SUNSET

Sustainable Social Network Services for Transport
www.sunset-project.eu

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Deliverable D3.2
"Individual Objectives versus System Objectives"

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Summary

SUNSET aims to design and test incentives that can make the mobility system of our society more efficient and sustainable. An incentive that is effective in motivating individual travellers to adapt different behaviour can bring positive impacts on the policy goals. This deliverable focuses on establishing the relationship between individual objectives and system objectives. The outcome of this deliverable, together with that of Deliverable 3.3, will be used in Deliverable 3.4 for designing a set of feasible and potentially successful incentives. These incentives will then be tested in the SUNSET living labs.

Individual objectives concern the objectives that individual travellers follow when making decisions on their trips; system objectives concern the policy goals that are commonly used for evaluating the performance of the traffic and transport infrastructure. Their relationship is established by considering individual behaviour, which results from the individual objects and has impact on the system objectives.

The methodology involves a behaviour modelling on the lower level and a network modelling on the higher level. The behaviour aspects relevant to trip making include the planning and scheduling behaviour:

- Trip decision and destination choices;
- Departure time choice;
- Mode choice;
- Route choice;

and the en-route behaviour (mainly for car drivers):

- Driver status and concentration;
- Longitudinal control of vehicle;
- Lateral control of vehicle;
- Compliance with traffic rules.

Behaviour modelling is applied where the individual objectives are formulated as optimisation problems, with the behaviour aspects given as decision variables. For each objective, the optimisation would lead to certain behavioural patterns in the travellers.

Networking modelling aggregates the results of the individual behaviour onto the network level. The efficiency based system objectives are quantified with theoretically defined formulae, while the externalities based system objectives are approximated using surrogate measurements that have been commonly adopted in practice. Qualitative analysis then establishes the general relationship between individual behaviour patterns and the network level system objectives.

By matching the results of the behaviour modelling with those of the network modelling, the relationships between the individual objectives and the system objectives are established. These relationships are presented as correlations: a positive correlation means that, if more travellers follow the individual objective, this would results in a positive outcome on the system objective.

The table below summarises the major correlations between individual and system objectives, using the following notation:

++	major positive correlation
+	minor positive correlation
--	major negative correlation
-	minor negative correlation
±	minor correlation with sign depending on circumstances
O	no (significant) correlation

For each pair of individual-system objectives, different behaviour aspects may lead to different (sign/strength of) correlations; this is denoted by the slash (/) in the correlation table. Pairs with major correlations are highlighted with yellow shading; pairs with both positive and negative correlations have the more dominating correlation displayed in bold typeface.

Individual objectives	**System objectives**				
	A. To maximise accessibility	B. To minimise congestion	C. To maximise safety	D. To minimise impact on environment	E. To maximise wellbeing
1. To minimise travel time	-	±/**--**	+/**-**	+/**--**	+/**--**
2. To minimise scheduling effort	O	±/**--**	±	±	O
3. To minimise cost	O	**++**/--	±	**++**/--	±/**-**
4. To maximise safety	O	**+**/±	**++**	±	O
5. To maximise capital	±	++/**--**	+/-	++/**--**	±/**-**
6. To maximise synergy with normality	-	--	**++**/-	--	±
7. To maximise identity recognition	+/-	+/**--**	+	++	++
8. To maximise pleasure	O	+	±	-	-

Congestion is shown to rise when travellers minimise their scheduling effort, meaning that they do not actively avoid the peak hour or the congested route. Car owners who try to maximise capital tend to use their car as much as possible. Emission, as well as personal wellbeing of citizens, has a strong dependence on travellers' mode choice. Non-car mode reduces emission. The active modes, i.e. walking and cycling, contribute to the personal health of travellers.

The major correlation pairs are the key focus areas of the incentive design. By taking into account the applicability in SUNSET, this deliverable recommends the following incentives for further investigation in SUNSET:

- **Intermodal information provision** of the travel time difference between the difference modes, together with (as compensation) the gains on environment protection and personal health with the sustainable modes.
- **Identity promotion** within individual travellers, using the personal mobility tracking service, and focusing on the "green" identity.
- Identity and **status recognition** among a group of travellers, utilising social networks.

Document Information

Authors

Name	Partner	Email
Jing Bie	UTWENTE	j.bie@utwente.nl
Eric van Berkum	UTWENTE	e.c.vanberkum@utwente.nl
Sander Veenstra	UTWENTE	s.a.veenstra@utwente.nl

Editor

Name	Jing Bie
Partner	UTWENTE
Address	University of Twente, Postbus 217, NL-7500AE Enschede
Phone	+31 (0)53 489 1054
Fax	+31 (0)53 489 4040
Email	j.bie@utwente.nl

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1. INTRODUCTION

SUNSET aims at making the mobility system of our society more efficient and sustainable, by providing incentives to the individual travellers. A crucial task within SUNSET is to design incentives that are effective, both in motivating individual travellers and in achieving the system goals. Work package 3 (WP3) addresses this task, producing the following four deliverables:

- Deliverable 3.1 (D3.1) defines the most relevant objectives that are being followed by individuals when they make their trips, and objectives that are being used by policy makers in defining policy goals;
- Deliverable 3.2 (D3.2) establishes the relationship between these individual and system objectives;
- Deliverable 3.3 (D3.3) assesses the impact of various incentives;
- Deliverable 3.4 (D3.4) identifies a set of feasible and potentially successful incentives.

This deliverable (D3.2) relies on the output of D3.1 (Hodgson et al., 2011), which defines the individual and system objectives. The outcome of D3.2, together with that of D3.3 (Kusumastuti et al., 2012), will be used in D3.4 for assessing the effectiveness of various incentives in achieving the policy goals. Combining this with technical feasibility, D3.4 produces a set of incentives that are expected to be successful in practice. These incentives will then be tested in the SUNSET living labs.

Individual objectives define what the traveller desires to achieve during their trip making. They are usually not the purpose or goal of the trip making, which mostly relates to the opportunities at the trip ends (e.g. to be at work/home, shopping, leisure). Instead, they act as preferences which the traveller aims to optimise when making the trip. Such preferences are multi-fold: travel time and travel cost are the obvious objectives which travellers prefer to minimise. Besides time and cost, personal safety and health also play a role. Furthermore, environmental awareness such as personal CO2 footprint is a relevant factor for many people when making their trip decisions.

System objectives relate to the performance of our mobility system as a whole. Some of them can be considered as the aggregation of the individual objectives, e.g. to minimise system travel time. Other objectives are defined only on the system level. They may not appear as simple linear accumulations of individual objectives, due to the interaction (and synergy) between the individual decisions. For example, while system emission can be calculated by summing up the individual emissions, air quality cannot be assessed in such a way and depends on the distribution and dispersion of emission over time and over space.

Often, the various individual objectives do not concur with each other. For example, a trip alternative which maximises personal safety may not minimise travel time. This is similar for the system objectives: minimising system travel time may lead to higher emission levels. Indeed, an individual traveller usually has multiple objectives (preferences), and the policy makers often define the policy goals as a combination of multiple objectives. Mathematically, this can be formulated as multi-objective optimisation, which may be solved by using a weighted average objective function or addressed by following the Pareto optimality (Pareto, 1897). A Pareto-optimal solution is achieved when it is no longer possible to improve any objective without making other objectives worse off.

In this document it is researched in what way individual ambitions may serve the common good. It is noted that individual objectives are not always in congruence with system objectives. A well-known example is the Braess paradox (Braess, 1969) where, if individual travellers try to minimise their own travel time, the system travel time as a whole is not necessarily minimised. Here, the relationship between individual objectives and system objectives is expressed as correlations: if more travellers follow a certain individual objective, how would this affect the system objectives. With such knowledge it is then possible to develop solutions of moving the mobility system into a better state through changes in individual behaviour.

1.1 Goals

Within SUNSET, the Work package 3 objectives are:

- Research the relationship between individual and system objectives;
- Investigate key factors that influence the use of information message;
- Develop a set of feasible and productive incentives to change mobility.

The objectives of Task 3.2 are:

Obj1 *Formulate the system and individual objectives as optimisation problems.*
Obj2 *Identify the individual behavioural aspects that are influenced by the individual objectives.*
Obj3 *Quantify the influence of individual objectives on the individual behaviour in terms of trip planning and scheduling.*
Obj4 *Quantify the influence of individual objectives on the individual en-route behaviour.*
Obj5 *Assess the influence of individual planning/scheduling behaviour on the network performance in terms of the system objectives.*
Obj6 *Assess the influence of individual en-route behaviour on the network performance in terms of the system objectives.*
Obj7 *Identify the relationship between individual objectives and system objectives.*
Obj8 *Assess the impact of given changes in behaviour (incentives) on system objectives.*

1.2 Main results and innovation

The main results of D3.2 consist of:

- Formulation of individual and system objectives as optimisation problems;
- Behavioural modelling of trip planning and scheduling behaviour under various individual objectives;
- Qualitative analysis on the effects of individual objectives on en-route behaviour;
- Impact analysis of individual behaviour on the system objectives;
- Relationship between individual and system objectives;
- Recommendations for designing incentives.

D3.2 contributes to SUNSET by helping WP3 identify a set of potentially successful incentives. D3.2 establishes the relationship between individual objectives and system objectives. D3.3 identifies how incentives affect individual behaviour. With such knowledge, it is possible to derive the likely impact of a certain incentive on the system objectives. Some incentive schemes are expected to be more effective than others.

The results of WP3 further contribute to the preparation and operation of the SUNSET living labs. In the living labs, the incentives are tested in the real world environment and with real end users. By preselecting the incentives that are expected to be effective, the living lab operations have a higher chance of being successful.

The contribution of D3.2 to the SUNSET innovations is listed in Table 1.1.

Table 1.1 Contributions of this deliverable to SUNSET innovations

SUNSET innovations	Contribution of this deliverable
Social mobility services that motivate people to travel more sustainably in urban areas	(a) knowledge of how individual motivation affects behaviour; (b) knowledge of how individual behaviour affects sustainability related measurements.
Intelligent distribution of incentives (rewards) to balance system and personal goals	(a) knowledge on the relationship between individual and system objectives; (b) recommendations on designing effective incentives.
Algorithms for calculating personal mobility patterns using info from mobile and infrastructure sensors	N/A
Evaluation methodologies and impact analysis based on Living Lab evaluations	N/A

1.3 Approach

A common way to approach the optimisation of transport network operations is through bi-level programming, where on the upper level the system is optimised and on the lower level the individual situations are optimised. This document follows a similar approach: we first study how individuals behave in optimising their personal objectives (lower level), which results in certain quantification on the behavioural indicators; we then aggregate these behaviour indicators to the network level, to assess their impact on the system objectives. Combining these results, we derive the correlation between individual objectives and system objectives.

The methodology is a combination of literature review and expert interviews with theoretical modelling. For each of the aims in Task 3.2 a set of activities were identified as well as responsibilities for the partners to complete each of the activities.

Aims and methods

- **Obj1 Formulate the system and individual objectives as optimisation problems**

Review Deliverable 3.1. Each objective is formulated as an optimisation problem, i.e. to maximise or minimise an objective function, subject to a set of constraints.

- **Obj2 Identify the individual behavioural aspects that are influenced by the individual objectives**

Literature review. Only mobility-related behavioural aspects are considered. These behavioural aspects are classified into two categories: trip planning and scheduling behaviour (i.e. before the trip), and en-route behaviour (i.e. during the trip).

- **Obj3 Quantify the influence of individual objectives on the individual behaviour in terms of trip planning and scheduling**

behaviour modelling, combined with literature review and expert interview. References are taken from published papers, project reports, government bulletins, and reported case studies. Decision theories (e.g. prospect theory) are applied to model individual behaviour. Traffic psychologists are interviewed for their opinions on the planning and scheduling behaviour of travellers under given individual objectives.

- **<u>Obj4 Quantify the influence of individual objectives on the individual en-route behaviour</u>**

Behaviour modelling combined with expert interviews (with behaviour/mobility experts in the SUNSET consortium). Motivation theory is applied for identifying the en-route behavioural pattern under given objectives. This is complemented by interviews with traffic psychologists. References will also be made from published papers, project reports, government bulletins, and reported case studies.

- **<u>Obj5 Assess the influence of individual planning/scheduling behaviour on the network performance in terms of the system objectives</u>**

Network modelling. On the general level, traffic assignment models are applied for assessing the consequence of individual planning behaviour on the network-level. Aggregate measurements can be derived with summation formulae, which can then be used to define the conditions for meeting a particular system objective.

- **<u>Obj6 Assess the influence of individual en-route behaviour on the network performance in terms of the system objectives</u>**

Microscopic modelling and aggregation analysis. En-route behaviour mainly affects traffic safety and air qualities. Surrogate measurements are adopted for safety evaluation. Emission models are applied for assessing the influences on emissions.

- **<u>Obj7 Identify the relationship between individual objectives and system objectives</u>**

Comparison and matching. The relationship can be derived by comparing and matching the influence of individual objectives on behaviour (obj3 and Obj4) with the influence of individual behaviour on system objectives (Obj5 and Obj6).

- **<u>Obj8 Assess the impact of given changes in behaviour (incentives) on system objectives</u>**

Apply the results of previous objectives. The objective here is to identify most effective incentives or behaviour aspects that the incentives should target, and to estimate the consequences of these incentives on the system level.

1.4 Document structure

This document consists of six chapters:

- This chapter (Ch1) provides an introduction and overview.
- Chapter 2 (Ch2) fulfils Obj1 and Obj2 by formulating the objectives with behavioural indicators.
- Chapter 3 (Ch3) fulfils Obj3 and Obj4 by quantifying the influence of individual objectives on behaviour.
- Chapter 4 (Ch4) fulfils Obj5 and Obj6 by assessing the impact of individual behaviour on the system objectives.
- Chapter 5 (Ch5) fulfils Obj7 by matching the results of Ch3 with Ch4, and Obj8 by applying the findings.

– Chapter 6 (Ch6) concludes the document with a summary and recommendations.

The structure of this document is illustrated in Table 1.2.

Table 1.2 Document structure

Content\Chapter	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6
Introduction						
Obj1		§2.1, §2.2				
Obj2		§2.3				
Obj3			§3.2			
Obj4			§3.3			
Obj5				§4.3, §4.5		
Obj6				§4.4, §4.5		
Obj7					§5.1	
Obj8					§5.2	
Conclusions						

2. OBJECTIVES AND BEHAVIOURAL ASPECTS

This chapter should fulfil the following objectives:

Obj1 *Formulate the system and individual objectives as optimisation problems*
Obj2 *Identify the individual behavioural aspects that are influenced by the individual objectives*

In SUNSET WP3, Task 3.1 has delivered D3.1 which defines the individual objectives that travellers follow when making trips and the system objectives that governments follow in defining policy goals. This chapter formulates the objectives as optimisation problems, where the objective function is being minimised (or maximised), subject to certain constraints.

The impact of the individual objectives on the system objectives is realised via an intermediate link—the travel behaviour of individuals. Travellers adopt behavioural patterns according to their objectives; in turn these behavioural patterns affect the network performance and the system objectives. This chapter identifies the relevant behavioural aspects. Chapter 3 explores the relationship between individual objectives and behaviour; Chapter 4 establishes the relationship between individual behaviour and system objectives.

2.1 Individual objectives

This section, together with §2.2, should fulfil Obj1 Formulate the system and individual objectives as optimisation problems.

Based on D3.1, the individual objectives are formulated here. Only "elements" of objective are listed. An individual's personal objective is often a (weighted) combination of these elements.

D3.1 (Hodgson et al., 2011) has identified the following individual objectives:

- Time
- Scheduling
- Household resources and costs
- Social networks
- Identities and culture
- Normative beliefs and expectations
- Pleasure

Based on these objectives, eight individual objective functions are identified:

1. **To minimise travel time**
2. **To minimise scheduling effort**
3. **To minimise cost**
4. **To maximise safety/security**
5. **To maximise capital**
6. **To maximise overlap/synergy with normative**
7. **To maximise identity recognition**
8. **To maximise pleasure**

Their detailed formulations are listed in Table 2.1. Each objective is formulated as an optimisation problem, where the objective function is to be maximised or minimised, subject to a set of applicable constraints.

