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Kapsch TrafficCom

CONDUITS-DST

Further development of the CONDUITS

Key Performance Indicators

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Predictive assessment of urban mobility management and Intelligent Transport Systems using CONDUITS_DST

Report for Phase II of the CONDUITS-DST project

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Executive summary

In recent research (FP7 CONDUITS) a performance evaluation framework for urban traffic management and Intelligent Transport Systems (ITS) was developed. The framework consists of a set of Key Performance Indicators (KPIs) for the strategic themes of traffic efficiency, safety, pollution reduction and social inclusion, and as part of the FP7 CONDUITS project, it was validated with real-world case studies from four European cities.

Follow-up work within the context of the CONDUITS-DST spinoff project, sponsored by Kapsch TrafficCom, has concentrated on integrating the CONDUITS KPIs with traffic microsimulation. The outcome has been a predictive evaluation tool for urban mobility management and ITS, called CONDUITS_DST, in which each of the four KPI categories are progressively being integrated. Starting with the KPI for pollution, the tool was initially developed in Phase I of the CONDUITS-DST project, and a first validation task was conducted using a case study from the city of Brussels.

The present report summarises the outcomes of Phase II of the CONDUITS-DST project. This consists of a number of achievements, including the more comprehensive definition and elaboration of the methodological background of the CONDUITS KPIs, the further development of the CONDUITS_DST tool to incorporate the KPI calculation modules for traffic efficiency and traffic safety, in addition to the pollution module, and the testing of the approach and the tool in four real case studies in the cities of Brussels, Tel Aviv, Haifa and Stuttgart.

1 Introduction

Cities today share common transport problems and objectives with respect to urban mobility management, and put great focus on Intelligent Transport Systems (ITS). The market offers decision-makers a variety of ITS solutions, from which they are required to choose the most suitable and effective ones. Making this choice is a non-trivial task, however, especially given that transport problems are multi-dimensional by nature. Hence, a performance evaluation framework that addresses the various dimensions of transport problems, while at the same time reflecting the perspectives and priorities of decision-makers, is required [1].

In recent research work (FP7 CONDUITS) such an evaluation framework was formulated, consisting of a set of Key Performance Indicators (KPIs) for four strategic themes of urban mobility management: efficiency, safety, pollution reduction and social inclusion [2]. The KPIs were subsequently validated through before- and after- evaluation of real-world case studies in the cities of Paris, Rome, Tel Aviv and Munich, using real data supplied by the local authorities and transport operators [3-4]. Through the conduct of the case studies, it was concluded that the KPIs were easy to apply and required already available data, thus forming a very useful evaluation tool for assisting decision-makers in the field of urban mobility management and ITS, and to some extent for identifying best practice and lessons learnt elsewhere.

Yet the necessity for extending the CONDUITS framework from its current state of a tool for evaluating existing systems to a tool for evaluating future systems becomes apparent, given the current economic climate and the increasing need of making as informed decisions as possible. Follow-up work within the context of the CONDUITS-DST spinoff project, sponsored by Kapsch TrafficCom, has concentrated on integrating the CONDUITS KPIs with traffic microsimulation. The outcome has been a predictive evaluation tool for urban mobility management and ITS, called CONDUITS_DST, in which each of the four KPI categories are progressively being integrated.

The first version of CONDUITS_DST was developed in Phase I of the project, which was documented in the corresponding progress report [5]. This addressed the pollution aspect of traffic management, in the form of greenhouse gas emissions from vehicle traffic, and

included the implementation of the pollution reduction KPI in the tool and its preliminary testing in a case study from the city of Brussels. The present report summarises the outcomes of Phase II of the CONDUITS-DST project. This consists of a number of achievements, including the more comprehensive definition and elaboration of the methodological background of the CONDUITS KPIs, the further development of the CONDUITS_DST tool to incorporate the KPI calculation modules for traffic efficiency and traffic safety, in addition to the pollution module, and the testing of the approach and the tool in four real case studies in the cities of Brussels, Tel Aviv, Haifa and Stuttgart.

The report is structured as follows: Chapter 2 provides a comprehensive description of the methodological background of the study, namely the predictive evaluation framework, as adapted from the CONDUITS KPIs. Chapter 3 then goes on to presents the CONDUITS_DST software tool, concentrating on the advancements made from Phase I of the project. Chapter 4 describes the application of the framework and the tool in the four case studies in Brussels, Tel Aviv, Haifa and Stuttgart, and reports on the results obtained and the analysis performed. Finally, Chapter 5 summarises the conclusions of the study and identifies areas of future work.

2 Predictive evaluation methodology

Performance measures have the ability to effectively evaluate the outputs of specific solutions. However, when attempting to conduct a higher-level evaluation through a multi-dimensional benchmarking scheme comparing different cities with each other, performance measures are generally not suitable. The reason is that such a task necessitates the systematic and synthetic description of the cities' transport policies and infrastructures and the analysis of their impacts, which can only be expressed by a set of measures reflecting each individual scheme evaluated [6]. This issue creates difficulties in the communication of the results to non-technical audiences, such as politicians and the general public, and a common way to deal with it is to combine individual performance measures into composite performance indices (KPIs) [7-8].

The main advantage of KPIs is simplicity, as it is much easier to understand and grasp a single number rather than a large collection of individual measures, whose meaning often requires trained insight and careful analysis. The disadvantage, nevertheless, is that an aggregate number does not provide immediate insight into which aspects of the performance are changing or why, making it difficult to distinguish the sensitivity of an index to changes in its component measures. However, this ambiguity may lead to some other advantages. The index increases the opportunity for all modes and markets to be included, conveys the idea that each service is important, and elevates the discussion about how to best measure and report system performance. This cooperation between modes and sectors enhances awareness, broadens perspectives and leads to more comprehensive solutions.

In line with the European Commission's strategy on the future of transport, as presented in the 2001 and 2011 white papers [9-10], a performance evaluation framework was defined by the FP7 CONDUITS project, consisting of a set of measures and KPIs for the four strategic themes of traffic efficiency, traffic safety, pollution reduction, and social inclusion [2]. One of the innovative elements of the CONDUITS KPIs is their ability to consider the transport policy layer, in the sense that the evaluation of the suitability and effectiveness of different ITS options is calculated in relation to the decision-maker's high-level transport policy rather than objectively. In other words, the CONDUITS approach has the ability to capture the fact that a certain ITS option that may be beneficial to one city (or country) may not be as

beneficial to another, not because of the impact that it may have, but because it may not agree with the latter's high-level policy.

For example, an ITS option that delivers moderate benefits in terms of reducing particulate matter (PM) emissions but has great benefits in terms of improving traffic safety may not be the best solution for a city in which pollution reduction is a more important high-level policy objective than road safety. From a decision-maker's point of view this policy-awareness is invaluable, as it provides the means to present results to non-expert audiences (such as politicians) in a simple, fast and effective way. The policy layer is integrated in the CONDUITS KPIs through weighting factors, whereby more important policy objectives are weighted more heavily in the calculation.

And while application of the KPIs is fairly straightforward when it comes to evaluating existing applications given the availability of real before- and after- data, the evaluation of planned measures and ITS is more complex, as the after-data are not available. The objective of the predictive evaluation methodology proposed, hence, is to obtain the necessary data for input to the CONDUITS KPIs, which originate from microscopic traffic simulation models.

Table 1: Variables included in vehicle record files of PTV VISSIM

Variable	Description
[t]	Simulation second
[Link]	Link number
[VehNr]	Vehicle ID
[Type]	Vehicle type ID
[VehTypeName]	Vehicle type name
[WorldX]	Simulation network X coordinate
[WorldY]	Simulation network Y coordinate
[WorldZ]	Simulation network Z coordinate
[Grad]	Road gradient
[a]	Acceleration [m/sec ²]
[vMS]	Velocity [m/sec]
[DistX]	Distance travelled by car [m]
[IntacP]	The travel status of vehicle (free, following, stop)

Microscopic traffic simulation is an efficient tool offering a detailed reflection of the implementation of a traffic management or ITS measure of the mobility patterns in the transport network. The output of such a model is a so-called vehicle record file, which contains detailed information about the state of each vehicle in the network for each time point of the simulation period. Such information contains a number of attributes, including location coordinates, speed, acceleration, vehicle type and traffic condition, and can be subsequently segregated and aggregated with other mobility-related data on different

aspects of the network (nodes/links/routes) and different transport modes. A list of variables included in vehicle record file produced by the PTV VISSIM microscopic traffic simulation package is given in Table 1.

The data contained in vehicle record files can be readily input in some of the CONDUITS KPIs, but for others the required input data are not readily available, and need to be either processed, or coupled with another existing model (e.g. emissions model, such as COPERT or AIRE II, for pollution, or predictive accident model for safety). The next sections describe how this can be done for the three selected KPI categories among the full set of the CONDUITS framework. These include the pollution reduction KPI for environmental assessment, the mobility and reliability KPIs for traffic efficiency evaluation, and the accidents, direct safety impacts and indirect safety impacts KPIs for traffic safety assessment. For each of them, different weighting scenarios are also defined, so as to take into account the effects of different transport policies.

2.1 Predictive environmental assessment

The first area of predictive evaluation considered is the pollution aspect of urban mobility management and ITS in the form of pollutant emissions from vehicle traffic, and the relevant CONDUITS KPI is tackled.

2.1.1 The CONDUITS pollution reduction KPI

The CONDUITS pollution KPI is defined in [2] as the weighted sum of all distance-averaged emissions per vehicle and per vehicle type in the network, i.e.

$$I_{pol} = \frac{\sum_{VT} \sum_{ET} w_{VT} w_{ET} Q_{VT,ET}}{\sum_{VT} \sum_{ET} w_{VT} w_{ET}} \quad (1)$$

where I_{pol} is the value of the pollution reduction KPI (with smaller values indicating less pollution, and hence better performance), w_{VT} denotes the weighting factor for each vehicle type in the network (passenger car, motorcycle, bus, Heavy Goods Vehicle (HGV), etc.), w_{ET} is the weighting factor for each pollutant emission type, and $Q_{VT,ET}$ is the variable expressing the quantity of a certain pollutant emission from a certain vehicle type. It should be noted here that the three main categories of air pollutants are considered, namely carbon dioxide

(CO₂), nitrogen oxide (NO_x) and particulate matter (PM).

Depending on the type of evaluation, the data source of the $Q_{VT,ET}$ quantity varies. Specifically, in a before- and after- evaluation of an already realised/implemented ITS scheme, $Q_{VT,ET}$ can be obtained from actual pollutant emission data collected from the field through sensors. In the case of predictive evaluation of a proposed scheme, on the other hand, $Q_{VT,ET}$ can be calculated from the output of microscopic traffic simulation models (such as PTV VISSIM, PARAMICS or AIMSUN), combined with an appropriate pollutant emissions model (such as AIRE, COPERT or ENVIVER).

The values of the weights w_{VT} and w_{ET} are the policy-aware element of the KPI, and can be set by the decision-maker to reflect high-level policy objectives, as outlined next.

2.1.2 Overview of air pollution policy objectives

Road transport is widely recognised as a major contributor of adverse effects on the environment, with air pollution being an important global issue needing to be addressed, especially in urban areas. For this purpose, fairly strict standards and guidelines with respect to pollutant emissions have been adopted by the automotive industry, such that car manufacturers increasingly develop vehicles that avoid these emissions directly (e.g. electric and ultra-low emission vehicles). At the same time, pollutant emission threshold values have been adopted by governments and local authorities, which have been integrated in their high-level policy objectives, and with which any transport scheme (including ITS) is expected to comply. The focus here is on the policy objectives of three pollutants, namely CO₂, NO_x and PM, which are to be used in the determination of the weighting factors in Equation (1) in relation to the importance of each one.

Governments and environmental bodies provide regulations for air pollution under various classifications. Limit values are the maximum acceptable concentrations that are provided for the protection of human health, while threshold values are defined as the levels at which the public must be informed of high concentrations of pollutants. Target values are the ones that should not be exceeded within a given time period, whereas critical levels refer to concentrations above which direct adverse effects may occur on trees or natural ecosystems, but not on humans.

As from the point of view of urban mobility and ITS the effects of pollutants on human health are of most importance, the limit values for the three pollutants tackled as set by a number of different countries are considered, and are shown in Table 2. It should be noted that limit values given in ppm (parts per million) have been converted to $\mu\text{g}/\text{m}^3$ based on

the molecular weight of the respective pollutant. Also, as some limits are given as ‘24-hour’ values with a certain number of allowed exceedances, ‘annual’ limit values have been devised for comparison purposes.

Table 2: Pollutant emission limit values for different countries ($\mu\text{g}/\text{m}^3$)

Country	CO ₂	NO _x	PM
European Union [11]	810,000	40	40
USA [12]	810,000	99.74	12
Hong Kong [13]	810,000	40	50
Australia [14]	810,000	56.45	8
Thailand [15]	810,000	56.45	50

It can be seen from Table 2 that limit values for CO₂ are much higher than the other two pollutants. This is because CO₂ is a global pollutant rather than a local one, and therefore is not a direct concern to local air quality (and to human health) except when in very high concentrations. In fact, limit values for CO₂ only exist for indoor areas, and the only standard addressing CO₂ at the national level is the Kyoto Protocol [16], which foresees CO₂ percentage target reductions rather than actual limit values. However, given that common outdoor levels of CO₂ range between 350 ppm to 450 ppm, and that concentrations over 500 ppm usually suggest that a large combustion source is nearby [17], it is reasonable to adopt a value of 450 ppm (810,000 $\mu\text{g}/\text{m}^3$) as the equivalent CO₂ limit value for the purposes of this work.

2.1.3 Weighting methodology

Having gathered information on high-level policy objectives for the three pollutants in question (PM, CO₂ and NO_x), a method for setting the weighting factors in the corresponding CONDUITS KPI is devised here. Focusing of the emission type weighting factors (w_{ET}), the first step is to consider the relevant importance of the pollutants, which will give an indication of the order of difference between the weights. In this respect, if the severity of the effects on human health is considered, PM should be weighted as most important, while CO₂ should be assigned the lowest weight. Specifically, intoxication of the blood is the most important adverse effect of CO₂, and this occurs almost exclusively in enclosed areas rather than outdoors. This order of difference is additionally confirmed by the limit values of the three pollutants, as outlined in Table 2; since PM generally has the strictest limit value, its weight in the KPI should be highest.

