approach for the U.S. Department of Transportation AERIS program

In addition to the established Japanese Energy ITS program and the European transport CO_2-reduction projects, the United States is starting to develop an approach to modelling energy and emissions reductions for their environmentally-focused ITS projects. In the U.S., there have been a number of different efforts to model the reduction of energy and emissions for ITS projects over the last two decades. These efforts have typically been part of individual projects and have lacked coordination between them. However in recent years, the U.S. Department of Transportation has established an environmentally-focused ITS research program called Applications for the Environment: Real-Time Information Synthesis or AERIS. The goals of the AERIS program focus on environmental ITS solutions by generating and acquiring environmentally-relevant real-time transportation data and then using these data to create actionable information that support and facilitate "green" transportation choices by transportation system users and operators. This is part of the larger connected vehicle research program to illustrate how connected vehicle data and applications will contribute to mitigating the negative environmental impacts of surface transportation. In this section, we briefly outline a general approach to modelling energy and emissions for a variety of ITS projects within the AERIS program based on initial documentation from the AERIS research team (see, e.g., [BAH 2012]). This approach is preliminary in nature and is being refined during 2013.

3.1. AERIS overview

As a part of the Research and Innovative Technology Administration (RITA) of the U.S. Department of Transportation (U.S. DOT), the Intelligent Transportation Systems (ITS) Joint Program Office (JPO) is charged with planning and executing the ITS program. One of the foundational elements of the ITS research effort is the environment research area is the Applications for the Environment: Real-Time Information Synthesis (AERIS) program. The overall AERIS program vision is to create "Cleaner Air through Smarter Transportation". To meet the vision, the AERIS program studies how generation, capture, and analysis of vehicle-to-vehicle (V2V) and infrastructure-to-vehicle (I2V) data, along with implementing important environmental applications, will reduce the environmental impacts of surface transportation system users and operators. Making up the key elements of the AERIS program are transformative concepts and applications that have the potential to significantly reduce environmental impacts of the surface transportation systems. These transformative concepts are integrated, operational strategies that use vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) data and communications to operate surface transportation networks and to help travelers make green travel choices with the aim of reducing the environmental impacts of transportation-related emissions and fuel consumption. The transformative concepts consist of applications or technological solutions designed to ingest, process, and disseminate data in order to address specific tasks and combine applications that result in significant environmental benefits to surface transportation networks. Currently there are six AERIS Transformative Concepts which include: 1) Eco-Signal Operations; 2) Eco-Lanes; 3) Dynamic Low Emissions Zones; 4) Support for Alternative Fuel Vehicle (AFV) Operations; 5) Eco-Traveler Information, and 6) Eco-Integrated Corridor Management (ICM). Further details on the AERIS research program and these transformative concepts can be found in [U.S. DOT RITA ITS JPO].

3.2. Energy and emissions modelling within AERIS

AERIS applications are designed to reduce the environmental impact of surface transportation. Modelling of these applications is considered by no means trivial or straightforward. One of the most difficult challenges is the ability to reflect the dynamic and “active” nature of the AERIS concepts. The energy and emission models need a dynamic evolutionary paradigm to be truly capable of capturing the AERIS concepts. One of the more challenging problems is the influence of AERIS applications on different elements of the trip chain: destination choice, mode choice, time of day choice, route choice and lane choice. This influence will vary from one application to another and feedback loops between behaviour and traffic assignment models will have to be created to capture these effects. In summary, a modelling approach is being developed that captures the effects of AERIS applications on all levels, regional to individual intersections.

On a regional level or macroscopic level, it is necessary to use the land-use patterns and socio-economic data for the region and estimate the regional travel demand. Typically a demand model is used that can receive these inputs and generate travel demand. Residential data, land-use data, geographical data, demographic data, and socio-economic data are the typical inputs into a demand model. These inputs are processed to generate individual trips in the region. The demand modelling should be able to capture policy effects such as congestion pricing, employee telecommuting options, use of HOV/HOT lanes, etc. The demand modelling also needs to be responsive to possible changes in routes, modes of travel, number of trips, trip chaining, and quantify induced demand due to implementation of traffic operational or other improvements brought on by AERIS applications.