Table 2.1 Formulation of individual objectives

Optimisation	Objective function	Constraints
1. To minimise	travel time, as a weighted sum of: - waiting time - in-vehicle time - time in congestion or delay time - productive time while travelling taking into account personal characteristics such as: - value of time - time-poor and time-rich and on-time arrival preferences: - early/late arrival penalty	-available facilities/modes - minimum/maximum transfer time requirements - minimum reliability
2. To minimise	scheduling effort, incl.: - time taken to coordinate and plan - effort required to coordinate/plan - complexity of the scheduling	- access to information and trip planning tools - available facilities/modes
3. To minimise	cost (in excess), namely: - fuel - fare - toll	- available resources - travel budget
4. To maximise	safety/security, such as - collision avoidance with fellow passengers/traffic - ability/control of (vehicular) movement, e.g. in car - privacy vs. public exposure - protection/isolation from public	- available resources
5. To maximise	"capital" (negative cost), incl.: - natural capital (e.g. good air) - political capital (e.g. voting, participation) - social capital (e.g. relations with others, exchange of favours, information) - financial capital (e.g. car available) - physical capital (e.g. parking privileges, infrastructure provision) - human capital (education, health, etc.)	- available resources
6. To maximise	overlap/synergy with normative beliefs/expectations in the social network, valuing: opinion from the peer groups one wishes to belong to	- available resources - cultural identity/roles (gender, ethnic group)
7. To maximise	identity recognition, culturally and historically, incl.: - membership of a group, e.g. the 'slow living' and not the 'rat-race'	- available resources - cultural identity/roles (gender, ethnic group)

	- roles, e.g. being a good parent - status, i.e. patterns/perception of ownership & consumption of goods - being green, such as to minimise one's carbon footprint - being healthy and fit	
8. To maximise	pleasure	- available resources

A few elements in Table 2.1 are deemed especially relevant in SUNSET:
- **Synergy with normative**, as SUNSET provides a social network environment where individual travellers can compare their mobility profile with their peers.
- **Carbon footprint and the green identity**, as SUNSET provides a tool for monitoring an individual traveller's mobility pattern and its impact on the environment.
- **The being healthy and fit identity**, as SUNSET provides a tool to facilitate the planning and monitoring of non-motorised trips (e.g. walking, cycling).

2.2 System objectives (policy goals)

This section, together with §2.1, should fulfil Obj1 Formulate the system and individual objectives as optimisation problems.

Based on D3.1, the system objectives are formulated here. Only "elements" of objective are listed. The objective of a government is often a (weighted) combination of these elements. Moreover, the objectives can also be presented as a target of increase/reduction, instead of an absolute maximum/minimum.

D3.1 (Hodgson et al., 2011) has identified the following system objectives:
- Economic development
- Reduced congestion
- Greener towns and cities
- Smarter towns and cities
- Improved accessibility
- Improved safety and security
- Greenhouse gases

Based on these objectives, five system objective functions are identified:
- **A. To maximise accessibility**
- **B. To minimise congestion**
- **C. To maximise safety**
- **D. To minimise impact on environment**
- **E. To maximise personal wellbeing of citizen**

Their detailed formulations are listed in Table 2.2. Each objective is formulated as an optimisation problem, where the objective function is to be maximised or minimised, subject to a set of applicable constraints.

Two categories of system objectives can be distinguished, namely **efficiency**-related objectives (accessibility, congestion) and **externality**-related objectives (safety, air quality). Personal wellbeing of citizens is dealt with by focusing on traffic noise (externality-related) and personal health, since the other traffic factors that directly affect personal wellbeing of citizens, such as congestion, accident and pollution, have already been taken into account by other system objectives. Another aspect of personal wellbeing is the ability to set and monitor personal objectives. This relates to the instrument a person uses for monitoring own behaviour and is not addressed in this deliverable.

Table 2.2 Formulation of system objectives (policy goals)

Optimisation	Objective function	Constraints
A. To maximise	accessibility, incl.: - the performance level of the transport infrastructure - accessibility to spatially distributed activities	- transport infrastructure (connectivity, capacity) - available activities
B. To maximise	congestion reduction, measured by e.g. car kilometres in congestion or: - travel time, waiting time, schedule delay - throughput, capacity	- transport infrastructure (connectivity, capacity)
C. To maximise	safety & security, measured by the reduced exposure to risks, incl.: - avoidance of cyclists for car drivers - awareness of local road and weather conditions - awareness of unusual conditions - avoidance of waiting times on dark and silent (railway) stations - reduced risk of getting robbed	- impact migration restrictions
D. To maximise	environment protection, namely: - reduced CO_2 emission - improved air quality - reduced noise pollution	- EU & local regulations on thresholds - impact migration restrictions
E. To maximise	personal wellbeing of citizen, incl.: - disturbance from traffic noise - Personal health and being fit - being able to set and monitor personal objectives	

2.3 Behaviour aspects

This section should answer <u>Obj2 Identify the individual behavioural aspects that are influenced by the individual objectives</u>.

The link between individual objectives and system objectives is made via an intermediate node, represented by individual behaviour (see Figure 2.1). Individual behaviour is the results or manifestation of individual objectives (and incentives when applicable). Individual behaviour determines the network performance, which further determines to the network-level evaluation and the system objectives (policy goals).

From a mathematical point of view, individuals try to optimise their objective function by carefully choosing their decision variables. In practice these decision variables are manifested in the form of individual behaviour. Only mobility-related behaviour aspects are considered. These are divided into two categories based on timing of the decision making: planning & scheduling behaviour and en-route behaviour. Table 2.3 lists the relevant behavioural aspects, based on a literature review on the state of the art on behaviour modelling.

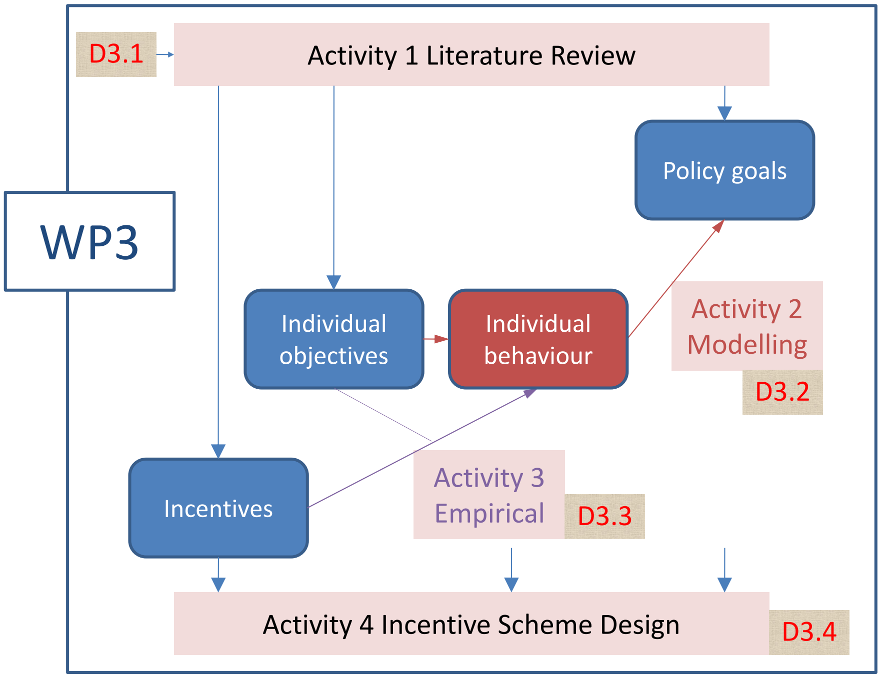

Figure 2.1 Role of Task 3.2 in Work package 3

Table 2.3 Behaviour aspects

Category	Aspects
1. Planning & scheduling behaviour	1a. Trip decision: – trip or not (e.g. home working, teleconferencing) – destination choice (e.g. shopping in the city centre instead of own neighbourhood)
	1b. Timing choice, especially in relation to congestion avoidance: – departure time choice to avoid peak hour – or strategic break-ups of the trip (e.g. an intermediate stop at gas stations) to avoid congestion
	1c. Mode choice: – car, – public transport (PT), or – alternative modes (e.g. cycling & walking) – combination of modes (e.g. P+R)
	1d. Route choice: – the route between origin and destination, esp. for the car mode as the road network is more dense than PT network

2. En-route behaviour (*mainly for the car mode*)	2a. Driver status: – workload: physical activities & mental stress – concentration: focus on the driving task, correlated to workload
	2b. Longitudinal control: – speed profile (within speed limit) – car following behaviour
	2c. Lateral control: – lane keeping/departure – lane change (e.g. gap acceptance) – overtaking
	2d. Compliance with traffic rules (if not included above) – red light violation – priority rules

Figure 2.2 illustrate the role of these behaviour aspects: the actual adopted behaviour of travellers is determined by their individual objectives; in turn it affects the network performance and the policy goals (or system objectives).

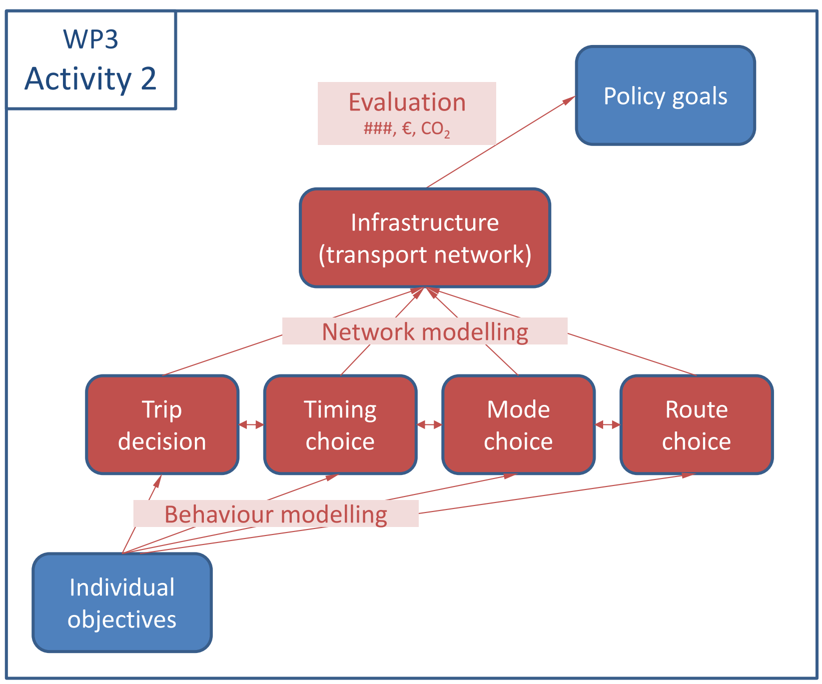

Figure 2.2 Behaviour aspects between individual objectives and policy goals

3. MODELLING: FROM INDIVIDUAL OBJECTIVES TO INDIVIDUAL BEHAVIOUR

This chapter should fulfil the following objectives:

Obj3 *Quantify the influence of individual objectives on the individual behaviour in terms of trip planning and scheduling.*

Obj4 *Quantify the influence of individual objectives on the individual en-route behaviour.*

First a comprehensive discussion (§3.1) is made on choice modelling. Travellers' behaviour can be quantified as a series of decision making process where individuals have to select from a set of options. Discrete choice modelling considers the decision of choosing an option from a finite set of alternatives. It has been widely applied to traffic and transport related studies.

Then the planning and scheduling behaviour of travellers (§3.2) is modelled with explicit mathematical models. The emphasis here is on mode choice and route choice. This is because the SUNSET services are expected to have major effects on travellers' mode and route choice decisions, and to a lesser extent on the departure time choice and trip decisions.

Afterwards the en-route behaviour (§3.3) is studied. This is only applied for the car mode, as en-route behaviour on non-car modes (e.g. transit) is not expected to have any significant impact on the system objectives. For the car mode, the en-route behaviour aspects (e.g. speed, distance keeping) are analysed based on driver motivation.

Finally a summary section (§3.4) concludes the chapter.

3.1 Discrete choice modelling

First generation transport models are often aggregated models, i.e. they are based on groups of travellers (or averages at a zonal level). Disaggregated models, such as discrete choice models, enable the modelling of choices on the individual level and are expected to bring more realistic results (Ortúzar and Willumsen, 2001). In general, discrete choice models are based on the following assumption:

The probability of individuals choosing a given option is a function of their socioeconomic characteristics and the relative attractiveness of the option.

Discrete choice modelling concerns the choice by an individual person (i.e. disaggregate) from a set of discrete (i.e. not continuous) alternatives. The choice set defines the possible alternatives (options, with the following properties:

1) Exhaustive: the choice set is all inclusive; sometimes an 'other' option is necessary.
2) Mutually exclusive: one and only one option can be selected.
3) Finite: the choice set includes a countable number of alternatives.

Utility is introduced to represent the attractiveness of an option, which the decision maker intend to maximise. Trip making by itself usually involves disutilities (i.e. cost instead of gain). Utility of a trip decision/choice is usually a combination of several variables, as the traveller has multiple concerns (objectives) in making the choice. Take route choice for example, the following are of concern: travel time, out-of-pocket money (fuel, any charges payable), safety, reliability, view, air quality, noise, etc.

Mathematically, we can only optimise one objective at a time. Utility is given as the aggregate objective which incorporates all concerns; e.g. it can be a weighted linear sum of objectives. The optimal choice is then on the alternative that maximises the utility function.

3.1.1 Random utility theory

In random utility theory, the *perceived utility* of an alternative *i* by an individual person *j* is a random variable (*r.v.*),

$$U_{ij} = V_{ij} + \varepsilon_{ij}. \tag{3.1}$$

Here V_{ij} is the *systematic utility* and ε is a *r.v.* representing *perception error*. The randomness here allows two apparent 'irrationalities' to be explained:

- Two individuals with the same attributes and facing the same choice situation may select different options;
- Some individuals may not always select the best alternative (due to the perception error).

Random utility theory is widely used to account for the stochasticity in travellers' choices.

The systematic utility is a measure on how desirable it fulfils the purpose of the choice making. A linear function is usually assumed:

$$V_{ij} = \sum_k \theta_{ki} x_{kij}. \tag{3.2}$$

Here **x** is the vector of alternative attributes and **θ** is the vector of weights (+/-). The attributes represent those factors that are of concern to the utility of an alternative, while the weights represent how (relatively) important a factor is in the utility evaluation. The weight has a positive sign (+) if the attribute is considered a utility (e.g. being safe) and a negative sign (-) if the attribute is considered a disutility (e.g. costing money).

Given the choice set $\mathbf{A} = \{A_1, A_2, ..., A_N\}$, the probability for the individual *j* to choose option *i* is given as

$$p_{ij} = \Pr\{U_{ij} > U_{mj},\ m = 1, 2, \ldots, i-1, i+1, \ldots, N\}. \tag{3.3}$$

It becomes apparent that, for the choice probabilities, only the relative values of utilities matter; adding a constant to the utilities of all alternatives does not change the choice probabilities.

For a population of S, the *expected* number of people choosing option i is

$$q_i = sum\{p_{ij}, j = 1, 2, ..., S\}. \tag{3.4}$$

Furthermore, if the choice probability function are identical among the individuals (i.e. the population is homogeneous: $p_{ij} = p_i, j = 1, 2, ..., S$), then the expected number of people choosing option i is

$$q_i = S p_{ij}. \tag{3.5}$$

Note here that the expected number is not necessarily an integer.

3.1.2 Multinomial logit model

The most popular discrete choice model under random utility theory is the multinomial logit model (MNL). MNL assumes that the random variables of perception error follow independent and identically distributed (i.i.d.) Gumbel distributions, which has the following cumulative distribution function (cdf)

$$F_{\varepsilon}(x) = e^{-e^{-\mu x}}. \tag{3.6}$$

The choice probabilities can then be derived as

$$p_{ij} = \frac{e^{\mu V_{ij}}}{\sum_{m=1}^{N} e^{\mu V_{mj}}}. \tag{3.7}$$

The scale parameter μ ($\mu > 0$) characterises perception precision. Figure 3.1 illustrates the cdf under various values of μ. Higher value of μ implies higher precision level and lower perception error. When $\mu \to \infty$, p_{ij} equals either 0 or 1. This is the case of perfect information, i.e. without perception error. The option with maximum (systematic) utility is always chosen; other options are never chosen. When $\mu \to 0$, $p_{ij} = 1/N.$. Here the perception error goes up to infinity. There is no useful information. All options are equally likely to be chosen.

An interesting property of MNL is the independence from irrelevant alternatives (IIA):

> *For a specific individual, the ratio of the choice probabilities of any two alternatives is entirely unaffected by the systematic utilities of any other alternatives.*

Mathematically, this means

$$p_{ij} : p_{kj} = e^{\mu V_{ij}} : e^{\mu V_{kj}} \quad \forall\, V_{lj}, l \neq i,k. \tag{3.8}$$

Initially this was considered an advantage of the model but nowadays this property is generally regarded as a disadvantage, as it makes the model fail in the presence of correlated alternatives (e.g. the red bus-blue bus problem).

Besides MNL, Probit model is an often discussed model which allows covariance of perception errors among alternatives. However, its choice probabilities have no closed form but are expressed in integrals, seriously limited its practical application (esp. to large scale networks).