Nevertheless, there is a further consideration that needs to be made with respect to the weighting factors of the pollutants, and this is the fact that there is an order of magnitude of

difference in the quantity of each pollutant emitted from traffic. For instance, Table 3 shows the total quantities of each of the three pollutants emitted from traffic on a road corridor in an urban area, as calculated using the AIRE emissions modelling tool in the initial CONDUITS_DST validation study [5]. It is evident that CO₂ dominates both NO_x and PM in terms of quantity (which is expected given that CO₂ is naturally present in the atmosphere as part of the earth’s carbon cycle), and also that NO_x dominates PM. In fact, it can be observed that the quantity of CO₂ is approximately 180.6 times higher than that of NO_x and approximately 4690.6 times higher than that of PM, and that the quantity of NO_x is approximately 25.97 times higher than that of PM.

Table 3: Pollutant quantities per vehicle type (mg) [5]

Vehicle type	CO ₂	NO _x	PM
Bus	190,160,226	5,503,500	140,620
Articulated bus	356,682	8,302	301
Car	2,155,459,269	5,277,315	314,706
HGV	135,273,041	2,951,044	73,357
TOTAL	2,481,249,218	13,740,161	528,984

As such, for the base scenario where the three pollutants are weighted as equally important to the decision-maker, the NO_x weighting factor (w_{NO_x}) should be approximately 180.6 times higher than the CO₂ weighting factor (w_{CO_2}), and the PM weighting factor (w_{PM}) should be 4690.6 times greater than w_{CO_2} and 25.97 times greater than w_{NO_x} . Taking a base value of $w_{CO_2} = 100$ for simplicity purposes, then the corresponding values for the other weighting factors will be $w_{NO_x} = 18060$ and $w_{PM} = 469060$; this is the base “unweighted” (UNW) scenario, where the weighting factors only balance out the order of magnitude differences between the pollutants.

Table 4: Pollutant weighting scenarios

	Scenario name					
w_{ET}	UNW	EU	USA	HK	AUS	TH
w_{CO_2}	100	100	100	100	100	100
w_{NO_x}	18,060	2,025,000	812,111	2,025,000	1,434,898	1,434,898
w_{PM}	469,060	2,025,000	6,750,000	1,620,000	10,125,000	1,620,000

Other weighting scenarios can be further defined on the basis of the pollutant emission limit values for the different countries, thus taking into account high-level policy objectives in that respect. These include the European Union (EU), USA, Hong Kong (HK), Australia (AUS) and Thailand (TH) scenarios and are shown in Table 4. It should be noted that while a base value of 100 is taken for w_{CO_2} , this is not restrictive, and different values could be used,

provided the values for w_{NOx} and w_{PM} are proportionally adjusted.

With respect to the weighting factors for the vehicle types (w_{VT}), these can be set as the inverse of the Passenger Car Unit (PCU) equivalent value of each type, as defined in Transport for London’s Traffic Modelling Guidelines [18]. It should be noted, though, that in the case of pollutant emissions, some vehicles, such as trams and bicycles, but also pedestrians, do not produce emissions, and are therefore assigned weighting factors of zero. The vehicle type weight values are shown in Table 5, while further vehicle type weighting scenarios are considered in the following sections, in relation to applications of traffic efficiency and safety evaluation.

Table 5: PCU equivalents and vehicle type weighting values

Vehicle type	PCU [18]	w_{VT}
Car	1.0	1.0
Bus	2.0	0.5
Articulated bus	3.2	0.3125
HGV	2.3	0.4348

2.2 Predictive evaluation of traffic efficiency

The second area of predictive evaluation considered is the traffic efficiency aspect of urban mobility management and ITS in the form of average travel time and congestion occurrences, and the relevant CONDUITS KPIs are tackled.

2.2.1 The CONDUITS traffic efficiency KPIs

A large number of urban mobility management and ITS applications aim at improving “traffic efficiency” – a term defined in different ways according to the closer scope of the application. A consolidation of those definitions in the CONDUITS project resulted in the definition of four KPIs for operational efficiency [2]: mobility, reliability, operational efficiency, and system condition and performance.

From the point of view of transport system operators, all KPIs are relevant to assess the full scope of the system’s performance, including not just the operational aspects, but also the quality provided to the customer. The first two KPIs target aspects of traffic efficiency that can be directly perceived by the customer and are therefore focussed on here.

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

A mobility KPI can be composed of different elements but essentially consists of the average travel time to different destinations in the private and public transport networks expressed in time units, normalised by the distance to the destinations, and weighted by importance according to the goals and objectives of the application under consideration. The mobility index, I_{MOB} , is defined in [2] as follows:

$$I_{MOB} = w_{PV} \cdot \frac{1}{|R_{PV}|} \sum_r \frac{ATT_{PV}^r}{D_r} + w_{PT} \cdot \frac{1}{|R_{PT}|} \sum_r \frac{ATT_{PT}^r}{D_r} \quad (2)$$

where r is a route (specific OD pair) among a set of selected R_{PV} and R_{PT} on the road and public transport network respectively, ATT_{PV}^r and ATT_{PT}^r are the average travel times for route r on the road and public transport networks, D_r denotes the length of route r , and w_{PV} and w_{PT} represent the weights of travel on the public transport and the road networks, and again represent the policy-aware element of the KPI.

As concerns reliability, this is another important function of transport systems, which expresses the ease of mobility. Since it is concerned with travel time variability, speed, system usage and system capacity, many reliability measures will come from the perspective of the suppliers of the modes and the infrastructure. A reliability index may, hence, be composed of different elements related to different modes of transport (e.g. public and private transport) and representing primarily the perspective of the suppliers who invest most of their efforts in reducing congestion hence providing better mobility.

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

$$I_{REL} = 1 - \sum_l \left(w_{PT} \cdot \sum_{pt} w_l \frac{CT_{pt}^l}{T_{w_l}} + w_{PV} \cdot \sum_{pv} w_l \frac{CT_{pv}^l}{T_{w_l}} \right) \quad (3)$$

where CT_x^l is the total congestion duration on link l in the “ x ” network, where $x=pt \in PT$ for public transport (e.g. bus, tram, ...) and $x=pv \in PV$ for the road (e.g. car, goods vehicle, motorcycle, ...) network, w_l denotes the relative importance of link l , w_{PT} and w_{PV} represent the weights of travel on the public transport and the road networks (and again are the policy-aware element of the KPI), and T_{wl} represents the examined period, in which congestion is monitored and to which w_l is attributed.

Elaborating more on the CT_x^l and T_{wl} values, the definition of what exactly constitutes a congestion occurrence can follow that adopted by the authority in question, but usually it relates to the difference between the free-flow travel time, TT_r , and the measured travel time, TT_m , for each route r of the network, to which link l belongs. The examined period, then, is the sum of the total measured travel times on all routes of the network, so:

$$CT_x^l = \sum_r (TT_m - TT_r) \quad \text{and} \quad T_{wl} = \sum_r TT_m \quad (4)$$

2.2.2 Weighting methodology

Introducing weights into the traffic efficiency KPI calculation helps stakeholders put different emphasis on the system’s effect on single modes or single mode groups. The weights may vary between different applications according to the goal of the evaluated urban mobility management or ITS measure and the local or high-level policy priorities. Table 6 introduces some examples for weighting scenarios, and the rationale behind these figures is explained next.

Table 6: Mobility and reliability weighting scenarios

w	Scenario name				
	Equality	PT priority	Space consumption	Sustainability	Pedestrian priority
Car	1	1	0.1329	1	1
HGV	1	1	0.0308	1	1
Bus	1	60	1.3846	50	5
Pedestrian	1	1	2.7778	50	20
Bicycle	1	1	0.3086	50	20

First, applications with a main focus on topics other than traffic efficiency might have a side-effect on efficiency nonetheless. There are also parts urban networks not facing significant saturation, and thus no mode has higher priority compared to others. For such cases the “Equality” scenario is proposed, in which all mode weights are set to 1. For certain

applications, however, such as priority at traffic signals, and in central urban areas where passenger volumes are highly bundled, a weighting strategy favouring public transport above other modes can be suggested, as portrayed by the “PT priority” scenario. The weight value of 60 derives from the average passenger load of a 12 m standard bus, but can be adjusted accordingly for longer vehicles and trams.

Further, central urban areas often face severe space problems forcing stakeholders to aim for a more efficient use of road space. It may be, thus, appropriate for applications in space-critical areas to weight the single modes according to the total space consumed per passenger on this mode. This leads to a higher weighting of low-capacity modes with low space consumption such as pedestrians, bicycles but also motorcycles, as well as public transport vehicles, as illustrated by the “Space consumption” scenario. The weighting of HGVs in this case is particularly low due to the large size of the vehicle carrying practically no passengers; this can be adjusted according to local policy for freight transport in the respective part of the network if necessary.

Then, assessing weights based on sustainability is less the result of mathematical calculation and more of political decisions in favour of environmental friendly modes – i.e. public transport and soft modes. In this case, a weight of 50 to 1 can be proposed as a means to receive a controllable KPI result, setting the importance of environmentally-friendly modes 50 times higher than the importance of motorised private modes, as portrayed in the “Sustainability” scenario. However, this value could be mathematically generated using, for example, the specific emissions per passenger of each mode.

Finally, for applications involving signal control (and especially green waves for cars or public transport), priority signals might have a negative side-effect on the traffic efficiency of pedestrians and cyclists. In certain areas of the network, mainly in central business and shopping areas, as well as near event venues showing high soft mode volumes, a different approach can be beneficial. A weighting as presented by the “Pedestrian priority” scenario can favour pedestrians and cyclists and still give buses a higher priority over motorised private vehicles.

2.3 Predictive evaluation of traffic safety

The third area of predictive evaluation considered is the traffic safety aspect of urban mobility management and ITS, and the relevant approach is described here.

2.3.1 The CONDUITS traffic safety KPIs

In the CONDUITS framework, safety is addressed through three indices, namely accidents, direct safety impacts and indirect safety impacts.

Starting from the accidents index, this relies on the quantification of the safety impact as the number of people injured or killed [19], and hence the main factors considered in the KPI are the ones influencing road injuries: exposure (the amount of travel), accident rate (the risk of accident per unit of exposure), and accident severity (the outcome of accidents concerning injuries). The accidents KPI is thus formulated as follows:

$$I_{ACD} = \sum_l \left(w_l \cdot \sum_{se} \left(w_{se} \cdot \sum_m \left(w_m \frac{ACD_{l,se,m}}{DTV_l} \right) \right) \right) \quad (5)$$

where I_{ACD} is the value of the accidents KPI (with lower values indicating lower accident impacts, and hence better performance), w_{se} denotes the weighting factor representing the importance of reducing the number of casualties in accidents with a specific severity se from the set of possible severity levels (uninjured, slightly injured, seriously injured or killed), w_m is the weighting factor representing the importance of reducing the number of casualties in accidents involving a specific traffic mode m from the set of possible traffic modes (car, truck, bus, motorcycle, bicycle, pedestrian, etc.), w_l is the weighting factor representing the importance of link (or junction) l among the set of links (and junctions) of the network in terms of safety, $ACD_{l,se,m}$ is the number of casualties of severity se involving users of mode m on link l on an average day, and DTV_l is the daily traffic volume on link l in million vehicles.

Moving onto the direct safety impacts index, this quantifies the safety impact as the number of actions/interventions taken by systems or users, which have the objective of averting a safety-critical situation; these include, for example, vehicle braking occurrences by drivers, or collision warning events by vehicle-based systems. The direct impacts KPI is thus formulated as follows:

$$I_{DS} = \sum_l \left(w_l \cdot \sum_m \left(w_m \frac{INTERV_{l,m}}{DTV_l} \right) \right) \quad (6)$$

where I_{DS} is the value of the direct safety impacts KPI (with lower values indicating lower safety impact, and hence better performance), $INTERV_{l,m}$ denotes the number of

actions/interventions for mode m on link (or junction) l on an average day, while w_l and w_m are the weighting factors representing the importance of mode m and link l in the network, and DTV_l is the daily traffic volume on link l in million vehicles.

Finally, for the indirect safety impacts index, this considers the total duration of critical occurrences/situations, which are not necessarily a result of users avoiding a safety hazard, but which can be associated with an adverse safety impact as a side-effect. These include, for example, exceedance of the speed limit, or instances of traffic flow breakdown on motorways. The indirect safety KPI is thus formulated as follows:

$$I_{IS} = \sum_l \left(w_l \cdot \sum_m \left(w_m \frac{CS_{l,m}}{T} \right) \right) \quad (7)$$

where I_{IS} is the value of the indirect safety impacts KPI (again with lower values indicating lower safety impact, and hence better performance), CS_l denotes the total duration of critical occurrences/situations on link l , w_l and w_m are the weighting factors representing the importance of mode m and link l , and T is the total time of observation.

As in the case of pollution and traffic efficiency, and depending on the type of evaluation, the data sources of the ACD , $INTERV$ and CS input quantities to the KPIs vary. Specifically, in a before- and after- evaluation of an already realised/implemented scheme, the values can be obtained from actual data collected from the field. In the case of predictive evaluation of a proposed scheme, on the other hand, the values can be calculated from the output of microscopic traffic simulation models (such as PTV VISSIM, PARAMICS or AIMSUN). Naturally, this only relates to the $INTERV$ and CS quantities, as ACD would not be available before implementation of the scheme. The values of the weights w_l , w_{se} and w_m are the policy-aware element of the KPIs, and can be set by the decision-maker to reflect high-level policy objectives, just like in the case of the pollution and traffic efficiency KPIs.

2.3.2 Brief overview of traffic safety impact assessment measures

A range of safety impact assessment measures have been developed, with the primary objective of assessing the road safety condition and helping to define appropriate transport management solutions to current problems. However, these measures can also be used for safety performance assessment of implemented transport applications.