Once the demand is generated, it is necessary to route the trips to their destinations. The routing could be influenced by various factors such as traffic congestion, incidents, tolls, time-of-day, etc. Implementation of some of the AERIS applications could affect the route and mode choices of users. As such, it is necessary to perform Dynamic Traffic Assignment (DTA) based on network conditions and also based on the effect of AERIS applications on the operations. This DTA tool must be capable of simulating V2V and V2I communications so that en-route changes can be addressed. The output of the DTA tool is a set of individual trajectories of vehicles. These trajectories cannot be used to obtain high resolution speed profiles for individual vehicles, which call for microsimulation of the region. The output of the DTA tool can be used to generate path flows and input volumes that can be used in a variety of microsimulation tools.

Microsimulation tools can be used to carry out a high resolution simulation of vehicles and capture their detailed trajectories for the modelled region. As is well known, it takes a great deal of effort and time to model and calibrate a large region in a microsimulation tool. Therefore the approach will be to use a variety of microsimulation tools to model key areas of activities (e.g., traffic intersections, corridors of coordinated ITS activities, links with specialized ITS elements, etc.) and then aggregate these results upward into the macroscale modelling. As such, efforts will be taken to establish the microsimulation "building blocks" and then use the results of the building blocks in the larger regional modelling.

A typical emissions model uses individual vehicle trajectories from a microsimulation tool and provides a detailed picture of the type and quantity of emissions and fuel consumption for individual vehicles. These individual emissions and fuel consumption results can be aggregated to look at the overall traffic energy and emissions. There are a number of very capable emission models that have been developed for the U.S., including the U.S. EPA's MOVES model (see [U.S. EPA]) and the Comprehensive Modal Emissions Model (CMEM, see [CE-CERT]).

Therefore, in order to model AERIS applications, a demand model is being adapted to generate travel demand, a DTA model is being employed to generate vehicle trajectories, and a variety of microsimulation tools in conjunction with microscale emission models are being utilized at a finer resolution to estimate the energy and emissions impacts of AERIS applications. The dynamic nature of AERIS applications calls for feeding back the outputs of the microsimulation and emissions back to the DTA tool so that the route and other changes are reflected in the next time step. The outputs of the DTA model can be fed back to the demand model as well to capture any medium and long term effects resulted by the implementation of AERIS applications, like telecommuting for the day or moving closer to a work place or changing work times.