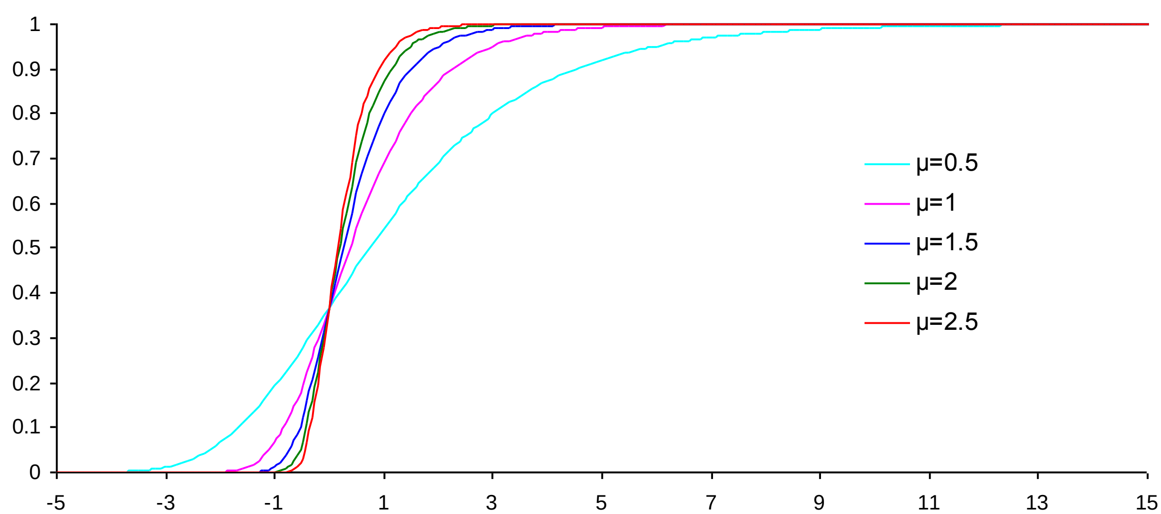

Figure 3.1 Cumulative distribution functions of the Gumbel distribution

3.1.3 Prospect theory and day-to-day choices

Prospect theory (Kahneman & Tversky, 1979) deals with the individual's decision making under conditions of risk and uncertainty. It is based on the principle of change-oriented framing, which states that choice alternatives are framed not by the expected states of them but by the expected changes they bring, relative to a *reference point*. People are risk aversive; they weigh *losses* much higher than *gains* of equivalent size. Moreover, the marginal value of both gains and losses generally decreases with their magnitude, representing a diminishing sensitivity. This means that the prospect value function is concave for gains and convex for losses. Furthermore, prospect theory postulates that people tend to overweigh extreme but unlikely event while at the same time under-weigh normal events. In mathematical formulation, it works as if people apply an S-shaped weighing function to the cumulative probabilities.

Prospect theory has recently been incorporated into travel behaviour modelling (Bonsall, 2004; Avineri & Bovy, 2008; Avineri & Chorus, 2010). In traffic assignment, prospect-based user equilibrium (PUE) (Xu *et al.*, 2011) arises when no travellers can improve their travel prospect value by unilaterally changing routes. Available studies have mainly looked at the static-state solution of PUE and its comparison with utility theory-based equilibrium (e.g. Avineri & Prashker, 2004).

Prospect theory has also been adapted for modelling day-to-day traffic dynamics (Bie et al., 2012). Standard prospect theory mainly concerns one-shot decision making. It does not take into account the feedback and consequent learning and adaptation effects over repeated trips. Besides, various definitions of reference points have been used in modelling departure and route choices (see Timmermans, 2010). Therefore updated reference points have been used which e.g. reflect the travellers' accumulated knowledge of the traffic network. The day-to-day traffic dynamics can then be modelled as a dynamical system (following Watling, 1999 and Bie & Lo, 2010).

Consider the current option r_0 having an experienced utility of w_0 and the alternative r_i having a utility outcome of x with probability (density) $p(x)$. In utility theory, the *expected utility* of r_i is given as the sum (or integral)

$$EU_i = \sum_x p(x)x, \text{ or } = \int_x p(x)x dx. \tag{3.9}$$

This expected utility is absolute and irrelative of the traveller's current experience.

In prospect theory, however, utility is evaluated relative to a reference point. For travellers currently choosing r_0, a reasonable reference point is w_0. Therefore, if alternative r_i has a utility outcome of x, the prospect value of this outcome is given as

$$g(x) = \begin{cases} (x - w_0)^{\alpha}, x \geq w_0; \\ -\lambda(w_0 - x)^{\beta}, x < w_0. \end{cases} \tag{3.10}$$

Here $\lambda \geq 1$ describes the degree of loss aversion, $\alpha, \beta \in (0,1]$ measures the degree of diminishing sensitivity. Thus, for travellers currently choosing r_0, the *prospect value* of r_i is given as

$$PV_{i,0} = \sum_x p(x)g(x), \text{ or } = \int_x p(x)g(x)dx. \tag{3.11}$$

Here, for simplicity, it is assumed that travellers do not apply the nonlinear weighting to the probabilities (as is commonly incorporated in prospect theory, e.g. in Xu *et al.*, 2011). Moreover, since the current option plays the role of reference point, its utility outcome is perceived as deterministic (at w_0) and its prospect value always takes the value of 0. Therefore the prospect values derived in (3.11) are relative to the current option, r_0.

The day-to-day traffic dynamics is captured by the option-switching process. In utility theory, travellers switch to alternatives with higher expected utilities. For the next day, travellers currently choosing r_0 would switch to r_i with probability

$$P_{i,0}^{UT} = \begin{cases} 0, & \text{if } EU_i \le w_0; \\ \kappa_0^{UT}(EU_i - w_0), & \text{if } EU_i > w_0. \end{cases} \tag{3.12}$$

Here $\kappa_0^{UT} > 0$ is a scaling factor that balances the switching ratios among the alternative options,

$$\kappa_0^{UT} = \frac{1-P_0}{\sum_{j:\,EU_j > w_0} (EU_j - w_0)}. \tag{3.13}$$

Here $P_0 \in [0,1)$ represents the travellers' probability of not considering switching and thus sticking to the current option.

In prospect theory, travellers switch to alternatives with higher prospect values. Since the current option always has a (relative) prospect value of 0, travellers switch to alternatives with positive (relative) prospect values. For the next day, travellers currently on r_0 would switch to r_i with probability

$$P_{i,0}^{PT} = \begin{cases} 0, & \text{if } PV_{i,0} \le 0; \\ \kappa_0^{PT} PV_{i,0}, & \text{if } PV_{i,0} > 0. \end{cases} \tag{3.14}$$

Here $\kappa_0^{PT} > 0$ is the scaling factor,

$$\kappa_0^{PT} = \frac{1-P_0}{\sum_{j:\,PV_{j,0} > 0} PV_{j,0}}. \tag{3.15}$$

PUE is achieved when, for each utilised option r (i.e. the amount of travellers choosing this option is positive, $f_i > 0$), all of its alternative routes have a non-positive (relative) prospect value. SUE is a special case of PUE, under the setting of $\lambda = \alpha = \beta = 1$. Mathematically, PUE is said to exist if and only if for any choice set $\mathbf{R}$ and for any option r_i in $\mathbf{R}$,

$$f_i > 0 \Rightarrow \{PV_{j,i} \le 0, \forall j : r_j \in \mathbf{R}\}. \tag{3.16}$$

Taking (3.16) into (3.14) we can see that under PUE,

$$P_{i,j}^{PT} = 0, \forall i, j. \tag{3.17}$$

This means at equilibrium option switching no longer takes place and the flows of travellers remain constant from day to day.

3.1.4 Choice behaviour as decision making process

Choice behaviour of travellers is very similar to consumer decision making. Buying a product involves five consecutive stages (Govindarajan, 2007; Newell et al., 2007):

(1) need or problem recognition,
(2) information search,
(3) evaluation of alternatives,
(4) selection or decision, and
(5) post decision behaviour.

By combining (1) and (2) to 'awareness' and (4) and (5) to 'decision', a simplified three-stage sequence is formed. In each of these three decision making stages, different psychological factors are at play which affect the individual behaviour.

It is important to realise the limitations in individual choice behaviour, a phenomenon also called "bounded rationality" (Vreeswijk et al., 2012). Figure 3.2 provides an overview of various factors that may lead to indifferences in travellers' choices (and thus "boundedly rational" behaviour). It should be noted that these factors are situation specific and therefore may vary from case to case. A detailed discussion on bounded rationality, together with its implications for traffic management, can be found in Appendix A.

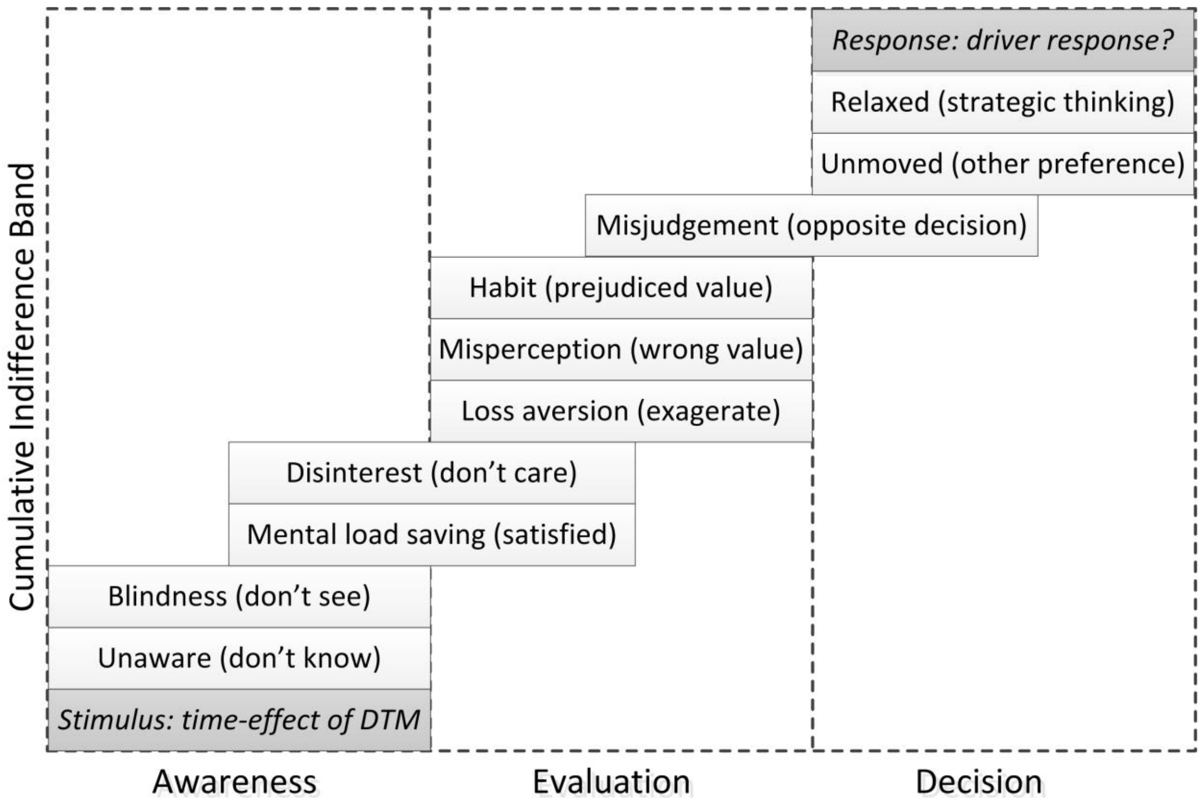

Figure 3.2 Factors of indifference in choice decision process

The behaviour modelling that accesses the influence of individual objectives of travellers on their behaviour, should therefore take into account the influence at all three stages of the choice decision process.

Major influences are expected at the decision stage where preferences are compared against each other. Given the same outcome of awareness and evaluation, different travellers may still select different options due to the difference in their personal preferences (individual objectives). This is considered as rational behaviour. Random utility theory and prospect theory can be applied to model such behaviour. Irrational behaviour arises when e.g. the traveller intentionally chooses the second-best option. However, its occurrence is deemed infrequent.

Significant influence is also expected during the evaluation phase. Travellers of certain objectives overemphasise the attributes related to these objectives and tend to misestimate attributes unrelated to these objectives. This would have the same effects on the choice outcomes as in the decision stage where selection is based on weighted averages, i.e. assigning higher weights to attributes of concern.

Some influence is also expected at the awareness stage, where traveller of certain objectives may be unaware of or disinterested in some choice alternatives. This often leads to different choice outcomes, compared to cases where the traveller should have full awareness (or information). An example is that frequent car users may even be unaware of the fact that public transport is a viable option for some of their daily trips. Another example that commonly occurs is the unawareness of P+R as an alternative (combination of) mode(s).

Besides the awareness of possible alternatives, another aspect of awareness is the awareness of relevant attributes. Traveller may be unaware of (the societal and environmental relevance of) e.g. their carbon footprint. As such, their choice decisions are made without the influence of these attributes. Trip attribute unawareness is of particular relevance to SUNSET since SUNSET provides a mobility monitoring service which increases the awareness on personal mobility profile (esp. personal carbon footprint). However, this aspect is not explicitly studied in this deliverable; here it is assumed that all relevant attributes are taken into account. Instead, its impact can be "simulated" by considering the different individual objectives, where different attributes are assigned different weights. Unawareness of an attribute would then have similar impact as if following an objective with a near-zero weight on this attribute. A more explicit study on the impact of trip attribute awareness on behaviour will be conducted during the empirical studies of the SUNSET living labs.

3.2 Planning and scheduling behaviour

This section will address Obj3 Quantify the influence of individual objectives on the individual behaviour in terms of trip planning and scheduling.

This section follows from the theoretical and practical findings of §3.1 and applies them to the choice behaviour regarding the planning and scheduling of trips. As discussed in §2.3, planning and scheduling behaviour encompasses the following choices:

- **1a. Trip/destination choice**
- **1b. Timing choice**
- **1c. Mode choice**
- **1d. Route choice**

Within SUNSET, mode choice is considered the most likely to be influenced, followed by route, departure time and trip/destination choices.

3.2.1 Individual objectives and mode choice

Mode choice is one of the most important decisions concerning a trip. For a trip with given destination and departure time, travellers will choose the mode with the highest utility. The choice set consists of the available modes:

- Private modes, e.g. driving (motor vehicle), cycling (bicycle), walking (on foot);
- Public modes, e.g. train, bus, tram, metro, ferry;
- Combinational mode, e.g. P+R.

Travellers usually preselect a number of likely modes (normally 2~3, up to 4~5), based on certain generic constraints (and/or preferences):

- The availability of a mode for the trip in discussion;
- The monetary/time constraints that render a mode undesirable.
- The travellers' personal characteristics (e.g. physical constraints) that render a mode impractical.

From this preselected choice set, travellers then make mode choice decisions based on their own reasoning. The multinomial logit model (§3.1.2) can be applied here for characterising the decision making in terms of mode choice. Under a given objective (§2.1), travellers evaluate each mode option based on the relevant attributes,

Utility (mode *i*) = (weight 1)*(attribute 1) + (weight 2)*(attribute 2)
+ … + (weight *K*)*(attribute *K*)

The mode with the highest utility has then the highest probability of being selected.

1. To minimise travel time

The objective is to minimise travel time from origin to destination. However, the decision is not as straightforward as it may sound. A door-to-door trip consists of several stages and the time spent at different stages are not equally evaluated.

Table 3.1 lists the most relevant mode attributes related to travel time. In-vehicle time is a major component of travel time. Time spent at other stages also plays an important role, especially waiting time as it adds to uncertainty.

Table 3.1 Travel time related attributes per mode

Mode	Private	Public	P+R
Attributes	In-vehicle time[1]		
	Parking time Walking time	Ingress time Waiting time Transfer time Egress time Productive time on board	Parking time Walking time Ingress time Waiting time Transfer time Egress time Productive time on board
	Reliability of travel time		

Note 1: For bicycle, cycling time; for walking, walking time.

A unique feature of travel time on public transport is the productive time on board. Travellers sitting on the train, for example, can work with their laptops. While all other components of travel time are regarded as disutilities, the productive time brings utility to the traveller. Therefore its weight in the utility function has a positive sign.

Another important attribute relates to the reliability (or variability) of travel time. Travel time is often not constant (or predictable). Consider travel time as a distribution: not only the mean values should be considered, but also the variation. It is noted that higher reliability (or lower variation) is preferred by the traveller.

2. To minimise scheduling effort

Scheduling effort captures the disutility related to the planning of a trip. In general, the effort per mode can be ranked from low to high as:

- Minimum effort: car, walking;
- Low effort: bicycle; train, metro, tram;
- Reasonable effort: bus, ferry;
- Medium effort: multi-mode public transport (e.g. bus-metro-bus);

– High effort: P+R.

Table 3.2 discusses the level of effort per mode. In terms of single-mode public transport trips, train, metro and tram are considered easier as their stations and routes are fixed and well signposted, compared to bus and ferry which are more mobile.

Multi-mode trips on public transport requires more effort due to the lack of integration and common platform planners. The extra effort here varies greatly per location. Some countries and municipalities have integrated services and planners, requiring little extra scheduling effort, while in other places different services are provided by independent operators.

P+R is considered the most difficult in terms of scheduling effort. In most countries, parking lots are privatised and no/limited centralised information is available. Also, there is currently a lack of reliable P+R planners. A well-known problem is the return journey: most P+R planners handle a return journey as two trips, with the likely outcome of suggesting different parking locations for the outbound and inbound trip.

Table 3.2 Scheduling effort related attributes per mode

Mode	Private	Public	P+R
Attributes	Scheduling effort over the road network; considered easy for the car/walking mode (esp. with the wide-spread of digital navigation); slightly less easy for the bicycle mode	Scheduling effort over the public transport network; considered reasonably easy for single-mode; less easy for multi-modal trips due to the lack of intermodal planners	Scheduling effort using P+R; considered most difficult, due to the complexity in planning and the lack of (mature) planners

3. To minimise cost

Here only out-of-pocket cost is considered (Table 3.3). Particular to the private mode (e.g. car, bicycle), depreciation, tax and insurance are not considered out-of-pocket costs. For the public mode, a transit pass paid by third parties (e.g. employer of the traveller) is also not considered as out-of-pocket cost.