The European Transport Safety Council defines transport safety performance measures as “any measurement that is causally related to crashes or injuries, used in addition to a count

of crashes or injuries in order to indicate safety performance or understand the process that leads to accidents” [20]. However, using the counts of accidents or injuries is usually insufficient to represent transport safety as a whole, due to a number of limitations. For example, the number of crashes or injuries depends on probability fluctuations of random events, and this implies that the underlying, long-term problems cannot necessarily be revealed by short-term recordings. Also, hazardous situations that did not cause an accident are often not recorded as near-miss incidents [21]. Instead, the use of wider safety performance measures can indicate risky problems at an early stage (before accidents happen) and allows to distinguish systematic improvements from random fluctuations.

In most countries, road user behaviour and road and vehicle engineering characteristics are employed to describe road safety performance. With respect of road user behaviour, commonly used safety performance measures include [20]:

- Speeding, with respect both to mean speed, variance, and speed limit violations;
- Percentage use of seat belts and child restraints;
- Percentage use of crash helmets;
- Incidence of drinking and driving;
- Failure to stop or yield at junctions or at pedestrian crossings;
- Inadequate headways – close following;
- Use of daytime running lights;
- Use of reflective devices, especially for cyclists and pedestrians; and
- Use of pedestrian crossing facilities (by pedestrians).

Many of these safety performance measures have formed the basis of various predictive safety models, which have been developed and tested both in simulation and real-world environments. For example, speed is one of the key parameters necessary to calculate time-to-collision, a fundamental variable in traffic conflicts models (e.g. the Swedish Traffic Conflicts Technique [22]). Speed is also the basis of Nilsson’s power model [23], which predicts changes in accident rates as a function of average speed changes. Alternatively, car-following behaviour with shorter headways than what is considered safe is commonly viewed as a near-accident situation and hence a safety risk, and is used in various models.

Most existing applications of such models focus predominantly on a particular phenomenon or localised case study rather than on a comprehensive assessment of performance of the network or parts thereof in terms of safety. Still, many such measures can be used in conjunction with the CONDUITS safety KPIs, as they can provide the input necessary for their computation. This is tackled next.

2.3.3 Predictive traffic safety evaluation methodology

The data contained in vehicle record files of microscopic simulation models can be readily input in the CONDUITS KPIs for traffic efficiency. Coupled with an appropriate emissions modelling tool (such as COPERT or AIRE II), appropriate input data for the KPIs for pollution can also be derived. In the case of safety, though, the required input data are not readily available, and need to be either processed, or coupled with another existing predictive safety model. The next paragraphs describe how this is done for the three KPIs presented.

Starting from the accidents index, and as accident numbers are not output from microscopic traffic simulation models, it is necessary to identify a proxy, which can be used as input to the relevant KPI in equation (5). The selected measure here is the average speed. In fact, it is recognised that driving speed plays an important role in road traffic safety measurement, as higher driving speed provides less time to respond to emergencies for both drivers and pedestrians, and as high speed injects additional momentum, increasing the severity of accidents [24]. It has been reported that excess and unsuitable speeds are responsible for a high proportion of road accidents and contribute to about one third of fatal crashes and 12% of all road crashes as main crash causal factors [25].

Looking in more detail at the relationship between speed and accidents, various empirical studies have suggested that that for every increase of average speed by 1 km/h, the number of accidents is likely to increase 3-4%, with more significant impacts found for serious accidents. Conversely, every 1 km/h of reduction in the average driving speed leads to a 5% decrease of the number of fatal accidents [20, 25]. A more formal expression of these findings is proposed by Nilsson's power model [23], which relates average speed changes with the number of crashes by severity (Table 7).

Table 7: Nilsson's power model relating accidents with speed changes [23]

Speed measure for accidents and injuries prediction	
Accidents (y)	Injured (z)
Fatal accidents	Fatalities
$y_1 = \left(\frac{v_1}{v_0}\right)^4 y_0$	$z_1 = \left(\frac{v_1}{v_0}\right)^4 y_0 + \left(\frac{v_1}{v_0}\right)^8 (z_0 - y_0)$
Fatal and serious injury accidents	Fatalities and severe injuries
$y_1 = \left(\frac{v_1}{v_0}\right)^3 y_0$	$z_1 = \left(\frac{v_1}{v_0}\right)^3 y_0 + \left(\frac{v_1}{v_0}\right)^6 (z_0 - y_0)$
All injury accidents	All injuries (including fatalities)
$y_1 = \left(\frac{v_1}{v_0}\right)^2 y_0$	$z_1 = \left(\frac{v_1}{v_0}\right)^2 y_0 + \left(\frac{v_1}{v_0}\right)^4 (z_0 - y_0)$
Where y_0 (z_0) is the initial number of accidents (injuries) before the speed change, y_1 (z_1) is the number of accidents (injuries) after the speed change, and v_0 and v_1 are the before and after average speed.	

Nilsson's power model is a suitable method for generating input for the CONDUITS accidents KPI on the basis of microscopic traffic simulation, as it relates accident numbers with traffic characteristics (left column of Table 7). However, it relies on the fundamental assumption that reliable initial accident numbers, differentiated by type, are known, which is, however, rarely the case, as such data are often either not available at all, or statistically insignificant. As such, it is very likely that the KPI of equation (5) cannot be computed as an absolute value. Instead, it is proposed calculating the CONDUITS KPI for accidents in relative terms, i.e. as

$$\Delta I_{ACD} = \frac{I_{ACD,0} - I_{ACD,1}}{I_{ACD,0}} \quad (8)$$

where ΔI_{ACD} is the improvement (positive) or deterioration (negative) in terms of accidents, and $I_{ACD,0}$ and $I_{ACD,1}$ are the values of the accidents KPI before and after the change in average speed respectively. It should be noted that although the y_0 term is not known, it cancels out in equation (5), and therefore the calculation of ΔI_{ACD} is possible.

Moving on to direct safety impacts, these include actions/interventions taken by systems or users, which have the objective of averting a safety-critical situation, and the selected measure in this category is vehicle deceleration, which corresponds to vehicle braking occurrences. In fact, acceleration and deceleration are important properties of vehicle performance and usually lead to accidents when vehicles start and brake suddenly without sufficient safety distance [26], and hence significant changes in acceleration and deceleration are empirically considered as responses to emergency situations and indicators for rear-end collisions. For instance, studies have suggested that deceleration, which usually refers to the braking rate, is closely related to the severity of accidents [27].

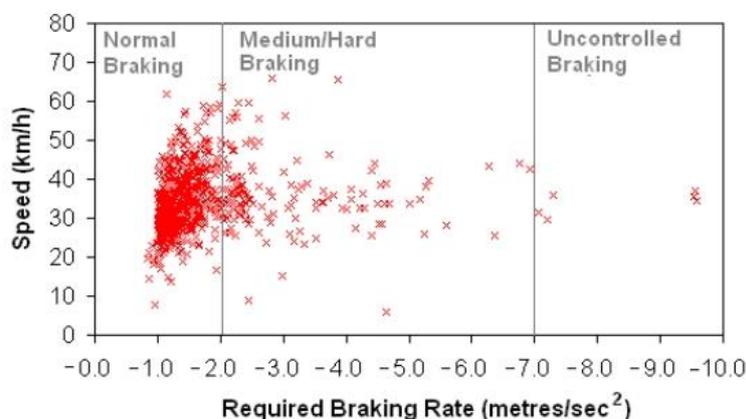


Figure 1: Severity of accident risk based on braking rate (deceleration) [27]

Using the categorisation of [27], shown in Figure 1, the deceleration allocated in the “uncontrolled” braking zone represents a high risk level of accidents, while the “medium/hard” zone implies a less severe accident risk. “Normal” braking behaviour can be regarded as non-accident-causing in terms of deceleration. The number of occurrences of uncontrolled braking (more than 7 m/s^2), or “abnormal” (more than 2 m/s^2) is available from microscopic traffic simulation and can, hence, be used as input in the direct safety impacts KPI of equation (6). However, it should be noted that the braking behaviour is also heavily influenced by the vehicle characteristics, and hence the calculation should be differentiated by mode (car, bus, HGV, etc.) and then aggregated with appropriate weighting factors in the KPI if desirable.

Finally, as concerns indirect safety impacts, these consider the total duration of critical occurrences/situations over the total duration of the period of observation. The situations considered are the ones which are not necessarily a result of users avoiding a safety hazard, but which can be associated with an adverse safety impact as a side-effect. The selected measure in this category is the speeding rate, i.e. the frequency of exceedance of the speed limit. Speeding behaviour is, in fact, one of the most commonly used indicators illustrating the relationship between driving behaviour and road safety, but it does not involve an action aimed at averting a safety hazard, so it is an appropriate measure for this category of safety impact.

The speeding rate can be extracted directly from the vehicle record files of microscopic traffic simulation packages, as the total time of exceedance of the speed limit (usually 50 km/h in urban areas) in vehicle-hours over the total time of observation, also in vehicle hours. This provides the values of the necessary CS and T input variables of the indirect safety impacts KPI of equation (7). The calculation can also be performed in a stratified manner disaggregated by mode, and the result can then be aggregated using appropriate weights in the KPI.

3 The CONDUITS_DST software

Based on its flexibility for the sources of the data used to calculate the KPIs, the CONDUITS evaluation methodology enables the assessment of real-life performance and impacts, but also the estimation of expected performance and impacts of traffic management measures and ITS. Concentrating on the latter, the procedure followed for predicting the potential impact of new traffic management and ITS applications combines real-life measurements on one hand, and the simulation of alternative scenarios on the other.

One of the most common transport modelling tools used for pre-deployment analysis is the PTV VISSIM microscopic simulator. This tool has the ability to estimate the likely impacts of ITS measures on mobility patterns and, as a consequence, the traffic-generated emissions. And while the first stage of the CONDUITS-DST project [5] focused on the development of the overall interface and the integration of the pollution KPI in a dedicated module of the CONDUITS_DST software, the second phase expands CONDUITS_DST and adds the modules of traffic efficiency and traffic safety, hence enabling the step forward from the one-dimensional to the multi-dimensional analysis of traffic management and ITS solutions.

The present chapter gives a brief overview of the structure of CONDUITS_DST and outlines some of the key functionalities added during the second stage of the development.

3.1 CONDUITS_DST structure

The CONDUITS_DST software is a specialised tool working as an additional module to microsimulation software packages, such as PTV VISSIM. The tool selects and aggregates relevant output data from simulation models and uses it as input to the calculation of the KPIs, as outlined in Chapter 2.

The structure of CONDUITS_DST and the flow of information between its individual components are illustrated in Figure 2, with the integrated components lying within the relevant box and the third-party components being located outside. As can be seen, CONDUITS_DST obtains the output of third-party traffic simulation tools in the form of links data and vehicle record files, and after performing some data aggregation operations, it

calculates the values of the efficiency, pollution and safety KPIs.

For the special case of pollution, CONDUITS_DST employs the AIRE model. AIRE is an ancillary software tool, provided courtesy of Transport Scotland, specifically designed to process the outputs from microscopic traffic simulation models and calculate vehicle emissions. Although a third-party software, it is fully integrated and interfaced with CONDUITS_DST and is therefore represented by the shaded rectangle to the right of Figure 2.

An important feature to note here is the transferability of CONDUITS_DST, as this is not bound to any particular microscopic traffic simulation platform and can work equally well with available modelling tools providing vehicle logs, such as PTV VISSIM, PARAMICS, etc. For instance, in the case of pollution, the AIRE tool has been specifically designed to be used directly with outputs from PARAMICS. CONDUITS_DST, however, incorporates a functionality that modifies the vehicle record files generated by VISSIM to meet the requirements set by AIRE (and hence matching those of PARAMICS). As such, it enables the calculation of emissions (and hence KPIs) regardless of the initial software used.

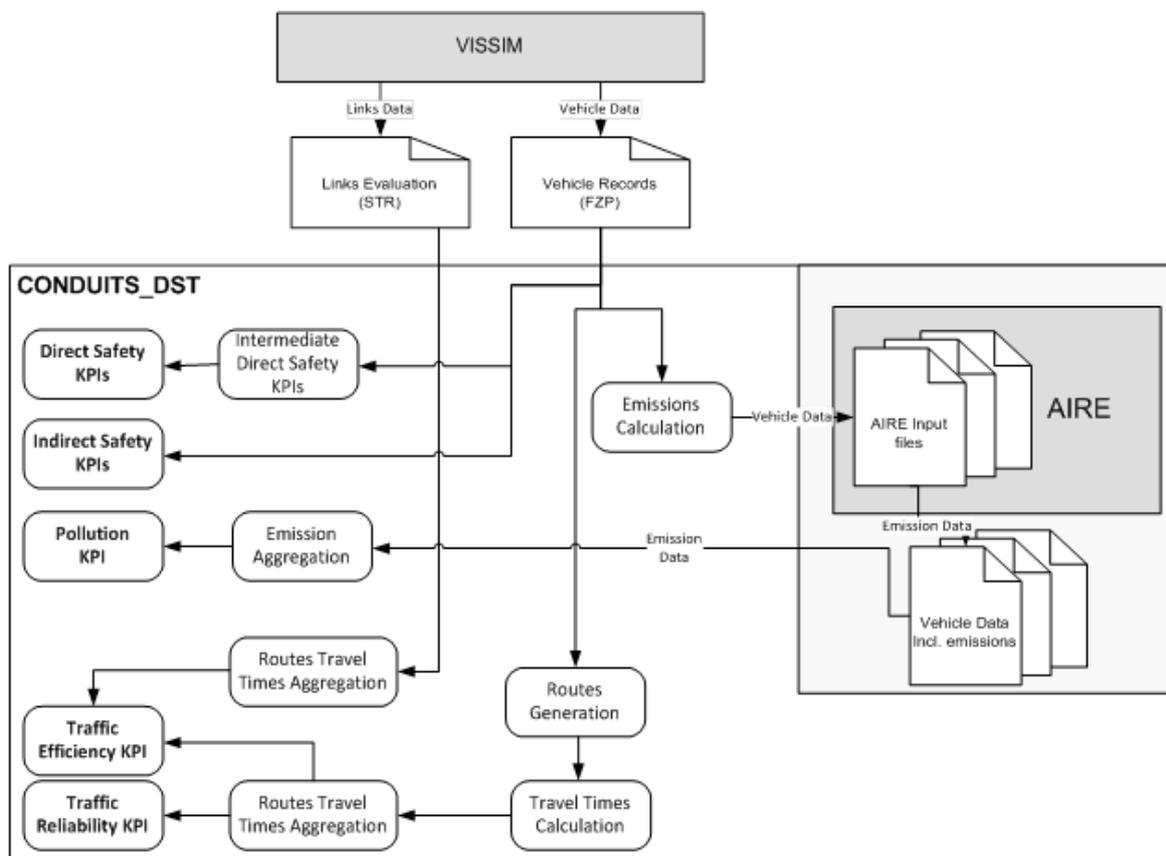


Figure 2: CONDUITS_DST architecture

3.2 Key new or enhanced components

This section outlines the key new components of CONDUITS_DST, added during Phase II of the development. These include the route generator, the seed aggregator, and KPI calculator and the reporting module.