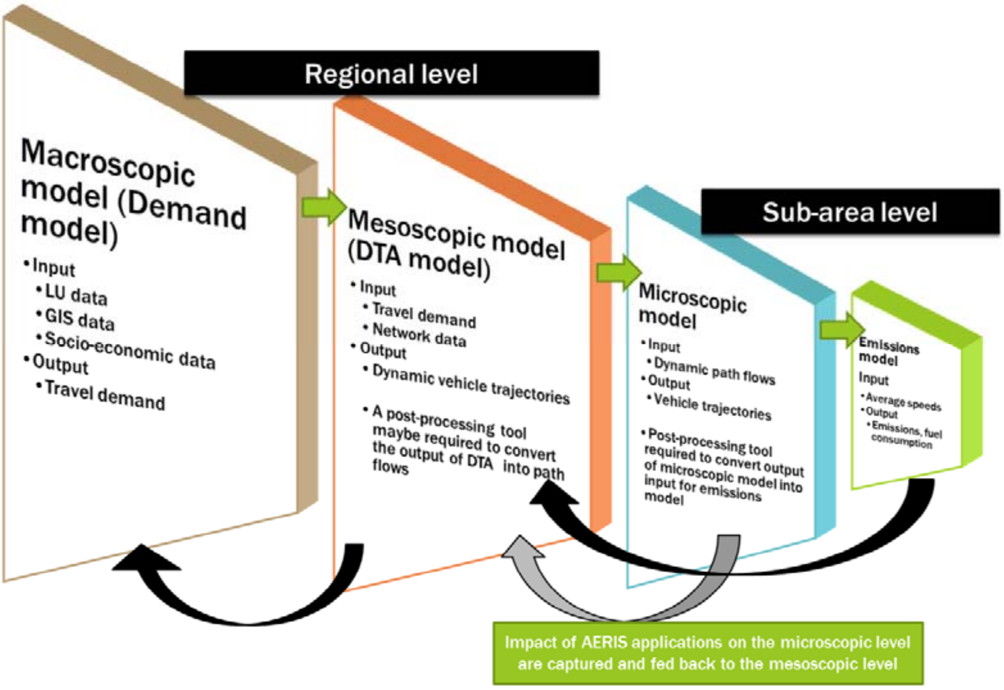

Fig. V.57 Overview of AERIS modelling structure (from [BAH 2012])

The overall approach is illustrated in Fig. V.57. On a macroscopic level, the demand model tries to capture the land-use and socio-economic characteristics that influence the travel demand. The DTA assignment that follows can generate dynamic vehicle trajectories. The speed profiles are not captured with the level of detail we require for AERIS applications by the DTA model, which is why a sub-area or specific facility microscale simulation is performed. The purpose of doing this is to obtain fine resolution spatio-temporal vehicle trajectories that are analysed by an emissions model to assess the environmental impact.

It is very important for these models to be integrated tightly in order to model AERIS applications. The outputs from the demand model are fed to the DTA model. The output of the DTA model are processed and fed to a smaller scale microscopic tool which in turn feeds the emissions model. There are four levels of integration involved:

1. The demand model is integrated with DTA model: The travel demand which is obtained in the form of dynamic OD matrices are input to the DTA tool.
2. Output from DTA model is fed to the microscopic tools: The output of the DTA tool is a set of vehicle trajectories. This data needs to be processed to generate path flows and input volumes for the microsimulation tool.
3. Output from microscopic tools is processed and input to the emissions model: The output of the microsimulation tool is speed profiles of individual vehicles. These need to be processed before they can be fed to an emissions tool, which outputs emissions and fuel consumption.
4. The extrapolated results from microscopic tool and emissions model are fed back to the DTA model. The DTA model needs to update routes as and when AERIS applications provide recommendations on alternate routes or the speed recommendations affect travel time which will indirectly influence route choice.
5. The DTA model also feeds back to the demand model to capture effects of AERIS applications that bring about changes in destinations or cancelling or rescheduling of trips. The OD matrices need to be updated to reflect these.

Based on the modelling approach, a set of modelling challenges have been identified:

1. The biggest challenge is the dynamic nature of the AERIS concepts: Need a multi-resolution model (macro, meso and micro), integrated demand and traffic assignment model with several feedback loops;
2. Model individual travelers at a fine-level of detail which will be very labor intensive at a regional level, which is why we are using a smaller sub-area for microsimulation;
3. Three levels of simulation need to be carried out: macro, meso and micro-simulation. Data flow between each of these should be carefully handled. For this reason, a flexible modelling framework that ties together all the models in a tight manner is being used;
4. It is very difficult to account for factors like the influence of external factors like road conditions. Appropriate assumptions can be made as required while modelling.

The modelling approach that is best for AERIS applications is a multi-tiered model with feedback loops that can dynamically capture the influence of AERIS applications at all levels of modelling.

Once the modelling is completed at a regional level, the results will need to be extrapolated to a national level. This will help determine the overall benefits of implementing AERIS applications from a national perspective. The general process is as follows: Initially unit benefits and costs are estimated for each application from the regional analysis. A baseline is then developed that provides the basic information for extrapolating the analysis to the nation. However, transportation and infrastructure characteristics vary widely from city to city (and urban versus rural) within the United States. To account for this variability, an extrapolation tool will be developed. The extrapolation tool has transportation-specific projections for a set of six “representative areas.” The extrapolation tool will take into account the differences in urban versus rural areas, large versus small cities, and very densely populated cities versus cities with larger footprints. The tool will be designed to derive a national estimate for benefits and costs taking into consideration the high variation in transportation infrastructure and driving behaviour in different types of locations in the United States without conducting an extensive - micro-simulation of individual cities, which would be both labor-intensive and expensive.