In general, the cost per mode can be ranked from low to high as:

– Low cost: bicycle, walking;
– Medium cost: car; public transport;
– High cost: P+R.

Table 3.3 Cost related attributes per mode

Mode	Private	Public	P+R
Attributes	Fuel cost Road toll Parking fee	Fare	Fuel cost Road toll Parking fee Fare (transit)

The difference between cost by car and cost by public transport varies per location: in metropolitan areas of Europe, public transport is often cheaper due to governmental subsidies; in locations not well services by public transport, the car mode is often cheaper. The latter comparison, however, greatly depends on the fuel price, which has been rising steeply over the past years.

4. To maximise safety/security
Safety mainly concerns traffic accidents, while security related to personal safety (free from violence and crimes).

In terms of accidents, statistics indicate that public modes are safer than the car mode. Safety-concerned travellers are therefore more likely to take the transit than driving. Cycling may be considered as unsafe depending on location and infrastructure.

Security by car is generally good. Security of public transport greatly depends on the time of day, location (city centre versus rural area; or presence of fellow passengers), and type of service (e.g. presence of personnel).

5. To maximise capital
This objective postulate that travellers will try to use their capital as much as possible. This means:

- For car owners: use car as much as possible;
- For bicycle owners: use bicycle as much as possible;
- For transit pass owners: use transit as much as possible.

Mathematically, possession of certain capital will add to the utility of the corresponding mode, making that mode more likely to be chosen.

Physical fitness may be considered also as a type of capital. This means that:

- Healthy people are more likely to use the bicycle/walking mode.

6. To maximise overlap/synergy with normative
This objective depends on the behaviour of peers. For mode choice, it means that people try to take the mode that their fellows do. Under this objective, the following observation can then be made:

- Students, in general, tend to use public transport;
- Colleagues often commute with the same mode, which means that, for an individual company, the majority of its employers commute with the same mode.

In terms of response to changes, traveller with this objective has a wide indifference band and require a large change before they will adjust their behaviour. However, once such momentum is started, others will follow suit. From a day-to-day point of view, this objective contribute positively to the stability of over-time dynamics of traffic.

Another point of discussion is the subjective perception of what is normative.

7. To maximise identity recognition
This objective is correlated to capital and synergy with normative. People identify themselves as belonging to certain social categories, which highly correlates with their possession of capital. Each category has its own standard possession and normative behaviour.

In terms of mode choice, it means that:

- Fans of automobile are more likely to drive;

– People who identify themselves as 'green' or care about their carbon footprint are more likely to use sustainable modes.

8. To maximise pleasure
Pleasure is subjective. Some people considered the transit mode as more pleasurable, while others find driving more pleasurable. For both groups, P+R will be less pleasurable.

3.2.2 Individual objectives and route choice

Route choice mainly concerns travellers on the car mode (and partially on the P+R mode). Route choices for other modes are quite limited. Car drivers choose route based on their objectives. Theoretically there can be an infinite number of routes connect an origin-destination pair. However, drivers usually consider a route set consisting of 2~5 typical routes.

Multinomial logit model should be applied with caution to route choice. Alternative routes usually overlap with each other, meaning their random terms are correlated, contrary to the i.i.d. assumption made in the model. Therefore, for route choice situations where the typical routes overlap with each other to a large extent, more advanced models should be applied such as the nested-logit model (Daly & Zachary, 1978) and the mixed-MNL (MMNL) model (McFadden & Train, 2000). As this deliverable only focuses on the general relationship between objectives and route choice and does not apply MNL for numerical results, this limitations of the MNL model does not affect the discussions below.

1. To minimise travel time
This objective means that the driver would choose the quickest route. The only attribute of concern is route travel time. Reliability of route travel time may also come into play if variation is high.

2. To minimise scheduling effort
Under this objective, the driver will follow the normal route (without in-car navigation system) or the suggest route (with in-car navigation system).

Consider the road network consisting of three road categories (Dijkstra & Drolenga, 2008):
- Highway;
- Distributor road (arterial);
- Access road (local/neighbourhood road)

The normal (or most logical) route usually follows the order: access-distributor-highway-distributor-access. In practice this means that drivers would just follow road-side direction sign (see Figure 3.3 for an example from Sweden).

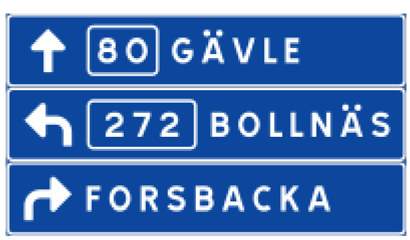

Figure 3.3 Road-side direction sign in Sweden

If an in-car navigation system is present, the driver will follow the route suggested by the system. Most navigation systems support route finding using three objectives:
- Quickest route (based solely on travel time);

- Shortest route (based solely on distance);
- 'Optimal' route (based on a combination of travel time and distance).

The 'optimal' option is often the default setting, meaning that the route will be chosen that minimises a weighted sum of travel time and distance.

With the increasing popularity of in-car navigation systems, it is expected that more and more car drivers will be equipped. Nowadays, newly developed car models even have the in-car navigation as a standard built-in feature.

3. To minimise cost

Cost here concerns fuel cost and road toll. Cost is closely correlated to distance and travel time. Route fuel cost can be estimated as a function of the speed profile, or distances driven per each speed level.

Drivers with the objective of minimising cost are likely to
- Choose route with shorter distance;
- Choose route with reasonable speed (neither too high nor too low);
- Avoid road toll.

4. To maximise safety/security

Route safety can be defined using the Dutch SWOV methodology (Dijkstra et al., 2007). For each route, its safety level is determined based on nine criteria (1-9):
- composition of road categories along the route (1-3) and their lengths (4-6),
- route travel time (7),
- number of left turns[1] (8), and
- number of intersections on the distributor roads en route (9).

A route is safer if it follows the order of access-distributor-freeway-distributor-access roads, and if the majority of it lies on the freeway. On the other hand, route distance, travel time, left turns (for driving on the right hand side of the road), and intersections are assumed to negatively impact route safety.

When evaluating a route, a score on the scale of 0~100 is given for each criterion, with 0 being the least safe and 100 being the safest. The average score for the nine criteria determines the overall safety score for the route.

The safety score defines the safety level of a route, relative to other routes in the route set. With the route safety scores, different routes can be compared based on safety. For each OD pair, the route with the highest score is selected as the safest route.

It is noted that the safety score as defined above addresses the impact of road quality and traffic volume in an indirect way. The quality and prevailing traffic volume of a road is indirectly represented by its road category, where higher category is assumed to be safer and roads within the same category are assumed to be equally safe. This is less problematic for countries such as the Netherlands, where the road infrastructure is highly standardised and the population distribution is more or less even. But for locations where roads in the same category vary greatly in terms of quality and traffic volume, the above method needs to be adjusted.

Moreover, the above method does not take into account factors such as the likelihood to be affected by fog (which depends on the geographical setting of the road) and the availability of

[1] This applies the locations where cars drive on the right hand side of the roads, such as the Netherlands. For left-driving locations such as the U.K., this should be replaced by right turns.

lighting at night. These additional factors should be added to the nine criteria when applicable (i.e. where localised fogging is a common occurrence, and at night).

Route security relates to the location of route and is particularly affected by the time of the day. Drivers concern with security will most likely choose route that is on the main road. They will not take a shortcut which passes a quite/remote area; the availability of road lighting is also a major concern, especially at night.

In general, it is expected that safe route and secure route coincide with each other to a large extent.

5. To maximise capital
This objective is believed to not significantly affect route choice behaviour.

6. To maximise overlap/synergy with normative
This objective is believed to have the same effect as the objective to minimise scheduling effort.

7. To maximise identity recognition
This objective is believed to not significantly affect route choice behaviour.

8. To maximise pleasure
Route choice may be affected depending on what type of pleasure is being sought. People who are fond of speed may prefer routes with higher speed (with speed carrying a heavier weight in the utility function). Other people may prefer routes with great landscape (with being scenic as an important route attribute).

3.2.3 Individual objectives and timing choice

Timing choice mainly concerns departure time choice, which may have limited options. For the car mode, departure time is more flexible. For transit mode, however, departure time choice may be quite restricted.

1. To minimise travel time
This objective does not affect the transit mode much, as travel time on public transport is normally constant over time (except due to the crowding effect and the within-day schedule variations). The same applies to the bicycle and walking modes.

For the car mode, this basically means that the driver would choose a departure time that minimises travel time. In other words, the driver would try to avoid congestion by departing earlier or later.

Due to arrival time constraints, this objective means that the morning peak-hour commuter will try to leave home early.

2. To minimise scheduling effort
This objective means that travellers would just follow the departure time as suggested by the trip planner. It is believed to not significantly affect departure time choice behaviour.

3. To minimise cost
Similar to travel time, this objective means that the driver would try to avoid congestion. For morning peak commuters, this means leaving home earlier.

For the transit mode, people may avoid peak hours in order to travel with off-peak discounts (e.g. the "*voordeelurenkorting*" of Dutch Railways).

4. To maximise safety/security
Similar to travel time and cost, to maximise safety means to avoid congestion.

Security is believed to not affect departure time choice.

5. To maximise capital
This objective is believed to not significantly affect departure time choice.

6. To maximise overlap/synergy with normative
This objective means that travellers would go with their peers, i.e. they like congestion on the road and crowdedness on public transport.

7. To maximise identity recognition
This objective is believed to have similar effect as the objective of maximising overlap/synergy with normative.

8. To maximise pleasure
Most people would consider congestion and crowdedness not very pleasurable. Therefore they would try to avoid peak hours, for both private and public modes.

Travellers on the car mode (i.e. driving) prefer to time their trip when the weather is good. They may therefore delay a trip by waiting for the rain to stop.

3.2.4 Individual objectives and trip decision

The traveller behaviour related to trip decision concerns the trip/no-trip choice and destination choice. People may decide to skip a commuting trip by working at home, or they may skip the shopping trip since the weather is bad.

1. To minimise travel time
People with this objective tend to make less and shorter trips. They try to avoid long trips and replace them with shorter trips, e.g. shopping nearby.

2. To minimise scheduling effort
People with this objective make very few spontaneous trips, as each such trip requires scheduling effort. They usually travel to the same places and do not tend to explore new locations.

3. To minimise cost
Similar with travel time, people with this objective tend to make less and shorter trips.

4. To maximise safety/security
People with this objective tend to make less trips, especially to remote areas.

5. To maximise capital
People with this objective tend to make more and longer trips, to visit various new locations.

6. To maximise overlap/synergy with normative
This objective is believed to not affect trip decisions.

7. To maximise identity recognition
People with this objective tend to make more trips, especially to locations where their peers frequent.

8. To maximise pleasure
This objective means that people will make more leisure trips and to pleasurable locations (e.g. attraction sites).

3.3 En-route behaviour

This section will address Obj4 Quantify the influence of individual objectives on the individual en-route behaviour.

The en-route behaviour mainly concerns the driving behaviour (i.e. when the chosen mode is, at least partially, "car"). The relevant aspects include:

- **2a. Driver status: workload & concentration**
- **2b. Longitudinal control**
- **2c. Lateral control**
- **2d. Compliance with other traffic rules**

The following personal objectives are believed to not affect en-route behaviour:

2. To minimise scheduling effort
4. To maximise security
5. To maximise capital

3.3.1 Individual objectives and driver status

Driver status here mainly concerns the driver workload and concentration. Factors related to the longitudinal and lateral control of the car, and compliance with traffic rules, are addressed in the subsequent subsections.

The following individual objectives are believed to not affect driver status:

1. To minimise travel time
3. To minimise cost
6. To maximise overlap/synergy with normative
7. To maximise identity recognition

4. To maximise safety
Drivers with the objective of maximising safety will be concentrating on the driving tasks and paying attention to any emerging safety hazards.

8. To maximise pleasure
Drivers with this objective may be distracted by activities that are not part of the driving task but pleasurable to them, e.g. enjoying the scenery, listening to music.

3.3.2 Individual objectives and longitudinal control

Longitudinal control concerns the speed profile of the car and, in the presence of a predecessor (the front vehicle), the car following behaviour.

Speed profile registers the distribution of speed over time, with which characteristics such as average/maximum speed, ac-/deceleration rate can be derived.

Car following behaviour is characterised by the headway that the driver tries to maintain, and the ac-/deceleration behaviour in response to the predecessor.

1. To minimise travel time
Drivers with this objective tend to have a higher speed and a shorter headway with the predecessor.

3. To minimise cost
Drivers with this objective try to maintain a steady speed profile. They tend to avoid unnecessary ac-/decelerations, in order to save fuel.

4. To maximise safety
Drivers with this objective tend to have a normal speed and a longer headway with the predecessor. Normal speed is the prevailing speed in the traffic stream. This is often bounded from above by the applicable speed limit.

6. To maximise overlap/synergy with normative
Drivers with this objective tend to have a normal speed and a normal headway with the predecessor. Normal headway depends on the prevailing traffic situation. The minimum suggested headway is 2 seconds in most driver manuals but drivers tend to hold a shorter headway nowadays.

7. To maximise identity recognition
Drivers who identify themselves as green or being aware of their carbon footprint tend to maintain a steady speed profile.

Drivers who self-identify as motor bikers tend to have excessive speed and ac-/decelerations, esp. when on motorbikes.

8. To maximise pleasure
For people who enjoy high speed, they tend to exceed the speed limit more often. Tailgating is also more likely.

3.3.3 Individual objectives and lateral control

Lateral control concerns the lane keeping and lane change/overtaking behaviour.

The following individual objectives are believed to not significantly affect drivers' lateral control behaviour:

- **3. To minimise cost**
- **6. To maximise overlap/synergy with normative**
- **8. To maximise pleasure**

1. To minimise travel time
Drivers with this objective tend to change lanes more often.

4. To maximise safety
Drivers with this objective tend to change lanes less often. When they do change lanes, the available gap is usually larger than normal.

7. To maximise identity recognition
Drivers who self-identify as motor bikers tend to make more lane change and overtaking manoeuvres, esp. when on motorbikes. They are also willing to accept shorter gaps.

3.3.4 Individual objectives and compliance with traffic rules

Besides longitudinal and lateral control, the driving task also includes vehicle control at intersections. Here the relevant behaviour aspects are:

- Compliance with traffic light;
- Compliance with priority (right-of-way) rules.

The following individual objectives are believed to not significantly affect drivers' compliance behaviour:

3. To minimise cost
8. To maximise pleasure

1. To minimise travel time
Drivers with this objective have a slightly higher likelihood of not observing traffic light and priority rules to the full extent.

For traffic light, a well-known phenomenon is the yellow light running: drivers attempts to catch the last few second of the yellow phase.

For unsignalised intersections, drivers can force their way into another traffic stream, even if the available gap is not long enough. This often requires the following vehicle to brake.

4. To maximise safety
Drivers with this objective tend to observe traffic light and priority rules to the full extent.

6. To maximise overlap/synergy with normative
Drivers with this objective tend to observe traffic light and priority rules to the full extent.

7. To maximise identity recognition
Drivers who self-identify as motor bikers tend to have a slightly higher likelihood of not observing traffic light and priority rules to the full extent, similar to travellers who aim to minimise their travel time.

3.4 Summary: the individual behaviour under given individual objectives

This section summarises the results of the previous sections.

Table 3.4 lists the most significant behavioural implications of the individual objectives. These implications, discussed in details in §3.2 and §3.3, have been derived by applying the discrete choice modelling framework (§3.1), complemented by expert interviews (with traffic psychologists in the SUNSET consortium). Significance is represented by the strength of the implications. Major implications exhibit the strongest connection, with minor implications less strong but still significant under certain specific scenarios.

For easy reference, the behaviour aspects are labelled here as:

Planning and scheduling behaviour:

- 1a. Trip/destination choice
- 1b. Timing choice
- 1c. Mode choice
- 1d. Route choice

En-route behaviour:

– 2a. Driver status: workload & concentration
– 2b. Longitudinal control
– 2c. Lateral control
– 2d. Compliance with other traffic rules

It should be noted that route choice and en-route behaviour apply mainly to the car mode.