3.2.1 Route generator

Focusing on the case of the traffic efficiency KPIs, their values are based on route-related measurements rather measurements made at specific points as listed in the vehicle record file output by traffic simulation software. It is, hence, the job of the route generator module to transform the instantaneous measurements at specific points to accumulated measurements along routes.

The fact that traffic simulation software generates a finite number of vehicles for a single simulation run and that vehicle identification numbers do not repeat themselves in a single run, it is possible to drastically reduce the route generation time by using an auxiliary function that retrieves variable values from a given record, under the assumption of a maximum vehicle identification number. This can be assumed to be no higher than the total number of vehicles (for all modes, including pedestrians) entering the model.

```
For RecordNum = StartRecord to EOF ' EOF of the VISSIM vehicle log file
  DO RecordBreake `this procedure retrieves the values of
    the needed variables from the vehicle log record

    If CA(CarID,0)=0 then CA(CarID,0) = t
  Else
    CA(CarID,1) = t
  End if

  CA(CarID,2) = DistX
  CA(CarID,3) = VehType
  CA(CarID,4) = VehTypeName

  If CA(CarID,6) <> LinkID then
    CA(CarID,5) = CA(CarID,5) & LinkID
    CA(CarID,6) = LinkID
  End if

End RecordNum
```

Figure 3: CONDUITS_DST route aggregator

The route generation algorithm uses the CA (X,7) that holds the vehicle data (StartTime-0,

EndTime-1, DistX-2, VehType-3, VehTypeName-4, Route-5, LastLink-6) and is detailed in Figure 3.

At the end of the procedure, the CA array is compacted and includes the routes, the distance travelled, and the travel time of each vehicle in the network. Hence, the calculation of the travel time of each mode on each of the routes can be easily derived. Using this fairly short algorithm, it is possible to generate the routes and route-related data of a 1.7GB vehicle record file in just few seconds on a common PC.

3.2.2 Seed aggregator

Valuable simulation results rely on the aggregation of many simulation runs with different seeds, and so CONDUITS_DST allows for more than a single mutation (seed) to be used to generate the input required by the KPIs using a seed aggregator. The role of the seed aggregator (Figure 4) is to collect and harmonise the measurements, either as calculated by the route generator (for traffic efficiency), or by the integrated AIRE tool (for pollution), or as directly measured by the traffic simulation platform during the runs. As each simulation run may include more than a single time frame, the aggregation is executed to each of the defined time frames separately. In doing so, the results generated by the tool enable easy comparison between different simulation runs and scenarios, as well as the evaluation of KPI trends over time.

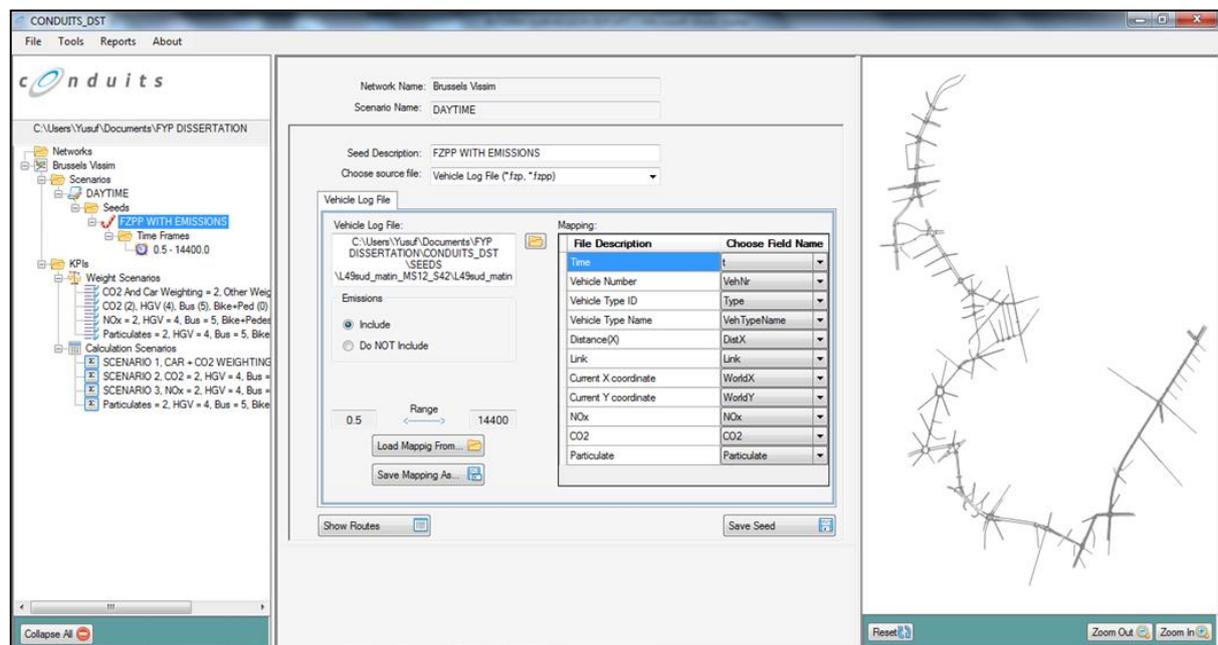


Figure 4: CONDUITS_DST seed aggregator

3.2.3 KPI calculator

The KPI calculator module allows for the calculation of the three KPI categories for traffic efficiency, traffic safety and pollution reduction, as outlined in Chapter 2. First, it allows for the user to set the weights for each of the KPIs through a dedicated interface, as shown in Figure 5. The user can set the weight values for the relevant decision variables in each KPI (e.g. pollutant emission quantities in the pollution KPI), as well as the ones relating to the geographical characteristics of the network (e.g. different links and junctions, depending on their importance).

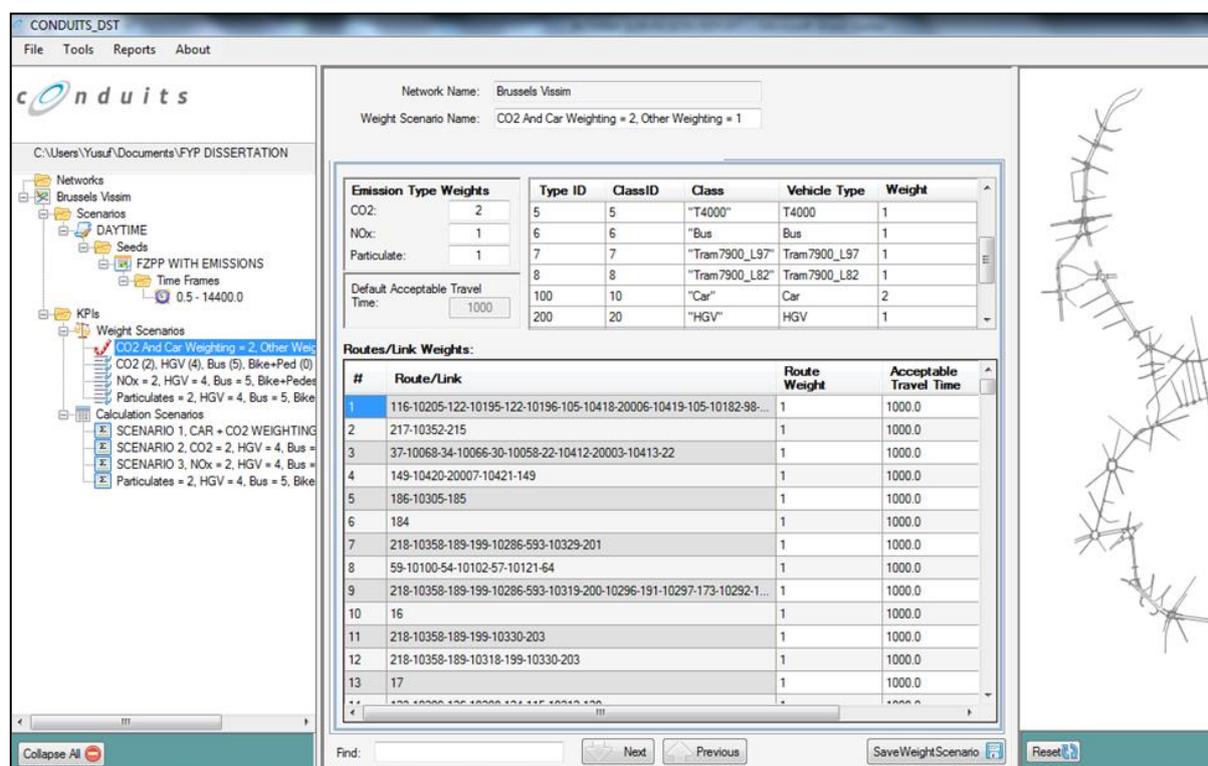


Figure 5: CONDUITS_DST KPI calculator – weighting

The KPI calculator then enables the calculation of the KPIs on the basis of different seeds and weighting scenarios, and taking the relevant decision variables from the simulation model. For instance, for the pollution KPI, the pollutant emissions values are used in the calculation of the pollution KPI, while the average travel time and the total duration of congestion are considered in the calculation of the traffic efficiency KPIs, as defined in equations (2)-(4). For traffic safety, the values of average speed, critical braking occurrences and speed limit violations are taken. Figure 6 shows the interface of the KPI calculator module for the example of the pollution KPI.

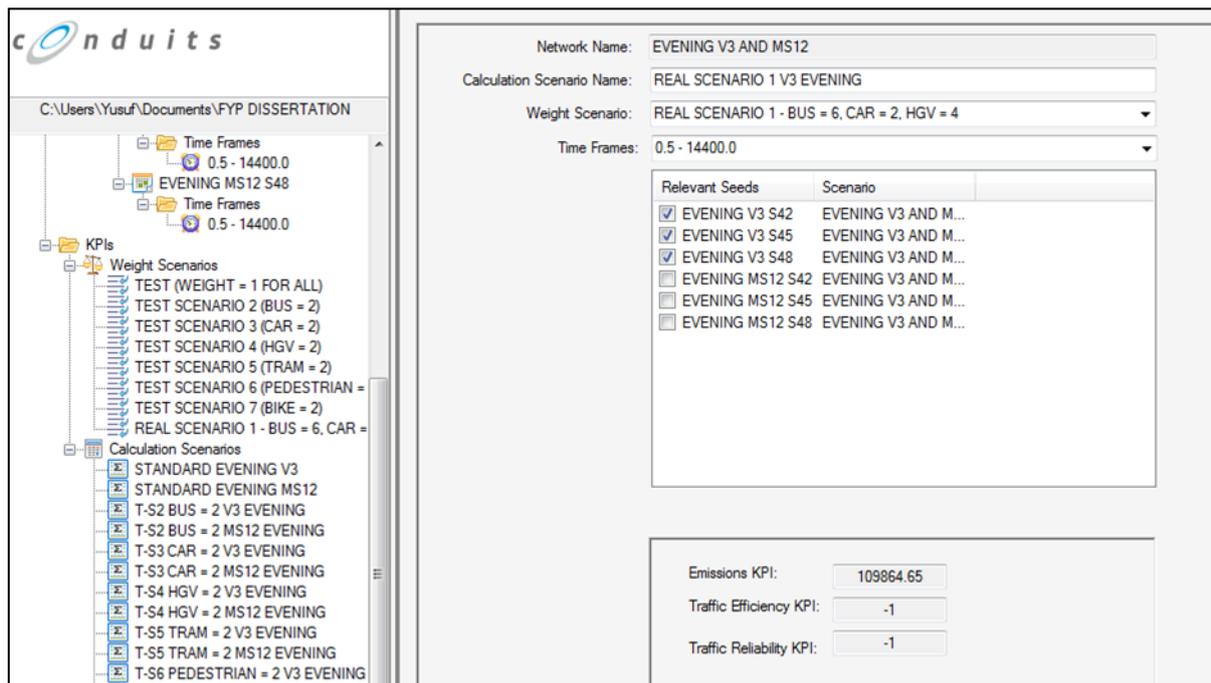


Figure 6: CONDUITS_DST KPI calculator

3.2.4 Reporting

CONDUITS_DST includes a basic reporting tool (Figure 7), allowing for the presentation of the results in the form of tables and figures. However, as the data generated, along with elementary definitions and results, are stored as XML files, the tool enables to export this data to MS Excel spreadsheets or other data analysis packages for further processing. Alternatively, the user has the option of performing the analysis himself/herself by hand or through purpose-developed tools.

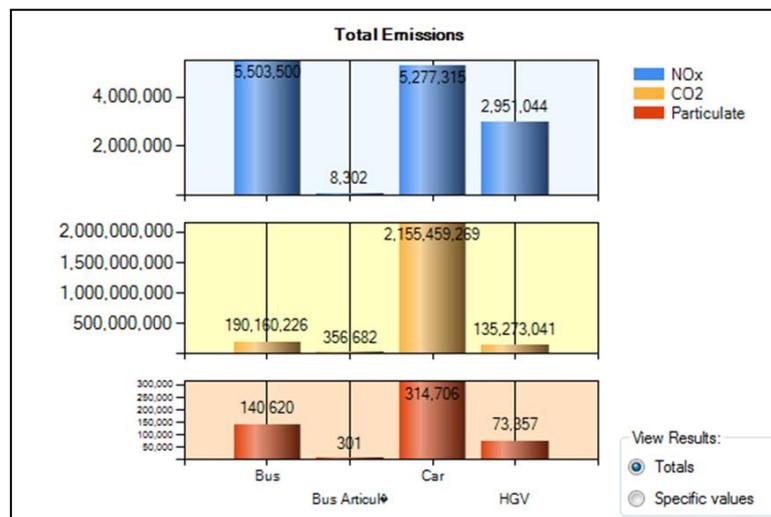


Figure 7: CONDUITS_DST reporting interface for pollution

4 Application case studies

The predictive evaluation framework for urban mobility management and ITS developed within the CONDUITS-DST project and implemented in the CONDUITS_DST software is validated by means of real-world case studies, supplied by city authorities themselves. The purpose of the validation stage is to assess the applicability of the method, the usability of the tool by decision-makers, and the plausibility of the results.