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CE-CERT, “CMEM: Comprehensive Modal Emissions Model”, see http://www.cert.ucr.edu/cmem/.

Appendix A: Inventory of Energy-saving ITS Applications

	Category	JPN Category	JPN Application	EU Application	EU Category
1	Improving driving behaviour	Eco-driving promotion	Promotion of eco-driving	Promotion of an energy-efficient style of driving	Driver Behaviour Change and Eco-Driving
			Support of eco-driving (information on fuel economy, diagnosis of driving, information on eco-route, etc.)	On-board assistance units to promote eco-driving	
			Support of idling stop		
			Vehicle maintenance (maintenance of tire pressure, engine oil)		
		Advanced Highway Cruising	Automated eco-driving		
			Air drag reduction by platooning		
			Intelligent cruise control （high functional adaptive cruise control）		

	Category	JPN Category	JPN Application	EU Application	EU Category
2	Energy-efficient traffic control for intersections and highway corridors	Intersection measures	Advanced traffic signal control（application of probes, application of signal information to vehicle control）		Traffic Management and Control
			Synchronized speed control for traffic signals	Plan based control, including ‘Green wave’ strategy	
				Isolated controlled intersections	
				Adaptive UTC with PT priority	
		Highway bottleneck measures	High efficiency utilization for lanes		
			Guiding low speed vehicles to climbing lane		
				Dynamic speed limits	
		Merging section measures	Merging support system		
		Toll gate measures	Electric toll gates	EFC Electronic Fee Collection	Demand and Access Management

	Category	JPN Category	JPN Application	EU Application	EU Category
3	Energy-efficient traffic management on a network scale	Dispersion of travel demand	Enhancement of route guidance information	Web-based pre-trip information services	Navigation and Travel Information
			Not to take wrong route	'Green' enhanced navigation services	
			Use of probe information	On trip routing via mobile devices	
			Forecast technology for optimum departure time	Dynamic on-trip routing	
			TDM support technology		
			Traffic violation vehicle detection technology		
				Ramp metering	Traffic Management and Control
				Restricted traffic zones (e.g. low pollution, low noise areas)	Demand and Access Management
		Measures for parking	Advancement of information system for parking lots	Parking/Loading /Delivery Management	Logistics and Fleet Management
			Guide to parking lots		
			Support of park & ride (parking lot reservation)		
			Violation vehicle pursuit （image recognition, vehicle ID）		
			Valet parking		
		Efficiency improvement after accidents	Detection of abnormal weather conditions	On-board accident prevention systems	Safety and Emergency Systems
			Advancement of emergency calls	Infrastructure based incident prevention systems	
			Emergency vehicle operation assist systems	Incident management systems	

	Category	JPN Category	JPN Application	EU Application	EU Category
4	Travel demand management	Load factor improvement	Advancement of priority traffic signal system		
			Automated vehicle connection and release		
			Joint delivery		
			Car sharing		
		Multimodal support	Enhancement of multimodal transfer information		
			Transit support		
			Promotion of person probes		
			Development of information infrastructure for ridesharing		
			IC card for transport		
			Next generation on-demand bus		
			Advancement of bus location system		
				EFC Electronic Fee Collection	Demand and Access Management
				Cordon pricing/Congestion	
				Pay-as-you-drive strategy	
				‘Carbon credit’ scheme	

	Category	JPN Category	JPN Application	EU Application	EU Category
5	Fleet management			Commercial Fleet Management services	Logistics and Fleet Management
				Automated Vehicle Management AVM + AVL systems	

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