Table 3.4 Behavioural implications of individual objectives

Objectives	Behavioural implications
1. To minimise travel time	Major: - 1c: choose the (combination of) mode(s) that is the quickest - 1d: always choose the quickest route Minor: - 1b: depart earlier or later to avoid congestion, subject to constraints (or delay and early arrival penalties) - 2b: tend to have a high speed and keep a short headway - 2c: tend to change lanes and/or overtake more frequently
2. To minimise scheduling effort	Major: - 1c: choose the travel mode that is available/known/offered as options (by the scheduling tool) Minor: - 1d: choose the "default" route (normally the fastest route) - 1a: tend to make less trips; tend to visit the destination available/known/offered as options
3. To minimise cost	Major: - 1c: choose the cheapest travel mode (based on out-of-pocket cost) - 1b: choose the cheapest departure time (e.g. off-peak discount fare on public transport) - 1d: choose the cheapest route (in terms of fuel cost and any applicable road toll) Minor: - 1a: avoid unnecessary/long trips - 2b: avoid unnecessary ac-/decelerations (in order to save fuel)
4. To maximise safety	Major: - 1d: prefer safer routes, incl.: (i) preference of the highway over local roads; (ii) avoidance of congested route; (iii) preference of heavily instrumented route (e.g. lighting), especially at night - 2b: prefer a safe (lower) speed and (longer) headway with the front vehicle - 1c: prefer safer/securer travel mode, e.g.: (i) car may be considered more secure than transit; (ii) bicycle might be considered as (un)safe with(out) exclusive bicycle lanes

	Minor: - 2a: higher concentration/attention level - 2c: less risky lane change/overtaking (i.e. longer critical gaps) - 2d: always comply with traffic rules
5. To maximise capital	Major: - 1c: prefer to use personally owned facilities (e.g. cars, bicycle) Minor: - 1a: tend to make more trips when facilities are available
6. To maximise synergy with normality	Major: - 1b: do not try to avoid peak hour or congestion - 1c: follow what peers use in mode choice - 1d: tend to follow the "default" route Minor: - 2b: comply with speed limit - 2d: tend to comply with traffic rules
7. To maximise identity recognition	Major: - 1c: more consistent in mode choice over time, e.g.: (i) travellers with 'green' identity prefer the transit mode; (ii) travellers with 'car user' identity always choose car - 2b: drivers with 'green' identity tend to have a steady speed profile; drivers with 'motor biker' identity tend to have high speed and make more ac-/decelerations - 1b: do not try to avoid peak hour or congestion Minor: - 1a: make more planned trips (esp. to locations where fellows frequent) and less spontaneous trips
8. To maximise pleasure	Major: - 1d: choose the most pleasurable route, such as route with good view or along attraction sites - 1b: choose departure time based on congestion avoidance and pleasure-related preferences, such as weather Minor: - 1c: choose the most pleasurable travel mode - 2a: may lose concentration (due to e.g. scenery, music) - 2b: tend to speed and tailgate when deemed pleasurable

4. ASSESSMENT: FROM INDIVIDUAL BEHAVIOUR TO NETWORK PERFORMANCE (SYSTEM OBJECTIVES)

This chapter should fulfil the following objectives:

Obj5 *Assess the influence of individual planning/scheduling behaviour on the network performance in terms of the system objectives.*

Obj6 *Assess the influence of individual en-route behaviour on the network performance in terms of the system objectives.*

The chapter starts by discussing the theoretical background of impact assessment (§4.1) and the quantification of system objectives (§4.2). Based on these, the impact of planning and scheduling behaviour will then be analysed using network modelling (§4.3). The chapter continues with the impact assessment of en-route behaviour, esp. on the externality-related system objectives (§4.4). The next section (§4.5) discusses the impact of behaviour on citizens' personal wellbeing (with a focus on traffic noise and personal health). Finally a summary section (§4.6) concludes the chapter.

4.1 Impact assessment

Impact assessment is the process of identifying the expected or actual impacts of a development intervention. Impact is defined as the differences between the base/before scenario (*status quo*) and the design/after scenario (with the development intervention). These differences are characterised by certain social, economic, and environmental factors. The intervention is termed here as the *subject* of the impact, and the characterising factors are the *object* of the impact, with the syntax "the impact *of* (a subject) *on* (an object)".

Impact assessment may take place before the approval of an intervention (*ex ante*) or after completion of the intervention (*ex post*). *Ex ante* assessment forecasts the potential impacts of an intervention. It supports the approval, planning, and design of the intervention. *Ex post* assessment identifies the actual impacts of the intervention, during and after its implementation. It helps the monitoring and review of the intervention, enables corrective actions to be taken if necessary, and provides information for improving future designs of interventions.

In SUNSET, the development intervention is the provision of the SUNSET services. Work package 3 deals with the *ex ante* assessment while Work packages 6&7 focus on the *ex post* assessment. For Task 3.2 in particular, the development intervention is represented by the changes in individual behaviour, which can be expected when the SUNSET services are implemented.

Here we focus on the impact of changes in individual behaviour on the system objectives. As discussed in §2.3, two categories of behaviour (subjects of impact) are of concern here:

Planning and scheduling behaviour

- 1a. Trip/destination choice
- 1b. Timing choice
- 1c. Mode choice
- 1d. Route choice

En-route behaviour on the "car" mode

- 2a. Driver status: workload & concentration
- 2b. Longitudinal control

– 2c. Lateral control
– 2d. Compliance with other traffic rules

The system objectives to be assessed (objects of impact) are (§2.2):

A. To maximise accessibility
B. To minimise congestion
C. To maximise safety
D. To minimise impact on environment
E. To maximise personal wellbeing of citizen

The objective of this chapter is to establish the relationship between the subjects of impact and the objects of impact. Mode choice (1c) is considered the most likely to be influenced by the SUNSET services; it is therefore the focus of impact assessment, followed by route, departure time and trip/destination choices. The en-route behaviour (only for the "car" mode) is expected to mainly affect the externality related system objectives.

4.1.1 Before and after analysis: changes in behaviour

Quantitative changes in behaviour are necessary inputs for a quantitative assessment of their impact on the system objectives. Direct measurements can be used for each of the behaviour aspects (Table 4.1). These include e.g. the physical measurements of the network status over the temporal and spatial dimensions, and incidence counts of certain events.

Table 4.1 Quantitative measurements of behaviour

Behaviour	Examples of quantitative measurements	Unit
1a. Trip/destination choice 1b. Timing choice 1c. Mode choice	OD-demand matrices, per time window, per mode	Volume[1]
1d. Route choice	Route traffic assignment (over time, over mode) – Network flows – Link travel times – Delays at intersections	 Volume[1] Time (s) Time (s)
2a. Driver status	Concentration level Number of distractions	Scale (1…5) Count (#)
2b. Longitudinal control	Amount of speed limit violations Distance driven under a certain speed level Time spent with a certain headway level	Count (#) Distance (km) Time (s)
2c. Lateral control	Amount of lane changes Lengths of critical gaps	Count (#) Time (s)[2]
2d. Compliance with other traffic rules	Amount of red light running Lengths of critical gaps at unsignalised intersections Amount of forced merging	Count (#) Time (s)[2] Count (#)

Note 1: Unit of traffic volume (or intensities) depend on modes. For the car mode, volume can be measured by veh/hr, or alternatively by pcu/hr (passenger car equivalent per hour). For the transit mode, volume is measured by the amount of passengers (psg/hr).

Note 2: Gaps can also be measured by distance (m) but time (s) is more representative as time also accounts for the difference in speed.

Changes in behaviour can then be quantified as changes in these measurements (Table 4.2). Changes are bidirectional (+/-) and can be expressed absolutely (in amounts, #) or relatively (in percentages, %).

Table 4.2 Quantification of changes in behaviour

Behaviour	Quantification of changes before and after
1a. Trip/destination choice	Changes (+/-, #/%) in OD-demand
1b. Timing choice	Shift of demand between departure time windows
1c. Mode choice	Shift of demand between modes
1d. Route choice	Changes (+/-, #/%) in road traffic assignment (over time) – Network flows – Link travel times – Delays at intersections
2a. Driver status	Changes (+/-, #/%) in concentration level Changes in number of distractions
2b. Longitudinal control	Changes (+/-, #/%) in amount of speed limit violations Changes in distance driven under a certain speed level Changes in time spent with a certain headway level
2c. Lateral control	Changes (+/-, #/%) in amount of lane changes Changes in lengths of critical gaps
2d. Compliance with other traffic rules	Changes (+/-, #/%) in amount of red light running Changes in lengths of critical gaps at unsignalised intersections Changes in amount of forced merging

4.1.2 Data requirement

The changes alone, absolute or relative, are not enough for conducting the *ex ante* assessment of impact, because impact also depends on the reference scenario. Therefore knowledge about the before scenario (status quo) is required. This requirement is often overlooked, where people expect a linear relationship between subjects of impact and objects of impact.

Consider S as the subject of an impact and O as the object. Denote X_S and Y_O as the state measurement of the subject and the object, respectively. The underlying assumption of impact assessment is that the relationship between subject and object remains unchanged before and after. Therefore,

$$\begin{cases} Y_O(\text{before}) = f\left(X_S(\text{before})\right); \\ Y_O(\text{after}) = f\left(X_S(\text{after})\right). \end{cases} \tag{4.1}$$

Here the development intervention is given by

$$\text{intervention} = X_S(\text{after}) - X_S(\text{before}), \tag{4.2}$$

and the impact quantified by

$$\text{impact} = Y_O(\text{after}) - Y_O(\text{before}). \tag{4.3}$$

The obvious question is whether impact is a function of intervention independent of the before state, i.e.

$$\text{impact} = g(\text{intervention}). \tag{4.4}$$

Consider the case where f is linear, i.e.

$$f(.) = m \times (.) + b. \tag{4.5}$$

Then we can derive

$$\text{impact} = m \times \text{intervention}. \tag{4.6}$$

That is, impact is proportional to intervention. However, when f is non-linear, impact depends not only on the intervention (net changes) but also on the reference point (status quo).

The SUNSET system objectives are believed to have a non-linear relationship with the changes in traveller behaviour. Therefore the minimum data requirement for conducting the impact assessment is the changes (absolute or relative) together with a reference measurement (e.g. of the before scenario).

Table 4.3 lists the different possible combinations of minimal data for impact assessment. They are all equivalent in terms of the fact that, as long as any combination has been defined, all other combinations can be derived. For example, with the knowledge of Combination 1, Combination 2 can be derived by applying

$$\textit{Changes}(\#) = X_S(\text{after}) - X_S(\text{before}). \tag{4.7}$$

Similarly, Combination 3 can be derived by applying

$$\textit{Changes}(\%) = \frac{X_S(\text{after}) - X_S(\text{before})}{X_S(\text{before})} \times 100\%. \tag{4.8}$$

Table 4.3 Data requirement for impact assessment

Combinations	**Sufficient data on the subject of the impact for conducting the impact assessment**			
	Before scenario measurements	***After scenario measurements***	***Changes (#) before/after***	***Changes (%) before/after***
1	√	√		
2	√		√	
3	√			√
4		√	√	
5		√		√

In practice, the most commonly used combinations are Combination 3 and Combination 2, where a base scenario measurement together with a change quantifier are indicated for the impact assessment. In SUNSET, however, the after scenario is always measured with mobility sensing. Different possibilities (Table 4.4) exist for collecting sufficient data:

– Combination 1: run a before scenario mobility sensing; or,

– Combination 4 or Combination 5: conduct empirical studies to identify the changes before and after, using stated preference questionnaires or experience sampling (self-reporting) techniques.

Given the measurements of sufficient data, impact on the SUNSET policy goals can be assessed. §4.2 below discuss how impact can be quantified, i.e. how to formulate the impact as a function of the intervention.

Table 4.4 Impact assessment in SUNSET: data collection possibilities

Combinations of sufficient data	Before scenario measurements	After scenario measurements	Changes (#) before/after	Changes (%) before/after
1	Mobility sensing	Mobility sensing		
4		Mobility sensing	Survey	
5		Mobility sensing		Survey

4.1.3 The effect of penetration level

When conducting impact assessment, it is important to realise that the subject of impact (the development intervention) may not reach all travellers. This depends on the type of intervention or measures in discussion. Infrastructure-oriented measures are enforced to all travellers, while traveller-oriented measures are usually applied to only a subgroup of the travellers. This is captured by the notion of penetration level.

The impact of many ITS applications, especially cooperative driver assistance systems, depends on their penetration levels, i.e. how many road users are equipped with the application. The benefit generated by such an ITS application usually has a non-linear relationship with its penetration level.

The SUNSET services can be considered as a type of ITS. The standalone features in SUNSET, such as mobility profile, is independent of the penetration level, because their impact is effectuated on the individual travellers and does not depend on the interaction between equipped users. However, the cooperative features in SUNSET, such as social networking services, is highly dependent of the penetration level. A low equipment rate would render the service as not very interesting to the end users.

A simulation-based case study on the impact of CACC (cooperative adaptive cruise control) systems (van Arem et al., 2006) shows that: (a) at a low penetration level of 20%, the average speed just before a lane drop is actually lower than the reference case (0% penetration); (b) at penetration levels higher than 40%, the average speed is higher than the reference case and the increase in speed is a convex function of the penetration level. Therefore it is crucial to consider potential penetration levels during the deployment phases of the ITS application.

Denote by B the traffic benefit produced by an ITS application (e.g. reduction of travel time and emission) to an individual driver. Denote by Q the penetration level of the application. B is said to be a function of Q, i.e.

$$B = f(Q). \tag{4.9}$$

Figure 4.1 illustrates an example of such a function (taken from the CACC example above). Lower penetration levels may bring negative impact to the traffic system. In this case there is a minimum penetration level (Q^*) in order to achieve positive benefit. At the maximum penetration level of 100%, the achieved benefit is denoted by B_{100}. As long as the function *f* is monotone for $Q > Q^*$, B_{100} is the maximum achievable benefit.

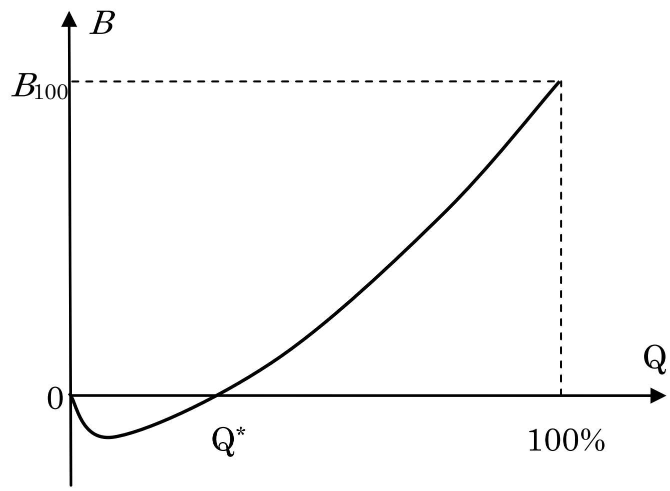

Figure 4.1 Traffic benefit of an ITS application (*B*) **vs. its penetration level** (*Q*)

Since a higher penetration level is desirable from a traffic point of view, it is argued (Bie & van Berkum, 2012) that the government (or the traffic management authority) should provide financial subsidies to the ITS developers in order for them to lower the retail price, so that more drivers will purchase and use the ITS application. Alternatively, economic incentives can be given to the driver instead, such as a partial reimbursement of the retail price. This is similar to incentive schemes that reward the driver for safe behaviour (Bie et al., 2010), where a win-win situation can also be achieved. A detailed discussion on this subject can be found in Appendix B.

4.2 Quantification of system objectives

This section provides the methodology to quantify the system objectives. The following sections (§4.3, §4.4, and §4.5) would then apply these quantification method to assess the impact of behaviour on the system objectives.

Quantification of the system objective "personal wellbeing" (E), is dealt with, as mentioned in §2.2, by considering traffic noise and personal health. Traffic noise is discussed here as an element of the externalities (§4.2.2). Personal health is only assessed qualitatively; this is discussed in §4.5.

4.2.1 Quantification of impact: efficiency

Efficiency concerns accessibility and congestion.

Accessibility

Accessibility in general can be defined as "the potential of opportunities for interaction" (Hansen, 1959). For passenger transport, we consider accessibility as (Geurs & van Wee, 2004)

> *"the extent to which lane-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)".*

Accessibility, defined as such, encompasses a number of components (Geurs & van Wee, 2004):

- The land-use component, incl. the opportunities supplied at each destination location and the demand for these opportunities at the origin locations;
- The transport component, generally representing the disutility (time, cost, effort etc.) for an individual to transverse from an origin to a destination;
- The temporal component, reflecting the temporal distribution of opportunities; and
- The individual component, incl. the needs and capability of individuals regarding the opportunities.

Accessibility can be measured in various ways (Geurs & van Wee, 2004):

- Infrastructure-based measurements, i.e. the performance level of the transport infrastructure;
- Location-based measurements, i.e. the level of accessibility to spatially distributed activities;
- Person-based measurements, e.g. the activities that an individual can participate;
- Utility-based measurements, i.e. the economic benefits derived from people's access to activities.

Table 4.5 provides an overview of the different measurement and their corresponding components. Infrastructure-based measurements are strongly correlated with congestion measurement, which will be discussed separately later in this section. In this study we measure accessibility mainly by location, where the contour measurement (Ingram, 1971; Wickstrom 1971; Wachs & Kumagai, 1973; Black & Conroy, 1977; Guy, 1983) is the most commonly used.

Table 4.5 Measurements of accessibility based on components

Measurements	**Components**			
	Land-use	**Transport**	**Temporal**	**Individual**
Infrastructure-based	–	Traffic speed; vehicle-hours lost in congestion	Peak-hour period	Stratification of trips
Location-based	Spatial distribution of demand/supply of opportunities	Travel time/cost between locations of activities	Distribution of travel time/cost over time	Stratification of population
Person-based	Spatial distribution of supplied opportunities	Travel time between locations of activities	Availability of activities over time	Individual-level accessibility
Utility-based	Spatial distribution of supplied opportunities	Travel cost between locations of activities	Distribution of travel time/cost over time	Individual- or group-based accessibility

Source: Geurs & van Wee (2004).