The application process and development of the tool are overlapping processes, such that the initial calculation runs – still providing statistically uncertain results – are used to gain valuable experience with running the software in different technical environments and in countries with different metric systems. This insight is then immediately used to improve the tool and to make it more robust for its dissemination to any public authority interested in its use.

Three case studies have been carried out in the cities of Brussels, Tel Aviv, Haifa and Stuttgart. In Brussels, the environmental and safety assessment evaluation methods are applied, while in Tel Aviv, Haifa and in Stuttgart the evaluation focuses on environmental assessment and traffic efficiency.

4.1 Application in Brussels

The first case study is provided by the Brussels-Capital Region, where a large-scale public transport priority programme is being planned and implemented. The major goal of the programme is the reduction of travel times by increasing the operational speed and by reducing delays around signalised junctions using priority signals for public transport vehicles. The details of the case study and of the predictive impact assessment carried out in terms of pollution and safety are given next.

4.1.1 Case study description

Following the EU directive and the high interest of the Brussels-Capital Region to provide a better quality of life to its citizens, the city authority has been constantly seeking for ways to

deliver a more efficient transport system on one hand, but a less polluting one on the other. One of the measures pursued involves increasing the share of public transport in the modal split, which requires making it more competitive compared to motorised private transport. With an already dense public transport network (70 public transport lines with a total length of more than 700 km), though, any improvements must be based on the existing system.

One of the means to introduce a more competitive public transport system is by reducing travel times. To achieve that, the Brussels-Capital Region has introduced a program aiming at increasing the operational speed of most of its public transport lines. The program focuses on reducing delays around signalised intersections by giving priority to public transport vehicles over other traffic. This strategy promotes the attractiveness of public transport, both in the short- and the long-term, by offering lower travel times; however, it is also likely to have an undesired side-effect of increased pollution levels from traffic, especially in the short-term, due to increased waiting (idle) times and more stops and accelerations by private transport vehicles. It is also interesting to see whether the strategy also has any negative impacts in terms of safety.

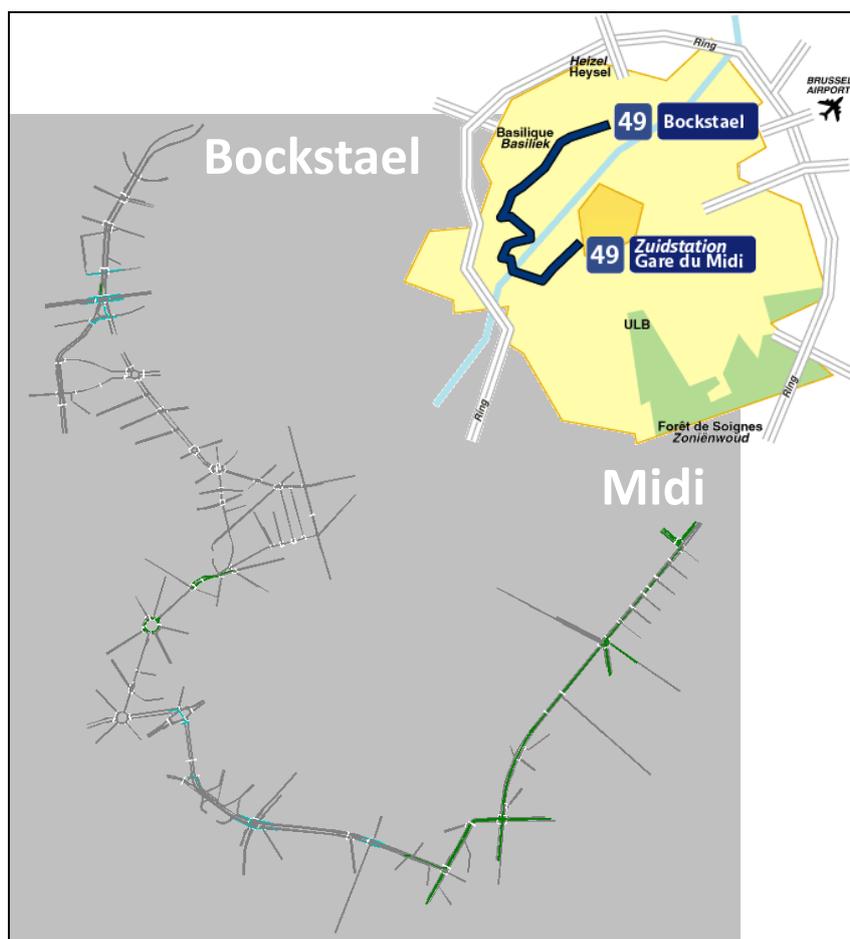


Figure 8: Line 49 and simulation network for the Brussels case study

These side-effects are evaluated using CONDUITS_DST, in conjunction with relevant high-level policy objectives. More specifically, the prospective pollution and safety impacts of the introduction of priority signals along bus line no. 49 are analysed, taking into account the policy objectives. The study consists of four cases, representing the states before and after the implementation of the system in the morning and evening peak periods, respectively. From the planning phase of the signal control a calibrated VISSIM simulation network has been developed for all four cases (Figure 8).

4.1.2 Environmental assessment

Several simulation runs are carried out over an evaluation period spanning three hours in the respective peak, extracting the necessary input data for the pollution KPI calculation in CONDUITS_DST. For each set of runs, the KPI calculation is carried out using each of the six pollutant weighting scenarios shown in Table 4, and the vehicle type weighting factors of Table 5.

Table 8 shows the results of the KPI calculation for pollution in the four peak periods before and after the implementation of the priority measures, for each of the pollutant weighting scenarios, i.e. UNW, EU, USA, HK, AUS and TH. As can be immediately observed, the values for the after-case are higher than the before-case across all six weighting scenarios. Table 9 shows the corresponding percentage increase for each case and weighting scenario, where this finding is confirmed, as KPI increases of 6-9% and of 4-5.8% are observed for the morning and evening cases respectively. A brief comparison with other indicators of the simulation, such as the number of stops and delay times, both for private and public transport, confirm this outcome. The results, hence, show that, while public transport observes a decrease of 20-60% in the number of stops and an increase of the average speed of 3-6%, car drivers experience an increase of their journey time, along with an increase in the pollution levels.

Table 8: Pollution KPI values for each scenario (equivalent emissions units)

Scenario	UNW	EU	USA	HK	AUS	TH
Morning before	258.79	1373.36	368.93	1515.88	409.96	1299.00
Morning after	274.39	1498.49	397.98	1654.64	443.00	1416.88
Evening before	302.43	1562.24	420.99	1724.20	467.46	1478.00
Evening after	315.13	1647.12	441.48	1818.23	490.60	1558.09

Table 9: Percentage change in the pollution KPI values

Scenario	UNW	EU	USA	HK	AUS	TH
Morning before	+ 6.0%	+ 9.1%	+ 7.8%	+ 9.2%	+ 8.0%	+ 9.0%
Morning after						
Evening before	+ 4.0%	+ 5.4%	+ 4.8%	+ 5.4%	+ 5.0%	+ 5.4%
Evening after						

Considering the percentage increase of the KPI between the different weighting scenarios, it can be clearly observed that the policy-aware KPI values (i.e. the ones based on the limit values of different countries) are higher than the respective increase in the UNW scenario (i.e. where pollutants are considered as equally important). This can be largely attributed to the fact that the PM and NO_x emissions are considered as more important by the authorities of the different countries and, as such, figure more prominently in their high-level policy objectives. In practical terms, this means that the foreseen “objective” 4-6% increase in pollution as a result of the implementation of the scheme may actually correspond to more severe increases from the point of view of decision-makers.

A further observation that can be made is that four-digit KPI values are obtained for the EU, HK and TH weighting scenarios, while the USA and AUS ones are three-digit and closer to the UNW scenario values. This can be explained by the fact that the USA and Australia appear to have less strict legislation with regard to NO_x and PM emissions compared to the EU, Hong Kong and Thailand. Practically speaking, this means that the same ITS scheme or solution will have different perceived impact severity by decision-makers in different countries as a result of the different high-level policy objectives. In other words, a scheme’s adverse impacts may be acceptable in one city or country but unacceptable in another one, purely due to alignment or non-alignment with policy objectives respectively, which is exactly what the weights are supposed to capture.

4.1.3 Traffic safety evaluation

The necessary input data for the three safety KPIs can be directly extracted from the vehicle record files. The evaluation follows a two-stage process, where at first it is conducted at the network level using each of the three KPIs, and then the same procedure is followed for four individual selected network links, so as to demonstrate applicability of the approach in both conditions.

Starting from the network-level evaluation, and using equation (8) the value of ΔI_{ACD} is calculated as the improvement (positive) or deterioration (negative) of safety performance

in terms of accidents. The calculation is carried out separately for the three different accident severity categories (fatality, serious injury, minor injury), which are then aggregated using the weights employed in [3], i.e. $w_{fat} = 0.85$, $w_{sinj} = 0.10$ and $w_{minj} = 0.05$ for fatalities, serious and minor injuries, respectively. The calculation is also carried out separately for the different traffic modes (car, HGV, bus, other public transport), so as to get a better mode-specific insight into the impacts.

Table 10: Accidents KPI change between before- and after-evaluation

ΔI_{ACD}		Fatality	Serious injury	Minor injury	TOTAL
Car	Morning	0.245	0.190	0.131	0.234
	Evening	0.067	0.051	0.034	0.064
	TOTAL				0.157
HGV	Morning	0.055	0.042	0.028	0.052
	Evening	0.253	0.197	0.136	0.242
	TOTAL				0.151
Bus	Morning	-0.041	-0.028	-0.061	-0.119
	Evening	-0.165	-0.122	-0.080	-0.157
	TOTAL				-0.137
Other public transport	Morning	-0.165	-0.121	-0.079	-0.156
	Evening	-0.320	-0.231	-0.149	-0.302
	TOTAL				-0.226

The results are shown in Table 10, where it can be seen that on average accident reductions of the order of 15% are foreseen for car and HGV traffic, arising mostly from the morning peak for cars and from the evening peak for HGVs. On the other hand, average increases of the order of 14% and 23% are foreseen for the accidents involving buses and other public transport. This is an expected result, as the average speed for car and HGV traffic has decreased after the implementation of the priority scheme, while that of public transport has increased. It should be noted, though, that this result is in relation to existing accident numbers, and hence the projected increases or decreases can be deemed significant or not depending on the accident data available. It should be also further stated that the result can be largely attributed to the trends in terms of fatalities, which are most heavily weighted in the KPI calculation, thus reflecting high-level policy objectives (and the near-zero tolerance to fatalities).

Considering direct safety impacts, as illustrated by the braking behaviour of drivers around the network, the relevant KPI is calculated using equation (6), and the results, differentiated by braking severity type and traffic mode before and after the implementation of the scheme, are shown in Table 11. As can be seen, the public transport priority system appears to slightly reduce the number of extreme braking events per vehicle (with deceleration of more than 7 m/s²), while slightly increasing the number of hard/medium braking

occurrences (between 2 m/s² and 7 m/s²), especially for buses. This suggests a marginal overall improvement in terms of direct safety impacts.

Table 11: Index for direct safety impacts calculated by braking severity and traffic mode

<i>I_{DS}</i> (actions/vehicle)		Uncontrolled		Hard/Medium		Normal	
		Before	After	Before	After	Before	After
Car	Morning	0.020	0.023	4.77	4.89	6.75	6.62
	Evening	0.041	0.036	4.97	4.96	8.01	8.07
	Total	0.030	0.029	4.87	4.93	7.38	7.35
HGV	Morning	0	0	0.98	1.07	19.09	18.78
	Evening	0	0	1.40	1.41	21.15	21.25
	Total	0	0	1.19	1.24	20.12	20.02
Bus	Morning	0.071	0.075	1.34	1.57	11.14	12.33
	Evening	0.136	0.111	1.74	1.80	13.54	13.7
	Total	0.103	0.093	1.54	1.68	12.34	13.01
Other public transport	Morning	0.004	0.005	1.97	0.889	9.84	6.89
	Evening	0	0	1.09	1.48	6.46	4.69
	Total	0.002	0.002	1.23	0.95	6.57	4.67

As concerns the indirect safety impacts as portrayed by the speeding behaviour of drivers in the network, the relevant KPI is calculated using equation (7), and the results, differentiated by traffic mode, are shown in Table 12. Marginal speeding rate (total time of exceedance of 50 km/h over total time of observation in vehicle-hours) reductions can be observed across the board, which can be reflected in the reduced KPI value. Considering the reduction in the total speeding duration over the entire period of observation as a pure number, however, this accounts to almost 40 hours, which is still a significant reduction, even though it may be slightly “downplayed” by the smaller KPI value reduction, which takes into account the traffic volume.

Table 12: Index for indirect safety impacts calculated by traffic mode

		Car		HGV		Public transport	
		Morning	Evening	Morning	Evening	Morning	Evening
Speeding duration (vehicle-hours)	Before	438.6	356.2	6.76	6.94	0	0
	After	407.8	347.4	6.75	7.11	0	0
Time of observation (vehicle-hours)	Before	1338	1378	35.85	39.37	61.05	55.57
	After	1348	1379	36.32	42.92	62.25	60.34
Speeding rate	Before	0.3275	0.2584	0.1885	0.1762	0	0
	After	0.3031	0.2519	0.1859	0.1655	0	0
<i>I_{IS}</i>	Before	0.2925		0.1821		0	
	After	0.2772		0.1749		0	

As such, it can be concluded that the priority system appears to deliver better safety in terms of indirect impacts. It should be further noted that no speeding occurrences are

recorded for public transport, either before or after the implementation of the system.

Moving onto the link-level evaluation, four typical links are selected from abundant links in the network and are evaluated individually as to the safety impacts of the priority system, namely: Link 50, a short straight low trafficked road that includes a roundabout for all modes; Link 93, a long bendy road with high traffic volume for all modes both in the morning and in the evening peak; Link 130, a long straight road with high traffic volume for all modes in the evening peak only; and Link 177, a short straight road with public transport access only. Aside from the topology, the traffic flow characteristics of these links are initially investigated from the simulation data, and it can be found that the average speed has slightly increased on all four of them, and this has often been accompanied with reduced speed variance (and hence more stable traffic flow). The links, therefore, appear to benefit from better mobility following implementation of the priority system, which may, however, be associated with worse safety. In particular in the case of Link 130, the 85th percentile speed exceeds the speed limit, which implies a high speeding rate.

Applying the relative accidents KPI of equation (8) to each of the four links with the same weights as in the network-level evaluation, the results of Table 13 are obtained. As expected given the speed increase, an improvement in terms of accidents is only reported on Link 50 in the morning peak, with decreased index values of different magnitudes found in all other links and times. The highest drop can be identified on Link 130, which can be attributed to the sharp increase in the expected fatality rate, which dominates the calculation due to the higher weight assigned; the severe average speed increase on this link explains this result.

Table 13: Accidents KPI change between before- and after-evaluation for the four links

ΔI_{ACD}		Fatality	Serious injury	Minor injury	TOTAL
Link 50	Morning	0.105	0.100	0.054	0.100
	Evening	-0.223	-0.211	-0.106	-0.211
	TOTAL				-0.035
Link 93	Morning	-0.207	-0.151	-0.098	0.052
	Evening	-0.255	-0.186	-0.120	0.242
	TOTAL				-0.218
Link 130	Morning	-0.304	-0.220	-0.142	-0.119
	Evening	-0.548	-0.388	-0.244	-0.157
	TOTAL				-0.391
Link 177	Morning	-0.158	-0.116	-0.076	-0.156
	Evening	-0.106	-0.078	-0.051	-0.302
	TOTAL				-0.125

Considering direct safety impacts as described by the braking behaviour of drivers, the critical (more than 7 m/s²) occurrences and the corresponding KPI values calculated through

equation (6) for each of the four links are given in Table 14. The results suggest that the implemented priority system generates positive direct safety impacts on the links with lower average traffic volume (50 and 130). However, a negative direct safety impact appears to arise on the more heavily trafficked Link 93, attributed mostly to the morning peak. As concerns the very lightly trafficked Link 177, this cannot be considered as statistically significant, as only a single occurrence of critical braking is identified.

Table 14: Critical braking occurrences and direct safety impacts KPI values for the four links

		Link 50	Link 93	Link 130	Link 177
Morning	Before	2	7	3	0
	After	1	9	2	0
Evening	Before	3	9	5	1
	After	2	5	4	0
TOTAL	Before	5	16	8	1
	After	3	14	6	0
<i>I_{DS}</i> (actions / 1000 vehicles)	Before	3.3	3.7	5.6	10.6
	After	2.7	4.1	1.6	0

With respect to the indirect safety impacts evaluation on the basis of the speeding behaviour of the drivers, the corresponding KPI values calculated through equation (7) for each of the four links are given in Table 15. It can be seen that on the links with lower speeding rate (Links 50 and 93), this appears to be very marginally (almost negligibly) increased after the implementation of the priority system. On the other hand, on the link with higher speeding rate (130), a drop is reported. No speeding is reported on Link 177, which is expected, as this is a public transport access only link. As such, the results suggest that the priority system appears to have a positive indirect safety impact on links with high speeding.

Table 15: Indirect safety impacts KPI values for the four links

Speeding rate	Link 50		Link 93		Link 130		Link 177		
	Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening	
<i>I_{IS}</i>	Before	0.0131	0.0168	0.0546	0.0511	0.2513	0.1868	0	0
	After	0.0147	0.0151	0.0560	0.0547	0.1312	0.2327	0	0
	Before	0.0145		0.0529		0.2212		0	
	After	0.0149		0.0552		0.1837		0	

4.2 Application in Tel Aviv

The second application case study is provided by the Municipality of Tel Aviv-Yafo, where a new public transport priority system is planned to be implemented along one of the city's

main arteries. The case study is performed as part of the CIVITAS 2MOVE2 project and the goal is to elevate the level of service of public transport, while at the same time ensuring the proper balance among all road users (public transport, vehicles, pedestrians, cyclists). The details of the case study and of the predictive impact assessment carried out in terms of pollution and traffic efficiency are given next.

4.2.1 Case study description

The city of Tel Aviv-Yafo is the nucleus of the Tel Aviv metropolitan area and serves as the financial and cultural centre of Israel. With a population of over 400,000 inhabitants and employment of about the same scale, the city's economy relies greatly on its transport system. To this end, the Municipality of Tel Aviv-Yafo considers public transport, walking and cycling to be key in supporting its economic growth and in contributing to its citizens' well-being, and as a result promotes public transport priority with all possible means, but is aware of the challenges introduced when these three "sustainable" modes meet.

As part of the CIVITAS 2MOVE2 demonstration project, in which the Municipality of Tel Aviv-Yafo is a partner, a system providing public transport priority along Ibn-Gabirol Street is deployed. Ibn-Gabirol Street (Figure 9) is characterised by an intense mix of land uses, and hence the provision of public transport priority needs to be done carefully in order to minimise negative impacts on pedestrians and cyclists. With very limited governance over the public transport network and operations, however, the Municipality, together with the Transportation Research Institute of Technion, have developed an innovative operational concept, which relies on a hybrid approach between a centralised and decentralised traffic management and the successive calculation of relevant performance measures, each time with modified parameters according to the experience gained. This feedback process is a fundamental factor for preserving the quality of performance for all road users (Figure 10).

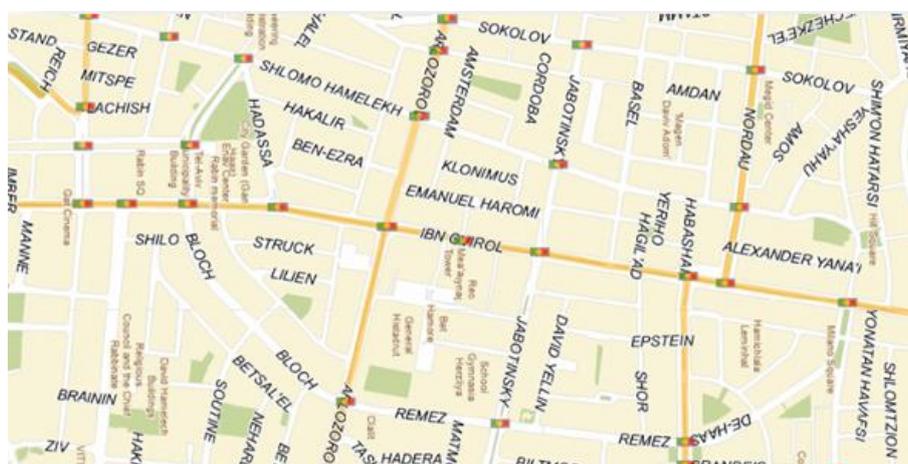


Figure 9: Ibn Gabirol St.- Frishman (South/Left Side) to Yehuda Hamakabi (North/Right Side)

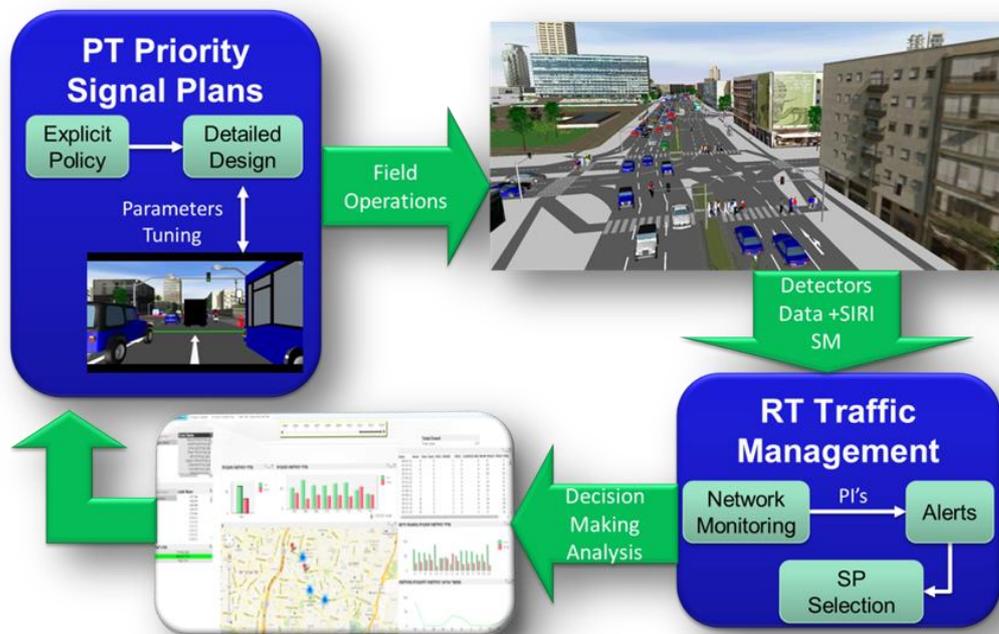


Figure 10: Public transport priority control feedback loop

Indeed, providing public transport priority along Ibn-Gabirol Street while at the same time meeting a sustainable policy is a challenge, especially since the various “sustainable” transport modes are competing. Establishing a balance which satisfies the needs of all road users both in terms of traffic efficiency and pollution calls for a thorough evaluation of the measure.

Three planning alternatives have been devised and are presented to the decision-makers, among which the most appropriate one with respect to both the 2MOVE2 goals and the municipal policy needs to be selected. These are:

- V1 – Aiming at public transport priority provision and a minor reduction of public transport travel times and travel time variability;
- V2 - Aiming at public transport priority provision and a moderate reduction of public transport travel times and travel time variability; and
- V3 - Aiming at public transport priority provision and a major reduction of public transport travel times and travel time variability.

The choice is assisted by the predictive evaluation methodology described in Chapter 2 and implemented in the CONDUITS_DST software, and the results are presented next.

4.2.2 Combined traffic efficiency and environmental assessment

The dimension and complexity of the problem is determined according to the project's goals and the city policy, and thus entails the following components (variables): public transport travel time and standard deviation; pedestrian green wave; pedestrian red duration distribution; and crossing street queue length. As expected, the results of the microsimulation show a mixture of trends, depending on the specific objective (i.e. reduction of travel times) and road user. With the help of CONDUITS_DST, it is anticipated to simplify this complex decision by presenting two figures per alternative: the traffic reliability KPI and the pollution reduction KPI, covering hence both the traffic efficiency and the environmental impacts.

The evaluation involves the five weighting scenarios introduced in Section 2.2.2 and outlined in Table 6, namely "Equality", "PT priority", "Space consumption", "Sustainability" and "Pedestrian priority". With respect to the pollution KPI, the weighting scenario derived from the EU limit values of pollutants, called "EU" and outlined in Table 4 is used. The results are based on the calculation of the KPIs with CONDUITS_DST for the morning peak using five seeds.

The charts in Figure 11 show the KPI results for each of the five policy weighting scenarios. The primary (left) vertical axis presents the CONDUITS traffic reliability KPI values, while the secondary (right) axis shows the CONDUITS pollution KPI values for the different planning alternatives. As can be seen, in four out of the five weighting scenarios examined, the provision of a minor public transport priority provides an overall more efficient transport system. The only exception is the weighting scenario in which the pedestrians and cyclists are considered most important; in that scenario, 1 second of walking/cycling is equivalent to 20 seconds of driving (or 1 person walking/cycling is equivalent to 20 drivers). All three planning alternatives aim at the provision of public transport priority on the main road, thus, naturally, causing increased delays to the crossing pedestrians. Amplifying these delays by a factor of 20 leads to a 0.5% reduction of overall traffic efficiency in the "Minor PT Priority" alternative. Nevertheless, the same planning alternative introduces a decrease of the pollution KPI by nearly 16% with an average decrease of 7.3% in particulate matter.

Estimating the impacts of the different planning alternatives given the five weighting scenarios shows that the "Minor PT Priority" is, actually, the most balanced option, both in terms of traffic efficiency and in terms of pollution reduction. Based on this evaluation, the Municipality has selected this planning alternative, and it is anticipated that the public transport priority scheme will be implemented within 2015.