A contour measure (also known as isochronic measurement) counts the number of opportunities that can be reached within a given travel time, distance or cost. An example is given in Figure

4.2 and Figure 4.3, which illustrate the locations that can be reached, within certain time, by car and by public transport, respectively, from the origin represented by the post code area of 7522 in the Netherlands (where the University of Twente campus is located). These charts are accessible via the website http://www.bereikbaarheidskaart.nl/. Obviously, accessibility on the car mode is higher in this case than accessibility on the transit mode.

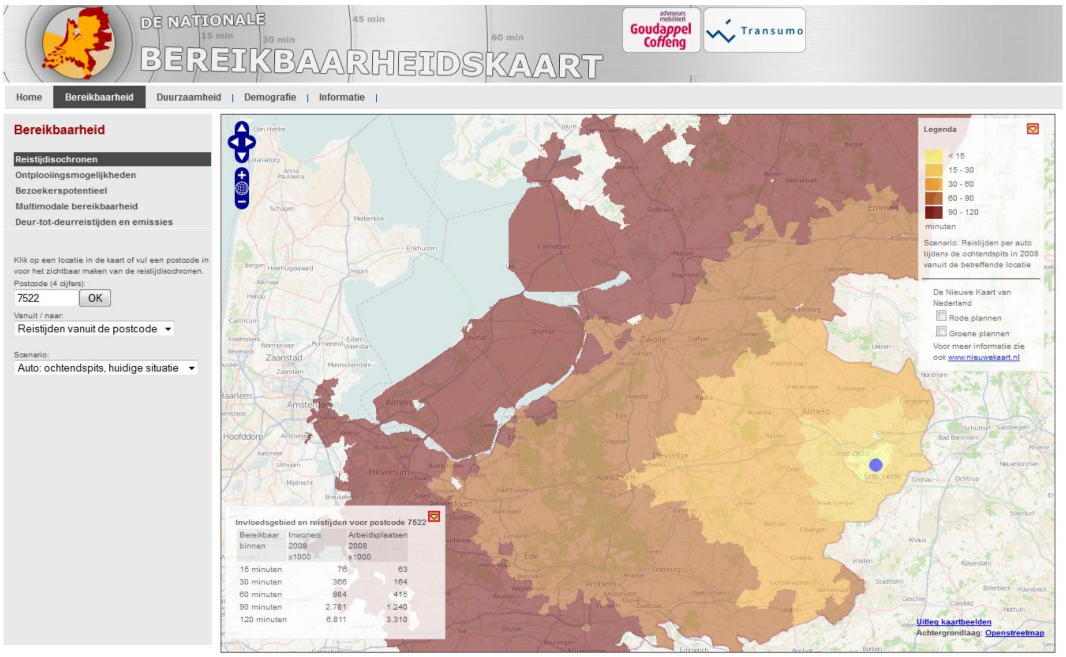

Figure 4.2 Isochrone map: accessibility per travel time by car

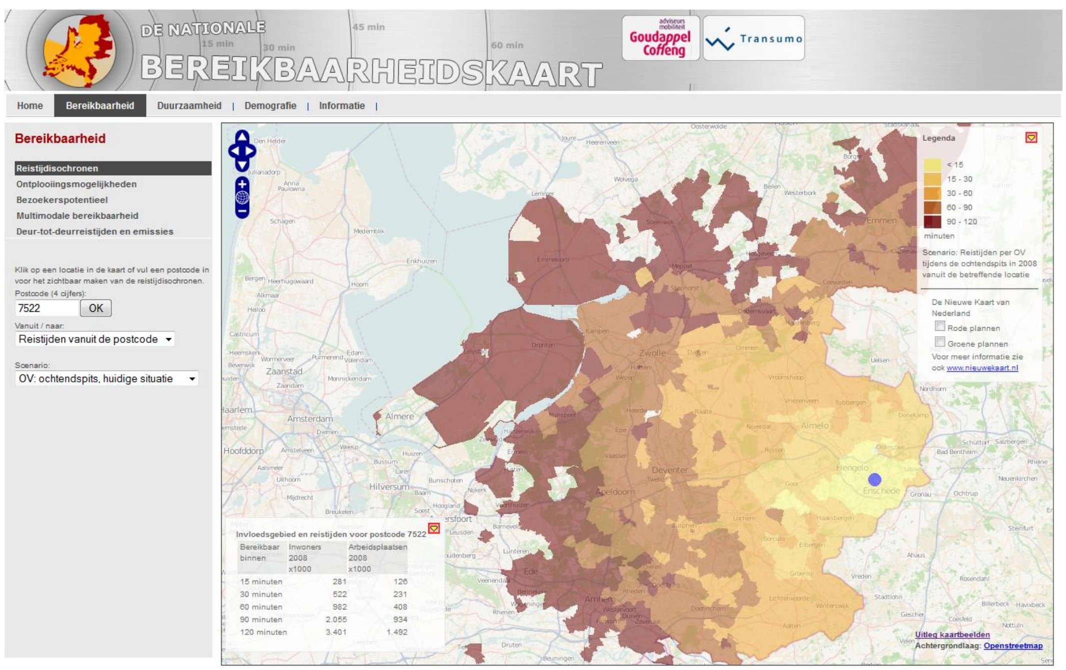

Figure 4.3 Isochrone map: accessibility per travel time by public transport

Congestion

Congestion, or network performance in general, characterised the service level of the network infrastructure (supply) in fulfilling the traffic (demand). Direct measurement of congestion can be made via the temporal and/or spatial dimension:

- Hours lost in congestion;
- Queue lengths.

Indirect measurements include e.g. operating speed (relative to the free flow speed). An example is the live traffic provided by Google.com (Figure 4.4).

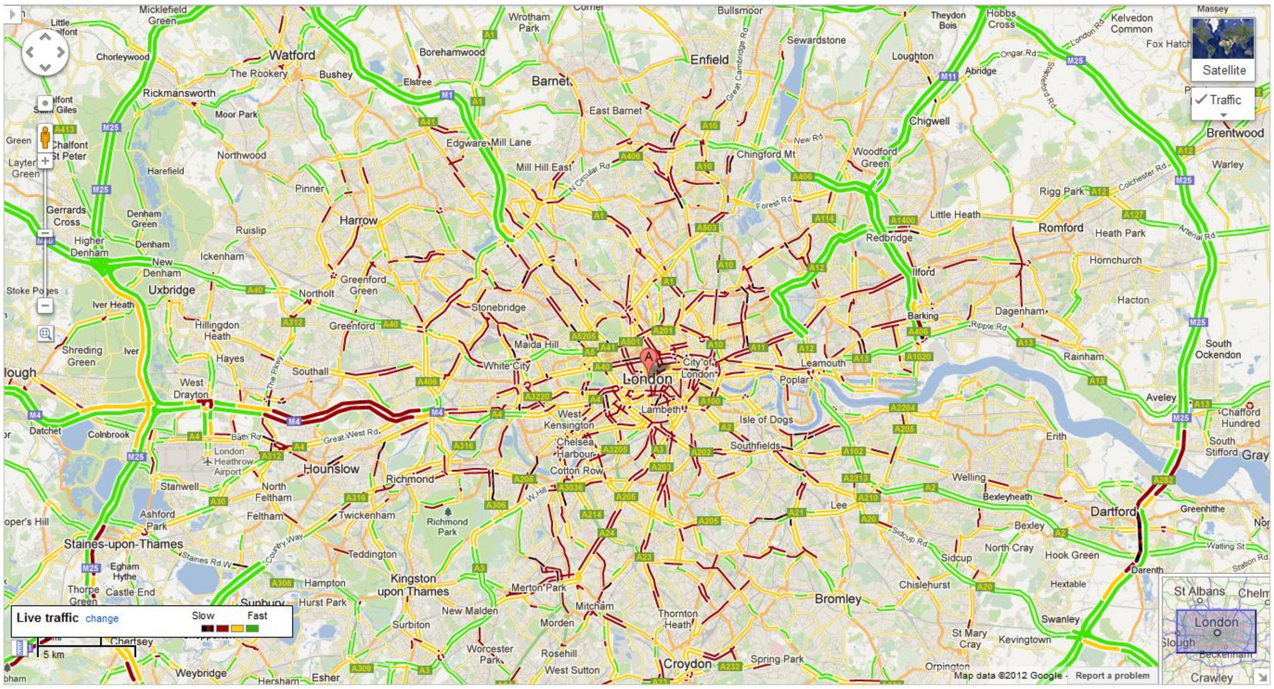

Figure 4.4 Live traffic by Google

Table 4.6 provides an overview of commonly used congestion measurements. As can be seen, congestion is often defined relative to uncongested or free flow situations. The acceptable travel rate/speed is usually interpreted as the rate/speed under uncongested condition. Congestion occurs because the traffic volume is approaching or exceeding the road capacity, which leads to lower speed and longer travel times.

Table 4.6 Congestion measurements

Congestion measurement	Definition/formula
Travel rate (min/km)	= Travel time (min) / Segment length (km) = 60 / Average speed (km/h)
Delay rate (min/km)	= Actual travel rate (min/km) – Acceptable travel rate (min/km)
Total delay (veh×min)	= [Actual travel time (min) – Acceptable travel time (min)] × Vehicle volume (veh)

Corridor mobility index, or Level of Service (LOS)	= [Passenger volume (psn) × Average travel speed (km/h)] / Normalising value[1]
Relative delay rate	= Delay rate / Acceptable travel rate
Delay ratio	= Delay rate / Actual travel rate
Congested travel (veh×km)	= Sum of all [Congested segment length (km) × Traffic volume (veh)]
Congested roadway (km)	= Sum of all Congested segment lengths (km)

Note 1: examples of the normalising value: 40,000 for streets, 200,000 for highway.
Source: Loma et al. (1997); Grant-Muller & Laird (2006).

Delay related congestion measurements are well understood and commonly used in practice. An example is the TomTom Congestion Index (TomTom, 2012), which is similar to the relative delay rate defined in Table 4.6. The TomTom Congestion Index is calculated as the percentage increase of travel times in peak hours compared to those during non-congested periods (free-flow). Travel times are collected from actual GPS data from over 50 major European cities during 2011 and the first quarter of 2012. The results are presented in Table 4.7 (TomTom, 2012).

Table 4.7 TomTom Congestion Index 2012: top European cities

Rank	City	TomTom Congestion Index (%)				
		Overall	Morning peak	Evening peak	Weekdays	Weekends
1	Warsaw	42	89	86	50	18
2	Marseille	41	79	81	46	23
3	Rome	34	76	66	40	17
4	Brussels	34	82	86	41	13
5	Paris	32	72	63	37	19
6	Dublin	30	70	62	35	19
7	Bradford-Leeds	28	63	60	31	15
8	London	27	48	50	30	18
9	Stockholm	27	65	62	31	13
10	Hamburg	27	49	42	30	15
	…					
18	Munich	23	50	36	26	14
	…					
29	Amsterdam	15	33	31	17	6
	…					
Ave.	Europe	24	–	–	–	–

Source: TomTom (2012).

The results show that, on average, European cities have a congestion level of 24%, meaning that peak hour travel times are 24% longer than free flow travel times. Trend analysis shows that this percentage remained stable (±3%) in the past five quarters. This indicates that congestion is currently a significant problem across Europe. The top 10 cities experience a congestion level as high as 50% during the morning and evening peak hours, with the worst cases (Warsaw and Marseille) almost reaching 100%.

One of the SUNSET living lab cities, Leeds, is listed together with Bradford as the 7th in Europe in congestion index. A closer examination of the congestion data from Bradford-Leeds reveals that, in average, a commuter of 30 minutes would have lost 86 hours per year due to congestion (Table 4.8). Moreover, the worst morning peak congestion appears to occur on Tuesdays, while the worst evening peak congestion takes place on Thursdays (Figure 4.5). These are interesting findings that may help identify and improve the SUNSET services provided in the Leeds living lab, if they also apply to the target areas under study in the Leeds living lab.

Table 4.8 Congestion profile: Bradford-Leeds (UK)

Measurement	Results
Total network length	760 mi (1220 km)
- Highways	98 mi (160 km)
- Non-highways	662 mi (1060 km)
Total vehicle miles	4,142,000 mi (6,666,000 km)
Average free flow speed	36 mph (58 km/h)
Average speed during worst peak period	30 mph (48 km/h)
Congestion level on highways	23%
Congestion level on non-highways	34%
Delay per hour driven in peak period	36 min
Delay per year with a 30 min commute	86 h

Source: TomTom (2012).

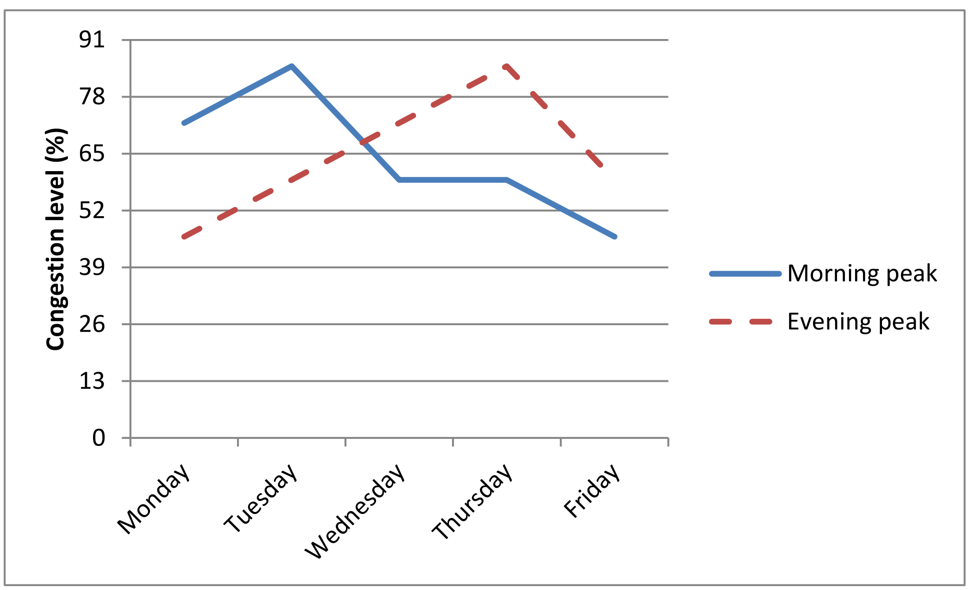

Figure 4.5 Weekly congestion pattern: Bradford-Leeds (UK)

4.2.2 Quantification of impact: externalities

With externalities we focus on safety, emission, and noise.

Safety

Generally safety is quantified by the number of accidents per severity. For *ex ante* assessment, it is difficult to estimate accidents, because accident occurrence is sporadic and random in nature and it is influenced by numerous factors which cannot be accurately captured within current traffic models. Instead, risk estimation and prediction models have been developed to assess the safety effects of measures.

Accident risk based models (ARBM) are based on the relationship between exposure and accident. Risk is defined as the number of accidents per exposure. The commonly used exposure metric is the amount of vehicle kilometres. Therefore risk is derived as the number of accidents per kilometre driven. The underlying assumption is that the individual probability of being involved in a traffic accident increases linearly with exposure, although field evidence has shown that this relationship is usually non-linear (e.g. Lord, 2002).

An example of ARBM is to derive risk levels per road category. Statistics kept by the Netherlands Road Safety Institute (SWOV) has shown that accident rate varies per road type (Table 4.9). Accident risk is the lowest on the highway and increases significantly for local roads (Janssen, 2005). Consider the vehicle mileages on the three road types as M_H, M_I, and M_U (million vehicle kilometre), respectively. Then the system risk can be calculated as

$$R = \sum_{i=H,I,U} M_i r_i. \tag{4.10}$$

Here $\mathbf{r}$ represent the risks levels of different categories. Take the Netherlands for example, it can take values such as $\mathbf{r} = [0.07, 0.32, 0.84]$.

Table 4.9 Risk per road category: statistics from the Netherlands

Road type	Accidents per million vehicle kilometres
Highway	0.06~0.08
Interurban roads	0.22~0.43
Urban roads	0.57~1.10

Source: Janssen (2005).

ARBM is a very simplistic approach for measuring safety, as it requires only aggregated data. It is suitable for descriptive analysis on a strategic level and for analysing the effects of route choice oriented measures. However, it lacks the vigour that is needed for addressing the safety effects of measures when traffic flow changes drastically. As discussed in §3.2.2, this method assumes that roads within the same category are equally safe; it also does not take into account factors such as the likelihood to be affected by fog and the availability of lighting at night.

Accident prediction models (APM), also called safety performance functions (SPF) or crash prediction models (CPM), are based on historical accident data to quantify the relationship between accidents and traffic-related variables (e.g. speed, flow). Most APM models use the annual average daily traffic (AADT) as the only input. Maximum likelihood methods are then applied to derive the relationship.

For a road link a, the number of accidents is predicted by a power function of the link flow F_a (Greibe, 2003; Lord et al., 2005, Reurings et al., 2006; Wismans et al., 2011),

$$A_a = \alpha F_a^{\beta} \exp\left(\sum_i \gamma_i x_{i_a}\right). \tag{4.11}$$

Here $\mathbf{x}$ are explanatory variables related to road characteristics; α, β, and γ are parameters related to the road geometry and environment. The number of accidents usually increases at a diminishing rate as flow increases, meaning $\beta < 1$. Take $\beta = 0.8$ for instance, the linear model in (4.10) would be transformed into

$$R = \sum_{i=H,I,U} M_i^{0.8} r_i. \tag{4.12}$$

This incorporates the diminishing effect into the prediction model.