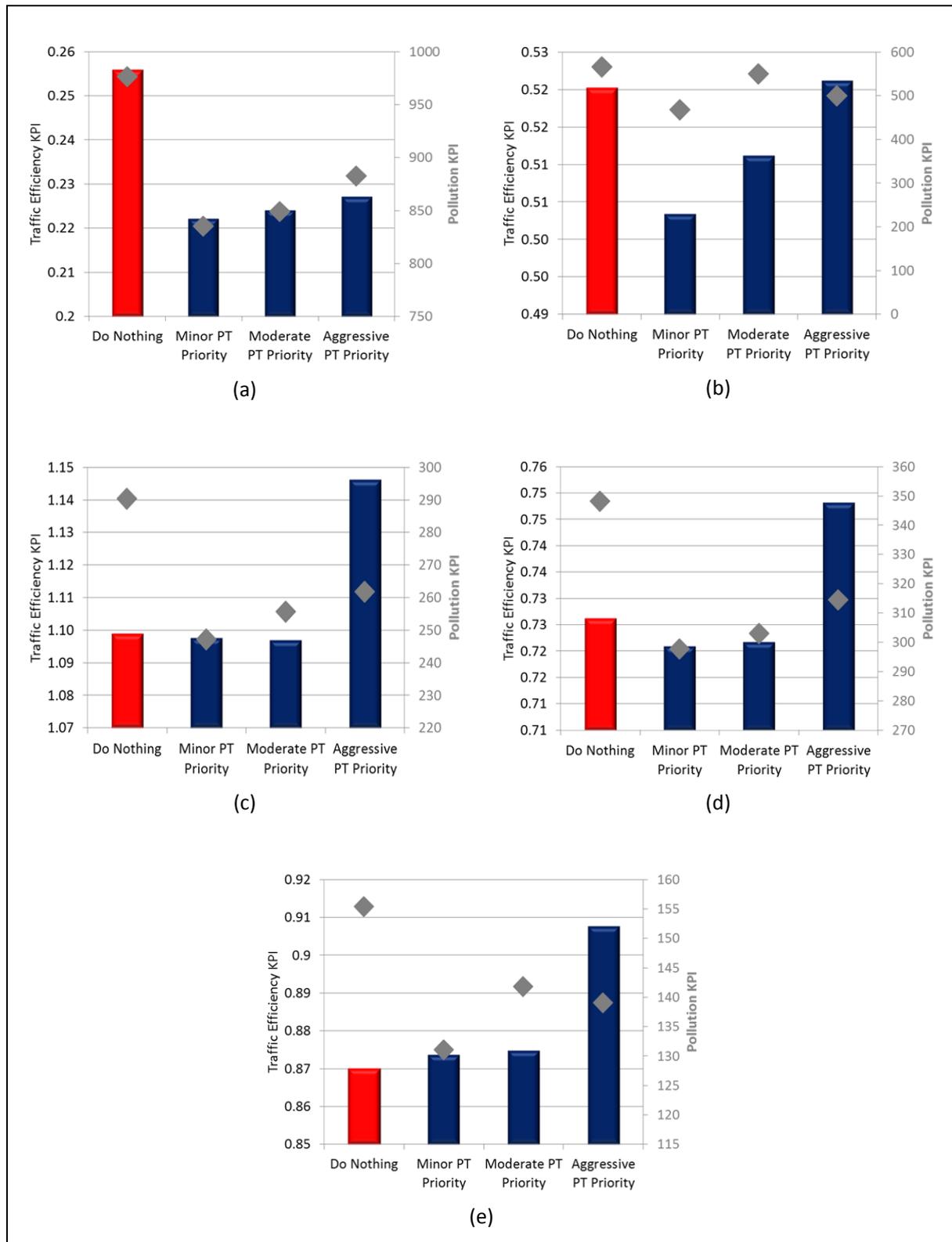


Figure 11: Traffic efficiency and environmental impact assessment results:

(a) "PT priority"; (b) "Equality"; (c) "Space consumption"; (d) "Sustainability"; (e) "Pedestrian priority"

4.3 Application in Haifa

The third application case study is provided by the Municipality of Haifa, where the impacts of various strategies with regard to the operation of a road tunnel are studied. Specifically, it is investigated whether the implementation of measures resulting in an increase in traffic volumes in the tunnel (and thus relieving other parts of the network) may result in negative pollution impacts. The details of the case study and of the predictive impact assessment carried out in terms of pollution and traffic efficiency are given next.

4.3.1 Case study description

Haifa is located right at the Mediterranean Sea, but also on a part of a mountain range, Mount Carmel. From 2008 to 2010, the city of Haifa constructed a tunnel through the Carmel Mountain, called the Carmel Tunnel, also known as Route 23 (Figure 12). The tunnel was built, as before the only way to get from east to west and vice-versa was using the coastal road, that still has high traffic volumes (near capacity), especially in the peak hours. The tunnel route cut the respective travel time from about 30-50 minutes down to 6-8 minutes.

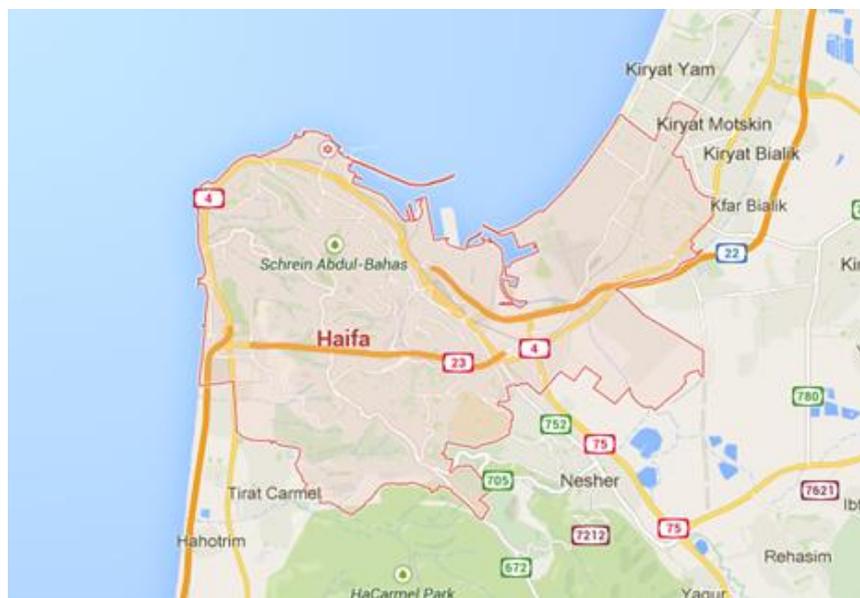


Figure 12: Overview of Haifa: The Carmel Tunnel is labelled as "23". © 2015 Google Maps GISrael

However, the traffic volumes through the tunnel are only about 66% of the predicted ones. As a result, the traffic volumes on the coastal route are still high and close to capacity, which leads to congestion, long queues and delays, especially in the peak hours. The high traffic volumes on the coastal route are not only a problem as concerns travel times, but also with

respect to air quality, as the pollution levels in Haifa Bay are amongst the highest in Israel, even though it is located next to the sea. In particular, ozone and particulate matter are a problem, as they exceed the thresholds of the WHO of 2005 (Figure 13).

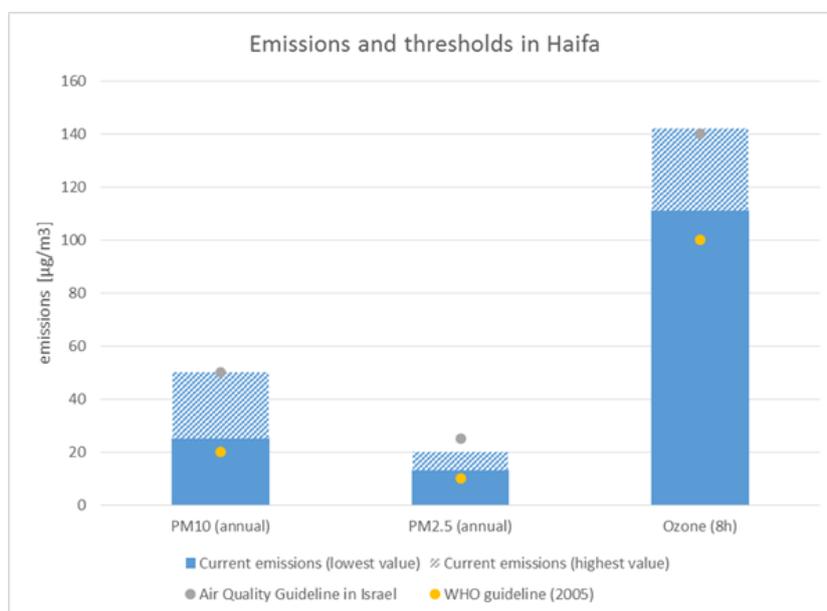


Figure 13: Emissions in Haifa compared to the 2005 threshold values of the WHO

The high pollution levels entail severe health risks: a 2013 study found that from 1998 to 2007 the hazard ration to develop cancer between Haifa sub-district to non- Haifa was 1.16 [28]. However, according to the Israel Environment Ministry, during the past six years air pollution levels have decreased by 70 percent.

Guiding more traffic through the Carmel Tunnel could help relieving the traffic situation on the coastal road, smoothing the traffic in the whole network. Additionally, the pollution levels of Haifa could be lowered through air filtering in the tunnel. In order to achieve this goal, variable message signs showing the estimated travel time to the city centre for both the coastal route and the Carmel Tunnel were installed in the South of the city. With the help of modelling the relevant parts of the network and the predictive evaluation methodology described in Chapter 2 for environmental and traffic efficiency impact assessment, it is examined here whether more measures should be implemented in future in order to further relieve the coastal route. Naturally, a key issue of any kind of traffic guidance is the compliance rate. However, it can be found in the literature (e.g. [29]) that compliance rates between 10% and 20% are achievable. Therefore, such compliance rates are investigated as part of different scenarios.

4.3.2 Environmental assessment

Starting from analysing the emissions, five scenarios are generated to study the influence of time and a certain share of guided traffic on the overall emissions:

- Current demand, no routing recommendation (state of play);
- Estimated demand in 2020, no routing recommendation (business as usual)
- Estimated demand in 2020, tunnel routing recommendation, 10% compliance
- Estimated demand in 2020, tunnel routing recommendation, 20% compliance
- Estimated demand in 2025, no routing recommendation (business as usual)

Each scenario is calculated with 10 seeds, and the increase of traffic volumes for 2020 and 2025 is based on a trend prediction of the up-to-date developments in Israel (which, according to the Central Bureau of Statistics of the State of Israel, demonstrate a linear behaviour, so far).

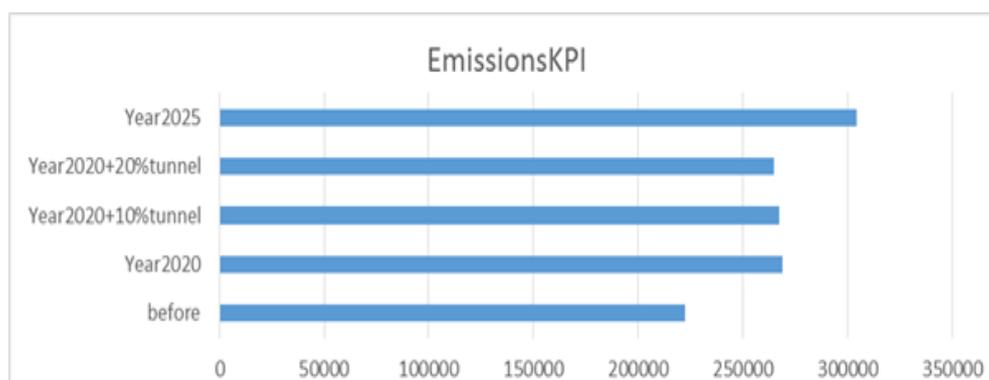


Figure 14: Pollution KPI value for each scenario

The results of the environmental assessment can be seen in Figure 14, where it can be clearly seen that the increasing traffic will increase the emissions in the coming years. This will also outweigh the decreasing fuel consumption of vehicles. Guiding vehicles through the tunnel only shows a small effect on emissions, which is not statistically significant ($\alpha > 0.05$), and so it can be concluded that other measures of traffic management have to be established in order to further decrease the level of pollution in Haifa.

A more differentiated weighting of routes might help to rate the relief of the city centre higher than the tunnel route, hence making the calculation closer to the policy objectives of the Municipality. However, the emission peaks at both ends of the tunnel would still need to be considered separately, as they represent major emission “hot spots”, so the calculated KPI values would remain critical.

4.3.3 Traffic efficiency evaluation

In the evaluation of traffic efficiency, both the mobility and the reliability KPIs are used. Eight scenarios are generated to study the influence of time and a certain share of guided traffic on traffic efficiency: this involves three more scenarios relating to the year 2030 in addition to the five used in the environmental assessment. The reason is that AIRE allows for the calculation of emissions only until the year 2025, and so a calculation for 2030 is not possible. The three additional scenarios are:

- Estimated demand in 2030, no routing recommendation (business as usual)
- Estimated demand in 2030, tunnel routing recommendation, 10% compliance
- Estimated demand in 2030, tunnel routing recommendation, 20% compliance

These scenarios are also calculated with 10 seeds each, and the results of the mobility and reliability KPIs can be seen in Figure 15 and Figure 16. With respect to mobility, again, the predicted impact of traffic guidance is low. However, the modelled years show clearly different results, and it can be seen that mobility will decrease in the next years from about 0.09 min/km to about 0.125 min/km in 2030 as a result of the increasing traffic volumes in the tunnel.

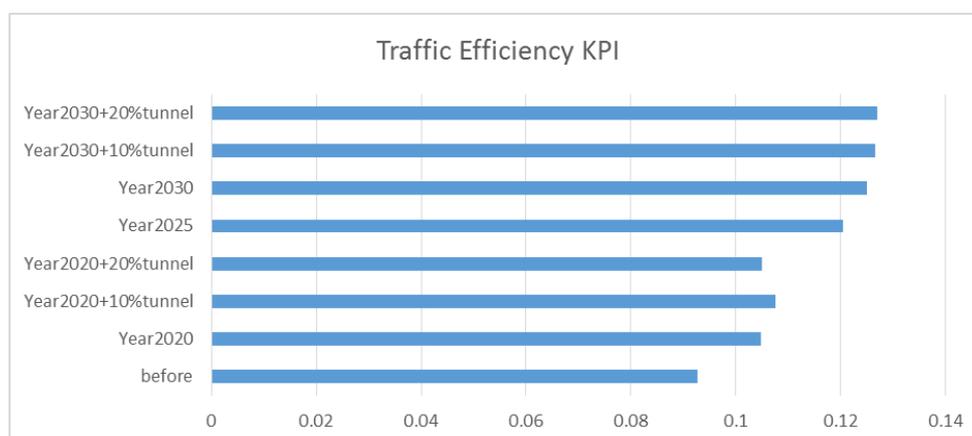


Figure 15: Mobility KPI value for each scenario

With respect to reliability, the results are more significant, as with higher traffic volumes the index decreases. In contrast to mobility, the results show clearly that routing traffic through the tunnel has an increase of the KPI and thus an increase in reliability. Assuming a compliance rate of 20%, the increase is statistically significant ($\alpha < 0.01$) for both 2020 and 2030.

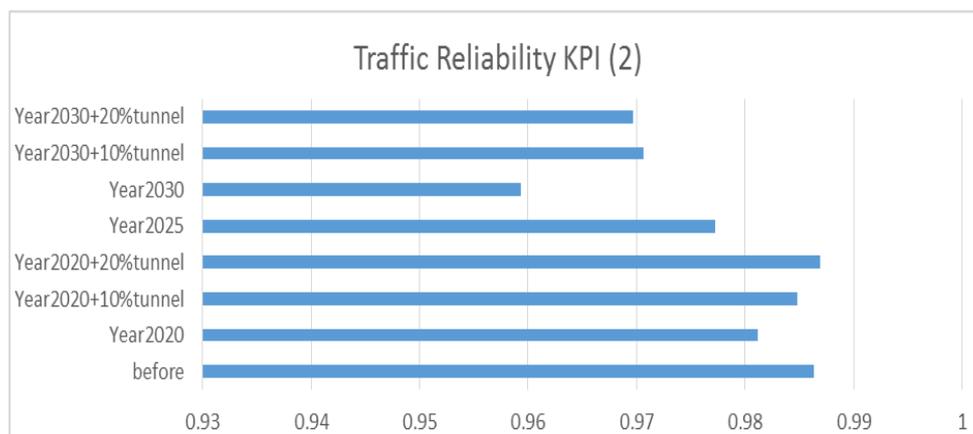


Figure 16: Reliability KPI value for each scenario

4.4 Application in Stuttgart

The fourth application case study is provided by the City of Stuttgart, where the impacts of a set of planned traffic management measures on a stretch of federal highway are studied. Specifically, the impact of the implementation of mandatory variable speed limits, coupled with corresponding enforcement and information provision, on traffic efficiency and pollution is investigated. The details of the case study and of the predictive impact assessment carried out are given next.

4.4.1 Case study description

The city of Stuttgart is the capital of the Baden-Württemberg state in Germany. The population of the municipality is, as of April 2015, 593,618 inhabitants, with approximately another 2 million inhabitants in the greater Stuttgart region. The city is located in the valley of the Neckar river, which often creates special micro-climate conditions that promote the accumulation of emissions over longer periods of time. Thus, eco-sensitive traffic management policies and ITS measures have been one of the municipality's priorities.

In 2012 the city implemented a bundle of measures aimed at relieving certain emission "hot spots", starting with the Hohenheimer Straße, which is the urban branch of federal highway B27. Parking management measures, static speed limitations and a dynamic optimal speed advisory system (communicated through variable message signs) were deployed in the uphill direction of the road. This resulted in the number of days when the NO_x limitations is exceeded to drop from 269 in 2011 to 196 in 2012 and to just 12 in 2013.

The success of the 2012 project has led the authorities to consider the implementation of

similar measures in further locations, and one of these is a stretch of federal highway B14 (Cannstatter Straße, Konrad-Adenauer-Straße), as shown in Figure 17. This proposed second implementation is part of two larger projects: the GDRs 173/2012, funded by the city council of Stuttgart; and the EU CIVITAS 2MOVE2 project, co-funded by the EU CIVITAS PLUS II initiative. The measures planned include:

- Variable speed limits (50 km/h, 40 km/h and occasionally 30 km/h) based on the emission levels;
- Enforcement of the speed limits with traffic cameras; and
- Increasing awareness with additional information measures.



(a)



(b)



(c)

Figure 17: (a) B14 corridor; (b) proposed variable speed limit and enforcement; (c) information provision

It is intended to examine the expected impacts of this project in terms of pollution and traffic efficiency with the methodology of Chapter 2 and the relevant KPIs using CONDUITS_DST. For this purpose, a VISSIM simulation model has been provided by the municipality of Stuttgart and their affiliated consultancy, SSP Consult GmbH, which contains traffic data for the years 2014 (current situation) and 2025 (prediction).

For the calculation of the KPIs, the “UNW” and the “Equality” weighting scenarios are adopted for the pollution and the mobility KPI, respectively, as outlined in Chapter 2. Furthermore, for the case of pollution, an additional scenario is adopted, called “EU Local”, which is a modified version of the “EU” scenario but with the weight for CO₂ set to zero. This is done to eliminate the effect of CO₂ in the calculation, especially since the implementation of the measures aims mainly at a reduction of local emissions (NO_x and PM).

The calculation scenarios include, besides the “before/after” consideration using the data of 2014, also a “business-as-usual”-scenario without measures for the year 2025, which allows for the consideration of the effects of the expected improvements in vehicle technology. For the purposes of the case study, only the speed limitation to 40 km/h is considered, since soft measures of information provision cannot be properly incorporated in the simulation.

The results of the case study in terms of environmental assessment and traffic efficiency evaluation are presented next.

4.4.2 Environmental assessment

Starting with the environmental assessment of the case study, the “business-as-usual” evaluation of the pollution KPI, comparing the scenarios with and without implementation of the measures for the years 2014 and 2025, shows a significant reduction in the pollution KPI, which comes about gradually over a period of 11 years (Figure 18). Comparing the results of the two different scenarios, it becomes evident that including carbon emissions in the overall consideration reduces the visibility of impacts in NO_x and PM reduction. This instance becomes obvious in the short-term “before/after” evaluation, in which the reduction in pollution is not as high.

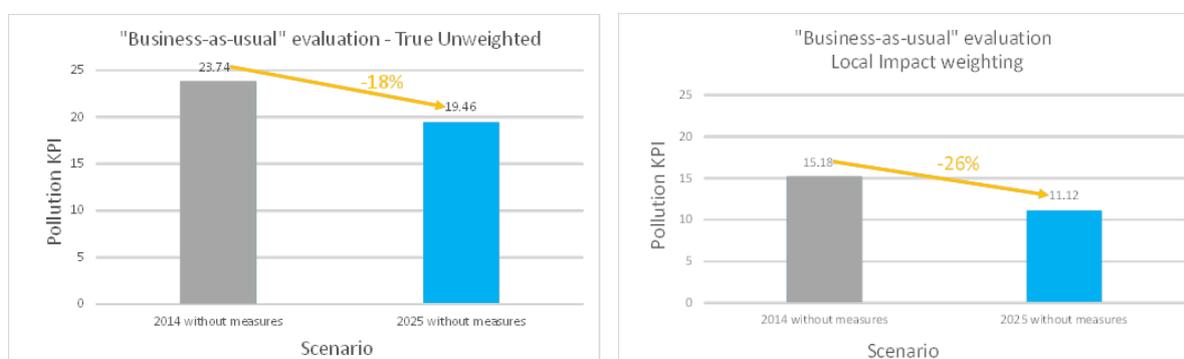


Figure 18: Pollution KPI in the “business-as-usual” scenario

The “before/after” evaluation shows the reduction of pollution achieved immediately after

the implementation of the measures. The reduction of the pollution KPI is obvious also for this scenario, yet naturally lower than the long-term scenario of 2025. The weighting scenario focussing of local emissions shows a reduction of 5.3%. It can be said, hence, that about 1/5 of the positive effects to be expected in the long term can be achieved earlier through the implementation of the measures.

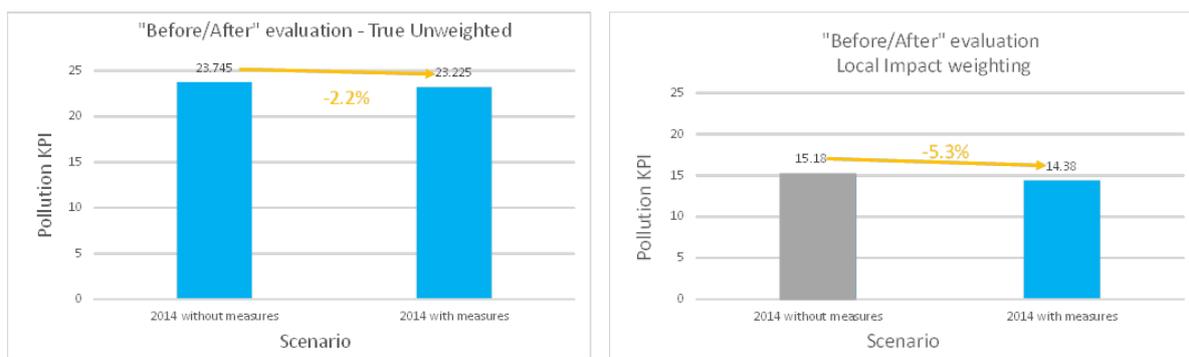


Figure 19: Pollution KPI in the "before/after" scenario

4.4.3 Traffic efficiency assessment

Since the measures do not have the direct goal of improving efficiency for certain modes, but are aimed primarily at reducing pollution, an "Equality"-weighting has been chosen for the evaluation of traffic efficiency using the mobility index. All modes are thus given the same significance and are weighted equally in the KPI calculation.

As expected, the "business-as-usual" scenario shows a slight increase (2.6%) in the mobility KPI, which translates in a reduction of traffic efficiency. The reason is the expected increase in traffic volumes, which causes an increase in travel time. This can be seen in the left diagram of Figure 20.

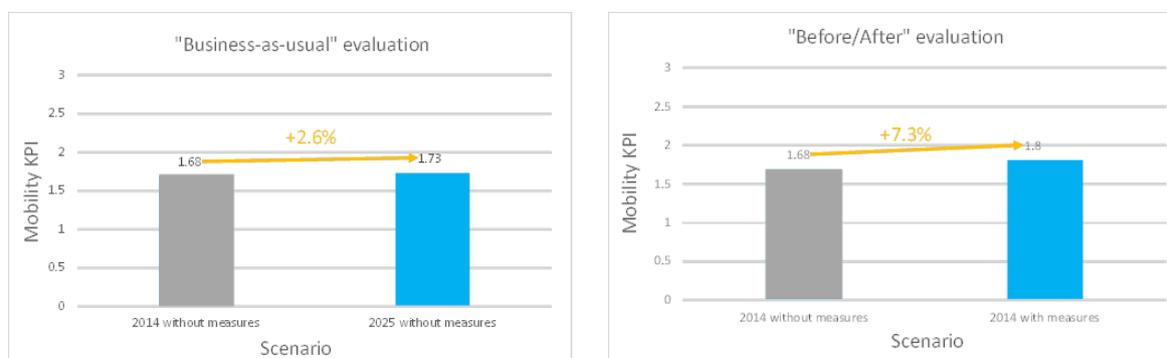


Figure 20: Mobility KPI in the "business-as-usual" and "before/after" scenarios

The implementation of an enforced speed limitation will inevitably also lead to a further

increase of travel time. As seen in the results of the “before/after” evaluation in the right diagram of Figure 20, the increase of the mobility KPI is found to be 7.3%. However, this is an instance that reflects the goals of the policy decision.

5 Conclusions and further work

Three main achievements have been made in Phase II of the CONDUITS-DST project, and the key conclusions that can be extracted from each one are outlined next.

Firstly, the methodological component of the predictive evaluation framework for urban traffic management and ITS has been reinforced. In particular, a systematic approach for setting the weights in the KPI of the pollution reduction module has been defined, and a method for linking traffic characteristics, as output by traffic simulation models, with safety-related variables that can be input into the relevant traffic safety KPIs, has been developed. A more comprehensive definition of the two traffic efficiency KPIs has also been provided. This has allowed for a more firmly-defined methodology to underpin the practical component of the evaluation process.

Secondly, the CONDUITS_DST software has been enhanced through the inclusion of two additional KPI modules, namely traffic efficiency and traffic safety, in addition to the previously implemented KPI module for pollution reduction. This has facilitated, for the first time, the multi-dimensional evaluation of urban mobility measures and ITS schemes, as opposed to the previous one-dimensional consideration. With the new version of the tool, it is now possible to capture both main and “side” effects, which enables stakeholders to make more informed decisions.

Thirdly, the predictive evaluation framework and the CONDUITS_DST software have been successfully tested in four real case studies in the cities of Brussels, Tel Aviv, Haifa and Stuttgart. This has enabled the shift from the “proof-of-concept”-type testing conducted as part of Phase I of the CONDUITS-DST project to the actual demonstration of the approach in different case studies and settings, with different priorities and requirements. Indeed, the four city authorities involved in the project already intend to make use of the evaluation results provided from the respective case studies in their decision-making, which, hence, demonstrates that the approach has reached a more advanced stage of maturity than in Phase I.

And while Phase II of the CONDUITS-DST project has facilitated significant progress, making the predictive evaluation method and CONDUITS_DST software invaluable tools for

decision-makers and city authorities, research and development work in this direction continues and a number of future activities are planned. As a first step, and following the successful implementation of the three KPI modules for pollution reduction, traffic efficiency and traffic safety, it is intended to further expand CONDUITS_DST to include the fourth KPI category of social inclusion and land use. Similarly to the safety module, data for the relevant KPIs are not readily available from traffic simulation, and therefore appropriate land use and demographic models will have to be considered, modified and employed. But what adds further complexity to this task is that impacts in terms of land use and social inclusion do generally not become evident until several years after implementation of a strategy or measure, as opposed to pollution, efficiency and safety, impacts for which appear almost immediately. It is, hence, likely that the task will have to be accompanied by a thorough calibration process, where large amounts of historical data will need to be analysed.

A further step to be undertaken is the development of more advanced weighting methodologies for all KPI categories. While several weighting scenarios have been defined for the pollution and traffic efficiency KPIs, these concentrate on the values of selected weights (pollutants, vehicle types), and no weighting strategies for individual network links or the safety KPIs are provided. It is an essential next step to conduct more analyses of the weighting factors and to develop an advanced calibration mechanism that planners can apply once to their specific settings so that they can then produce policy-aware evaluation results, tailored to their needs. It is also important to be able to systematically incorporate the views of experts in the evaluation procedure, and so work will continue along this direction in order to derive more robust weighting scenarios for all CONDUITS KPIs, which incorporate expert knowledge.

Furthermore, it is important to continue developing the user interface of CONDUITS_DST. With the approach and the tool now on the way to maturity, it may be useful to consider involving a professional programmer in the development, in order to improve the efficiency and the appearance of the tool. Apart from the user-friendliness of the evaluation process that will be improved, such development will additionally enable the consideration of each evaluation category as part of a broader multi-objective problem alongside the other themes, rather than individually. This means that solutions will be able to be compared by decision-makers directly on the basis of their KPI values in the different themes, thus providing a more informed and comprehensive evaluation process. As it is likely that trade-offs will have to be made between meeting objectives in different themes to varying extents, the decision-making process can become a highly complex problem, opening great prospects of further research in the development of multi-objective optimisation algorithms using the different KPIs as decision variables to facilitate this.

Finally, aside from the further development of the methodological framework and tool, future work could also concentrate on the conduct of additional case studies in different cities, featuring the combined use of all developed modules. This will enable, apart from the further validation of the approach, also the extraction of case-study-specific conclusions, thus providing the opportunity to start offering a service to city authorities and decision-makers. The four cities involved in Phase II have already identified additional case studies of theirs, in which the CONDUITS approach and CONDUITS_DST software can be further applied, with more cities having expressed interest in providing a case study.

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