Various studies (e.g. Greibe, 2003) have estimated APM based on daily volumes for specific situations (incl. speed limit, road width etc.). APM allows non-linear relationships between risk and exposure and is suitable for comparative analysis and accident approximations. However, it is difficult to estimate and validate. Moreover, it needs to be recalibrated before application to a different case.

Safety performance indicators (SPI), or surrogate measures, attempt to describe the quality of traffic safety but not necessarily in terms of accident numbers (cf. APM). It focuses on measurements of the quantity and quality of road-user behaviour and interaction. Instead of accidents, SPI measures the spatial and temporal proximity of safety critical events which is assumed to bear an established relationship with accidents.

Most SPI studies apply the traffic conflict techniques where safety is quantified by certain surrogate measurements. Most surrogate measurements are developed in combination with microscopic models. Examples include time to collision (TTC), post-encroachment time (PET), potential collision energy (PCE) on the microscopic level, and shock wave frequency, delay or queue length on a more aggregated level (Archer, 2005; Wismans et al., 2011).

TTC, also called time to contact or time of impact (TOI), calculates the time it takes before two objects collide with each other, under the assumption that both preserve with their current speed. Consider a lead vehicle with speed v_L and a following vehicle with speed v_F. If their current spacing is H (in distance) and $v_L < v_F$, then

$$TTC = \frac{H}{v_F - v_L}. \tag{4.13}$$

The longer TTC is, the safer the situation is. Situations with TTC less than 1 second is usually considered safety critical. TTC is commonly used in car following studies to examine the safety effects of driver assistance systems. If a system is shown to reduce the occurrence of safety critical situations, it is then believed to improve safety.

Table 4.10 provides an overview of the various measurement models for traffic safety. In SUNSET, network-wide measures are being implemented, with which macroscopic level measurement are more suitable. Therefore the ARBM and APM approach will be adopted in this study.

Table 4.10 Externality modelling: traffic safety

Characteristics	**Type of models**		
	ARBM	***APM***	***SPI***
Function type	Continuous	Continuous	Discrete
Input level	Road section	Road section	Continuous
Road characteristics	Road type, intersection type	Road type, intersection type	–
Vehicle characteristics	–	–	(Vehicle class)
Driving characteristics	–	–	Space-time behaviour
Traffic characteristics	Flow	Flow, speed, density	Shockwaves, delay
Example	SWOV-method	–	TTC, PET, PCE

Source: Wismans et al. (2011).

Emission
Emission assessment include two types of substances:

- Air pollutants;
- Carbon dioxide (CO2).

Air pollutants mainly include nitrogen oxide (NOx) and particulate matter (PM). They can damage the ecological system and are hazardous to human health. CO2, on the other hand, is not considered as pollutant. It, however, is a major greenhouse gas (GHG) and contributes greatly to the greenhouse effect.

Air quality assessment focuses on the concentration of pollutants. It requires two steps:

- first calculate the amount of emission (per location, over time);
- then apply the **dispersion** model to derive concentration (per location, over time).

Dispersion modelling requires comprehensive knowledge of the locale regarding its environment, including topological layout of the locale, wind direction, and wind speed. This is beyond the scope of this study. Here we shall focus only on emission.

There are many factors that influence the amount of emission. They can be considered at two levels (Wismans et al., 2011):

- vehicle level: vehicle characteristics, driver behaviour;
- road section level: traffic volume, road design, traffic circulation.

In general the amount of emission on road link a is determined by the following formula:

$$E_a = \alpha M_a. \quad (4.14)$$

Here M_a is the vehicle mileage and α is the emission factor.

Various models exist regarding how the emission factor should be calculated. **Aggregated** models apply the same emission factor to the same vehicle type. It does not take the driving type into account but may account for the traffic situation by including the level of service. This means, in aggregated models,

$$\alpha \sim \{\text{vehicle class, LOS}\}. \quad (4.15)$$

Average speed models consider the emission factor as a function of the average speed during a trip,

$$\alpha \sim \{\text{vehicle class, average speed}\}. \quad (4.16)$$

Instead of average speed, **instantaneous speed** can be used. Emission estimate is related to the speed as well as the acceleration of the vehicle over time (typically considered at 1-second intervals),

$$\alpha \sim \{\text{vehicle class, speed over time}\}. \quad (4.17)$$

In **regression** models, a set of descriptive parameters are considered to form a driving cycle, incl. speed, acceleration, and frequency of stops. Each driving cycle is then characterised by its own emission factor,

$$\alpha \sim \{\text{driving cycle}\}. \quad (4.18)$$

Alternatively, the vehicle operation can be categorised into different **driving modes** (e.g. idle, cruise, acceleration, deceleration), with each mode characterised by its own emission factor,

$$\alpha \sim \{\text{driving mode}\}. \quad (4.19)$$

Instantaneous power models considers the engine power requirement over time. It attempts to capture the physical and chemical phenomena that generate emission,

$$\alpha \sim \{\text{engine power over time}\}. \quad (4.20)$$

Table 4.11 summarises the various models discussed above. Apparently, the more complex a model is, the more accurate the emission results are expected to be. As this study focuses on the (relative) impact on emission, high accuracy is not required for the absolute values of emissions. Thus we adopt the instantaneous speed model to measure emission, i.e.

$$E_a = \alpha(v_a(t))M_a. \quad (4.21)$$

Here $v_a(t)$ is the speed over time on link a. The emission will be calculated considering speed and the variation of speed over time.

Table 4.11 Externality modelling: emissions

Characteristics	**Type of models**		
	Aggregated	***Average speed***	***Instantaneous speed***
Function type	Discrete	Continuous	Discrete/continuous
Input level	Trip or road section	Trip	Continuous
Road characteristics	Road type	–	–
Vehicle characteristics	Vehicle class	Vehicle class	Vehicle class
Driving characteristics	–	–	Driving cycle
Traffic characteristics	Flow, level of service	Flow (adjusted), average speed	–
Example	CAR, HBEFA	ARTEMIS	MODEM
Characteristics	**Type of models**		
	Regression	***Driving mode***	***Instantaneous power***
Function type	Continuous	Discrete	Continuous
Input level	Trip	Road section	Continuous
Road characteristics	–	–	–
Vehicle characteristics	Vehicle type	Vehicle class	Vehicle type, engine load
Driving characteristics	Driving cycle	Distribution of driving modes	Driving cycle, gear
Traffic characteristics	–	–	–
Example	VERSIT+	UROPOL	CMEM

Source: Wismans et al. (2011).

Noise

Similar to emission, noise estimate is done by sound emission at source in the first step, and then sound dispersion to determine the sound power levels at a receiver location.

The major sources of traffic noise are

- Rolling noise (due to tyre-road interaction);
- Aerodynamic noise;
- Propulsion noise of the vehicle.

Rolling noise and aerodynamic noise are considered to be linearly related to the logarithm of speed, while propulsion noise is described as a linear function of speed. At high speeds rolling and aerodynamic noises dominate propulsion noise (Wismans et al., 2011).

The general formula for measuring the sound power level of a single vehicle is

$$Lw = \alpha + \beta f\left(v, v_{ref}\right) + \gamma. \quad (4.22)$$

Here the reference speed v_{ref} is introduced, as the function is usually fitted for reference conditions. The correction factor γ accounts for the influences of road surface, weather and driving conditions.

4.3 Impact of planning behaviour

This section, together with §4.5, should fulfil Obj5 Assess the influence of individual planning / scheduling behaviour on the network performance in terms of the system objectives.

Network modelling is applied to assess the impact on the system objectives due to changes in the scheduling and planning behaviour of travellers. The behaviour aspects in discussion are:

- 1a. Trip/destination choice
- 1b. Timing choice
- 1c. Mode choice
- 1d. Route choice

Two levels of modelling will be applied:

- On the lower level, traffic assignment modelling accounts for the impact of route choice, taking demand and mode choice as input;
- On the higher level, demand modelling accounts for the impact of trip decision, departure time and mode choices, with route choice embedded as an implicit sub-model.

4.3.1 Road traffic assignment

Route choice concerns travellers' choice of path between their origin (O) and destination (D). It is relevant mainly for the car mode. Given the OD demand $Q_{IJ}(T)$, where I,J,T denote, respectively, the origin zone, the destination zone, and the departure time window, the outputs of route traffic assignment are the route flows

$$Q_{IJP}(T), P \in \mathbf{R}_{IJ}. \qquad (4.23)$$

Here P is a path (route) connection I and J, with the route set denoted by $\mathbf{R}_{IJ}$. Alternatively, the route flows can be replaced by link flows

$$q_{ij}(T), ij \in \mathbf{A}. \qquad (4.24)$$

Here $\mathbf{A}$ represents the set of links (arcs) in the network and ij denotes the link from node i to node j.

§3.2.2 has identified the following relevant behaviour aspects regarding route choice:

- Choose the quickest route;
- Choose the shortest route;
- Choose the "optimal" route;
- Avoid toll road;
- Choose the safest route.

These behaviour patterns can be unified under one framework where the traveller always chooses the optimal route but the objective function of the optimisation varies,

$$\min \left\{ \begin{array}{l} \alpha(\text{route travel time}) + \beta(\text{route distance}) \\ +\gamma(\text{route toll}) + \delta(\text{route safety}) \end{array} \right\}. \qquad (4.25)$$

The parameters $\alpha,\beta,\gamma,\delta$ represents the relative weight of the four objectives. They also act as conversion rate since the objectives take different metrics. The usual procedure is either to convert all objectives to time (then we can set $\alpha = 1$) or to convert all objectives to money (then we can set $\gamma = 1$).

To study the impact of route choice behaviour on the system objectives, is equivalent to study the impact of the weighting parameters. We will consider four extreme cases, while all other cases can be considered as an interpolation of these four cases. The comparison of these four cases is shown in Table 4.12.

Case 1: $\alpha = 1, \beta = \gamma = \delta = 0$

This case is used as the reference scenario. And the route choice impact is defined as relative to this scenario. In other words, this case is taken as the status quo.

Case 2: $\alpha = 0, \beta = 1, \gamma = \delta = 0$

In this case all travellers choose route per distance. This means less traffic on the highway but more traffic on local roads.

Case 3: $\alpha = \beta = 0, \gamma = 1, \delta = 0$

This case is applicable only when toll is present in the network. It should be interpreted in combination with other cases. Taking Case 1 as the reference scenario, this case means that travellers with choose the quickest route that is without toll.

Table 4.12 Impact of route choice behaviour

System objectives	Quantification (min/max)	Route choice impact
A. Accessibility	Trips made within satisfactory travel time (max)	Case 1: reference Case 2: slight decrease (with longer travel times) Case 3: slight decrease Case 4: no impact
B. Congestion	Total delay (min)	Case 1: reference **Case 2: increase** (decrease on the highway, increase on local roads) Case 3: slight decrease Case 4: no impact
C. Safety	System risk (ARBM) (min)	Case 1: reference **Case 2: increase** (decrease on the highway, increase on local roads) Case 3: minimal impact Case 4: slight decrease
D. Emission	Vehicle kilometre × factor of speed (min)	Case 1: reference Case 2: slight decrease (decrease on the highway, increase on local roads) Case 3: slight increase Case 4: no impact
E. Personal wellbeing	*Addressed separately in §4.5.*	

Note: bold typeface means that the impact/change is most significant, in comparison to other impacts.

Case 4: $\alpha = \beta = \gamma = 0, \delta = -1$

In this case all travellers maximise traffic safety. This means that they will choose route according to the SWOV methodology (Dijkstra et al., 2007). Such a route coincides with the quickest route in 90% of the cases (Dijkstra & Drolenga, 2008). Therefore this case is expected to have the same impact as Case 1, expect that it is considered to slightly impact safety.

4.3.2 Demand modelling

Demand modelling concerns trip decisions, destination, timing, and mode choices.

Mode choice

A multitude of modes are available to the travellers but often the trip is made via one of the four ways as defined below (cf. §3.2.1):

- Motorised private mode (M), i.e. car or motorbike;
- Non-motorised private mode (N-M), i.e. bicycle, walking;
- Public transport (PT), i.e. single mode or inter-modal transit (e.g. metro+bus);
- Combined mode (usually P+R).

The impact assessment is then based on four cases:

- **Case M**: the majority of travellers take the motorised private mode;
- **Case N-M**: the majority of travellers take the non-motorised private mode;
- **Case PT**: the majority of travellers take the transit mode;
- **Case P+R**: the majority of travellers take the P+R mode.

Case M will be used as the reference scenario. The mode choice impact is therefore defined relative to this scenario. In other words, Case M is taken as the status quo.

Impact assessment of mode choice is made by differentiating two types of trips:

- Short trips, usually within a city;
- Long trips, such as intercity trips.

For short trips, it is sensible to exclude P+R in mode choice, whereas for long trips, non-motorised private mode is usually consider infeasible. The qualitative impact assessment results are shown in Table 4.13 for short trips and Table 4.14 for long trips.

Table 4.13 Impact of mode choice behaviour: short trips

System objectives	Quantification (min/max)	Mode choice impact
A. Accessibility	Opportunities fulfilled within acceptable travel time (max)	M: reference **N-M: decrease** (as travel time generally increase) PT: slight decrease (if M is quicker) or slight increase (if PT is quicker)
B. Congestion	Total delay (min)	M: reference **N-M: major decrease** (urban congestion will be almost eliminated) **PT: decrease on the road**; slight increase on transit (due to crowdedness)
C. Safety	System risk (ARBM) (min)	M: reference **N-M: decrease** (with exclusive cycling/walking infrastructure) or **increase** (without exclusive infrastructure)

		PT: decrease
D. Emission	Vehicle kilometre × factor of speed (min)	M: reference **N-M: major decrease** **PT: (major) decrease**
E. Personal wellbeing	*Addressed separately in §4.5.*	

Note: bold typeface means that the impact/change is most significant, in comparison to other impacts.

Table 4.14 Impact of mode choice behaviour: long trips

System objectives	Quantification (min/max)	Mode choice impact
A. Accessibility	Opportunities fulfilled within acceptable travel time (max)	M: reference **PT: decrease** (in general[1]) P+R: slight decrease (in general[1])
B. Congestion	Total delay (min)	M: reference **PT: major decrease** (highway congestion will be almost eliminated) P+R: decrease or slight decrease (depending on the P+R arrangement)
C. Safety	System risk (ARBM) (min)	M: reference **PT: major decrease** P+R: decrease or slight decrease
D. Emission	Vehicle kilometre × factor of speed (min)	M: reference **PT: major decrease** **P+R: decrease** or slight decrease
E. Personal wellbeing	*Addressed separately in §4.5.*	

Note: bold typeface means that the impact/change is most significant, in comparison to other impacts.

Note 1: for long trips, transit mode is in general slower than car mode. Exceptions exist (e.g. with high speed rail).

Timing choice

Naturally departure time is a continuous choice as the temporal dimension is continuous. However, in practice, departure time choice is often discretised into departure period choices. The analysis in §3.2.3 indicates that departure time choice mainly concerns the choice between:

- Peak hour departure; and
- Off-peak departure.

In other words, departure time choice is a choice of whether to avoid the peak hour or not.

Impact assessment (Table 4.15) is based on the development intervention which results in more people departing during the off-peak hours (i.e. peak hour avoidance). In the Dutch Spitsmijden project (Spitsmijden, 2009), it is shown that

- When drivers are awarded for travelling off peak, less car traffic during peak hours leads to significant reduction of congestions.
- When public transport passengers are awarded for traveller off peak, less transit patronage during peak hours leads to reduction of congestion (or delay) on the transit facilities.

Table 4.15 Impact of departure time choice behaviour

System objectives	Quantification (min/max)	Departure time impact (of peak hour avoidance)
A. Accessibility	Opportunities fulfilled within acceptable travel time (max)	**Decrease**, if opportunities refer to time-poor activities (e.g. job, appointment) **Increase**, if opportunities refer to time-rich activities (e.g. shopping, visiting friends)
B. Congestion	Total delay (min)	**Decrease** (as congestion mostly occurs during peak hours)
C. Safety	System risk (ARBM) (min)	Minimal impact (it is debatable whether it is safer to drive in the peak hour [slower speed but higher density] or in the off-peak)
D. Emission	Vehicle kilometre × factor of speed (min)	Slight decrease (distance remains unchanged but speed improves, with less stop-and-go/idling)
E. Personal wellbeing	*Addressed separately in §4.5.*	

Note: bold typeface means that the impact/change is most significant, in comparison to other impacts.

Destination choice

Destination choice mainly concern the choice of fulfilling the same opportunity at different locations. The analysis in §3.2.4 has identified that traveller under various individual objectives may make shorter or longer trips, such as a shopping trip in the local supermarket instead of the city centre, or a relaxing picnic in the countryside park 10km away instead of the small park next door.

Impact assessment of destination choice behaviour is made by considering two possible scenarios, defined relative to the status quo (reference scenario):

- Shorter trips: travellers prefer destinations nearby;
- Longer trips: travellers prefer destinations further away.

The qualitative results are summarised in Table 4.16.

Table 4.16 Impact of destination choice behaviour

System objectives	Quantification (min/max)	Destination choice impact
A. Accessibility	Opportunities fulfilled within acceptable travel time (max)	Shorter trips: slight increase (as travel time reduces); Longer trips: slight decrease.

B. Congestion	Total delay (min)	Shorter trips: slight decrease (less highway congestion); **Longer trips: increase**.
C. Safety	System risk (ARBM) (min)	Shorter trips: slight decrease (distance reduces but more local road); Longer trips: slight increase.
D. Emission	Vehicle kilometre × factor of speed (min)	Shorter trips: slight decrease (distance reduces but may involve more idling); **Longer trips: increase**.
E. Personal wellbeing	*Addressed separately in §4.5.*	

Note: bold typeface means that the impact/change is most significant, in comparison to other impacts.

Trip decisions

Trip decisions concern whether to make a physical trip for fulfilling certain opportunities or to replace it with alternative activities that do not require a physical trip. Examples include: commuting vs. home-office, meeting friends vs. telephone conversation, etc.

Impact assessment of trip decisions is made by considering two possible scenarios, defined relative to the status quo (reference scenario):

- Less (spontaneous) trips: more travellers stay at home;
- More trips: more travellers take it to the road.

The qualitative results are summarised in Table 4.17.

Table 4.17 Impact of trip decisions

System objectives	Quantification (min/max)	Destination choice impact
A. Accessibility	Opportunities fulfilled within acceptable travel time (max)	Less trips: minimal impact (as activities are replaced by alternatives, or slight decrease) More trips: minimal impact (or slight increase)
B. Congestion	Total delay (min)	**Less trips: decrease** (less congestion); **More trips: major increase** (esp. for locations already congested).
C. Safety	System risk (ARBM) (min)	**Less trips: decrease**; More trips: slight[1] increase.
D. Emission	Vehicle kilometre × factor of speed (min)	**Less trips: decrease**; **More trips: increase** (or major increase, if network is already congested).
E. Personal wellbeing	*Addressed separately in §4.5.*	

Note: bold typeface means that the impact/change is most significant, in comparison to other impacts.

Note 1: taking into account the diminishing effect related to risk and exposure.

4.4 Impact of en-route behaviour

This section, together with §4.5, should fulfil Obj6 Assess the influence of individual en-route behaviour on the network performance in terms of the system objectives.

The quantification methodologies described in §4.2.2 are applied here to study the impact of en-route behaviour. These behaviour aspects are:

- 2a. Driver status: workload & concentration
- 2b. Longitudinal control
- 2c. Lateral control
- 2d. Compliance with other traffic rules

Their impact mainly concerns the externalities, and their impact on efficiency related objectives (i.e. accessibility and congestion) is deemed insignificant, except for the following aspects, which may bring some minor impact:

- Lower speed lengthens travel time [May, 1990].
- In car following behaviour, longer reaction time and higher sensitivity lead to platoon instability, which worsens congestion [Rothery, 1992].
- Multi-anticipation contributes to platoon stability, thus reducing congestion [Ossen, 2008].

4.4.1 Safety evaluation

Safety is measured by the system risk, defined in (4.10). Two measurement components are needed for the safety assessment:

- Vehicle-kilometre: this can be derived from the traffic volume and route;
- Risk factor: this defines the risk level of each exposure and relates to the driver and traffic conditions during the exposure.

The vehicle mileage is not affected by en-route behaviour. En-route behaviour is considered to affect traffic safety via the risk factor.

The risk factor mainly relates to the road category, and to a lesser extent, also to the driving style (i.e. en-route behaviour). Road categories remain unchanged by en-route behaviour. Therefore en-route behaviour is considered to affect safety to a lesser degree, compared to planning and scheduling behaviour. The relevant en-route behaviour aspects are derived in §3.3 and their impacts are summarised in Table 4.18.

Table 4.18 Impact of en-route behaviour on safety

En-route behaviour		Impact on system risk
2a. Driver status	Higher concentration level	Minor decrease: higher concentration can avoid accident occurrence or reduce accident severity.
	Lower attention level (e.g. mobile phone)	Slight increase: it leads to higher accident risks, therefore more accidents.
2b. Longitudinal control	Higher speed or speed limit violation	Minor increase or slight increase, depending on the extent of speeding [Belonitor, 2005].
	Shorter headway	**Increase**: similar to shorter TTC, this is known to significantly add to accident risk.
	Steady speed profile	Minor increase: due to late decelerations

2c. Lateral control	More frequent lane changes	Minor increase: lane change is a risk-prone manoeuvre.
	Lane change with shorter gaps	Slight increase: insufficient gap is known to contribute to lane change collisions, esp. in angle collisions [Wang & Knipling, 1994]..
2d. Compliance	Yellow/red light running	Minor increase: due to potential conflict with other moving vehicles.
	Forced merging	Slight increase: similar to lane change with shorter gaps.

Note: bold typeface means that the impact/change is most significant, in comparison to other impacts.

4.4.2 Emission evaluation

If emission is measured using the average speed model (§4.2.2), then en-route behaviour would have no effect on emission. On the one hand, this is due to the simplifications in the model; on the other hand, en-route behaviour plays only a minor role in affect emission, compared to planning and scheduling behaviour. Here the instantaneous speed model is applied to assess the impact of en-route behaviour on emission. The results are summarised in Table 4.19.

Table 4.19 Impact of en-route behaviour on emission

En-route behaviour		**Impact on emission**
2a. Driver status	Higher concentration level	No impact
	Lower attention level (e.g. mobile phone)	No impact
2b. Longitudinal control	Higher speed or speed limit violation	Slight increase: mainly due to incomplete combustion.
	Shorter headway	No impact
	Steady speed profile	**Decrease**: this makes efficient use of the vehicle momentum/inertia and therefore consumes less fuel.
2c. Lateral control	More frequent lane changes	Minor increase: requires more variation of speed (ac-/deceleration) over time.
	Lane change with shorter gaps	No impact
2d. Compliance	Yellow/red light running	No impact
	Forced merging	No impact

Note: bold typeface means that the impact/change is most significant, in comparison to other impacts.

4.5 Personal wellbeing of citizens

As discussed in §2.2, here we consider noise and personal health as the representative indicators of citizens' personal wellbeing. The other aspects related to wellbeing, such as the ability to set up and monitor personal goals, are not addressed in this deliverable.

Noise produced by an individual vehicle is related to its speed profile. This is addressed by the en-route behaviour. Traffic noise from roads is the collective of all vehicle noises. This mainly depends on the volume and (temporal/spatial) distribution of traffic.

Personal health is assessed qualitatively by considering the following factors:

- Public transport is considered more healthy than the sedentary car mode;
- Active travel, i.e. walking and cycling, contribute to a more healthy lifestyle.

4.5.1 Impact of planning behaviour

Planning and scheduling behaviour has impact on both traffic noise and personal health.

Traffic noise

Similar to the analysis of efficiency and externality impact in §4.3, the impact of planning and scheduling behaviour on noise is derived by examining the behaviour aspects identified in §3.2. The results are summarised in Table 4.20.

Table 4.20 Impact of planning behaviour on noise

Planning behaviour		Impact on personal health
1a. Trip decision	More/less trips	**Linear increase/decrease**
	Longer/shorter trips	**Increase/decrease**
1b. Timing choice	Peak avoidance	**Decrease**, mainly due to decrease of peak noise (which is often the most disturbing).
1c. Mode choice	More motorised private mode	**Linear increase**
	More non-motorised private mode	**Major decrease**: due to switch to non-noise mode.
	More transit mode	**Decrease**: transit generally produces less noise per traveller.
	More P+R	Slight decrease
1d. Route choice	Prefer quickest route	**Decrease**; due to less traffic on local roads.
	Prefer shortest route	**Increase**: due to more traffic on local roads.
	Avoid toll road	No impact
	Prefer safest route	**Decrease**: same as quickest route.

Note: bold typeface means that the impact/change is most significant, in comparison to other impacts.

Personal health

The impact of planning and scheduling behaviour on personal health mainly relates to the physical movement involved in a trip. The more physically active a trip is, the more healthy it is. The results are derived by examining the behaviour aspects identified in §3.2 and summarised in Table 4.21.

Table 4.21 Impact of planning behaviour on personal health

Planning behaviour		Impact on noise
1a. Trip decision	More/less trips	Minor impact
	Longer/shorter trips	Minor impact
1b. Timing choice	Peak avoidance	No impact
1c. Mode choice	More motorised private mode	Slight decrease
	More non-motorised private mode	**Major increase**: due to switch to walking and cycling.
	More transit mode	**Increase**: transit generally involves more physical movement.
	More P+R	**Increase**: as in transit mode; also due to the transfer between the P+R modes, which usually involves walking.
1d. Route choice	Prefer quickest route	No impact
	Prefer shortest route	No impact
	Avoid toll road	No impact
	Prefer safest route	No impact

Note: bold typeface means that the impact/change is most significant, in comparison to other impacts.

4.5.2 Impact of en-route behaviour

En-route behaviour mainly affects traffic noise. It has minimal impact on personal health, except for the damages to personal health due to traffic accidents, which is dealt with under traffic safety (cf. §4.4.1). The impact of en-route behaviour on noise is derived by examining the behaviour aspects identified in §3.3. The results are shown in Table 4.22.

Table 4.22 Impact of en-route behaviour on noise

En-route behaviour		Impact on noise
2a. Driver status	Higher concentration level	Minor impact
	Lower attention level (e.g. mobile phone)	Minor impact

2b. Longitudinal control	Higher speed or speed limit violation	**Increase**: sound power increases with speed.
	Shorter headway	Minor impact
	Steady speed profile	Slight decrease: due to less ac-/decelerations.
2c. Lateral control	More frequent lane changes	Minor increase: lane change produces extra noise.
	Lane change with shorter gaps	No impact
2d. Compliance	Yellow/red light running	Minor impact
	Forced merging	Minor impact

Note: bold typeface means that the impact/change is most significant, in comparison to other impacts.

4.6 Summary: system impact of individual behaviour

This section summarises the results of the previous sections.

Table 4.23 lists the most significant impacts of behaviour (changes) on the system objectives. These impacts, discussed in details in §4.3, §4.4, and §4.5, have been derived by applying the network modelling and impact quantification techniques (§4.1, §4.2). Significance is assessed by examining the functional form of the system objective measurements and identifying the major contributors.

It should be noted that route choice and the en-route behaviour aspects only apply to the (partially) car mode. Their impacts on the system objectives are therefore of the second order; the planning and scheduling behaviour has generally stronger impacts on the system objectives.

For easy reference, the system objectives are labelled here as:

A. To maximise accessibility
B. To minimise congestion
C. To maximise safety
D. To minimise impact on environment
E. To maximise personal wellbeing of citizen

And the impact is classified into four categories:

- **O: no or little impact;**
- **X: minor impact;**
- **XX: medium impact;**
- **XXX: major impact.**

Table 4.23 The impact of behaviour on system objectives

Behavioural aspects	Impact on system objectives
1a. Trip decision	A: O
	B: XXX – High demand leads to heavier congestion. X – Longer trips also increase congestion.

	C: XX – High demand leads to more exposure to accidents.
	D: XX – High car traffic demand leads to more pollution. X – Longer trips also increase emission.
	E: XX – More trips lead to more noise.
1b. Timing choice	A: XX – Peak hour avoidance may improve/degrade accessibility, if the traveller is time rich/poor.
	B: XX – Less car traffic during peak hours leads to significant reduction of congestions.
	C: X – Less car traffic during peak hours reduces the accident risk due to congestions (crowdedness).
	D: X – Less car traffic during peak hours reduces the amount of emissions due to congestions (inefficient fuel economy).
	E: X – Peak hour noise (usually the most disturbing traffic noise) decreases due to peak avoidance.
1c. Mode choice	A: XX – Choosing a non-car mode generally decreases accessibility.
	B: XXX – Choosing a non-car mode significantly reduces congestions on the road network.
	C: XX – Less car traffic means less exposure to road accidents.
	D: XXX – Less car traffic reduces emission.
	E: XX – Choosing a non-car mode reduces noise. XX – Choosing an active mode (walking, cycling) improves personal health.
1d. Route choice	A: O
	B: XX – More traffic on local roads leads to more local congestion.
	C: XX – More traffic on local roads increases accident risk.
	D: X – More traffic on local roads reduces local air quality.
	E: X – More traffic on local roads generates more noise disturbance.
2a. Driver status	A: O
	B: O
	C: X – Driver inattention leads to higher accident risks.

	D: O
	E: O
2b. Longitudinal control	A: O
	B: X – In car following behaviour, longer reaction time and higher sensitivity lead to platoon instability, which worsens congestion.
	C: X – Higher speed leads to more severe accidents. XX – Insufficient headway (following distance) leads to shorter time-to-collision and higher accident risks, esp. in rear-end collisions.
	D: X – Smoother speed profile reduces emission.
	E: X – Higher speed leads to higher noise level.
2c. Lateral control	A: O
	B: O
	C: XX – Shorter critical gaps in lane change and overtaking leads to higher accident risks, esp. in angle collisions.
	D: X – Lane change and overtaking require ac-/deceleration and contribute to more emission.
	E: O
2d. Compliance with traffic rules	A: O/X - Accidents due to violation of traffic rules may disrupt the network connectivity.
	B: O/X – Accidents due to violation of traffic rules may disrupt the network flow and lead to severe temporary (short-term) congestions.
	C: X – Noncompliance of traffic rules leads to higher accident risks, especially at traffic intersections.
	D: O
	E: O

5. THE RELATIONSHIP: INDIVIDUAL VERSUS SYSTEM OBJECTIVES

This chapter should fulfil the following objectives:

Obj7 Identify the relationship between individual objectives and system objectives.
Obj8 Assess the impact of given changes in behaviour (incentives) on system objectives.

The previous two chapters have mapped individual objectives into behaviour aspects (Chapter 3), and behaviour aspects into system objectives (Chapter 4). It then becomes straightforward to the link individual objectives with the system objectives (§5.1).

Evidences from practice (§5.2) are then provided to complement the qualitative results.

These results are then applied to examine the impact of incentives (§5.2), in order to draw useful implications for the design of incentives within SUNSET.

5.1 Linking individual objectives with system objectives

This section should fulfil Obj7 Identify the relationship between individual objectives and system objectives. The results are further complemented by §5.2.

5.1.1 Summary: individual vs. system objectives

This section summarises the relationship between individual and system objectives. This is achieved by pairing and matching the results derived in Chapter 3 and Chapter 4.

For easy reference, the system objectives are labelled here as:

A. To maximise accessibility
B. To minimise congestion
C. To maximise safety
D. To minimise impact on environment
E. To maximise personal wellbeing of citizen

And the relationship is represented by correlation index:

- ++/+ means major/minor positive correlation (i.e. more traveller following this individual objective leads to a positive outcome for the system objective);
- --/- means major/minor negative correlation;
- ± means correlation varies or depends on circumstances;
- O means no (significant) correlation.

All major correlations are highlighted in bold typefaces.

Table 5.1 Relationship between individual and system objectives

Individual objective	Correlation with system objectives
1. To minimise travel time	A: - More car traffic (instead of transit) leads to heavier congestion on the road and longer travel times.

	B: **-- More car traffic (instead of transit) leads to heavier congestion on the road and longer travel times.** ± Always choosing the quickest routes means heavier congestion on popular routes (e.g. highways), and lighter congestion on less popular routes (e.g. local roads).
	C: - More car traffic (instead of transit) leads to heavier congestion on the road and longer travel times. + The quickest route is often on the highway, which is safer than local roads.
	D: **-- More car traffic (instead of transit) leads to more emission.** + The quickest route is often shorter in distance and with less interruption (e.g. intersections).
	E: **-- More car traffic (instead of transit) leads to more noise and deteriorating personal health.** + The quickest route is often on the highway, where noise is less disturbing for citizens than noise on local roads.
2. To minimise scheduling effort	A: O
	B: ± The mode choice depends on the scheduling tool being used. Negative if the tool has preferences that result in the car mode. **-- Following departure timetables (blindly) means no attempt to avoid peak hours or congested route, leading to heavier congestion.**
	C: ± Same as in B.
	D: ± Same as in B.
	E: O
3. To minimise cost	A: O
	B: **--/++ If the car/transit mode is cheaper then there is more/less congestion on the road.** **++ Travelling off peak is usually cheaper, leading to less congestion during peak hours.**
	C: ± If the car/transit mode is cheaper then there are more/less traffic as well as accidents on the road.
	D: **--/++ If the car/transit mode is cheaper then there is more/less emission on the road.** + Drivers try to avoid unnecessary ac-/deceleration, reducing emission.
	E: ± If the car/transit mode is cheaper, there is more/less car traffic. - More travel on local roads generates more noise disturbance.

4. To maximise safety	A: O
	B: + Safer routes usually avoids local roads (e.g. rat-runs), alleviating local congestion. ± If the car mode is safer (less safe) than transit/cycling/walking, then there is more/less traffic on the road, less/more traffic on transit, cycling, and waling.
	C: + Safer routes usually avoids local roads (which is less safe than highways). **++ Lower speed and longer headway lead to less (severe) accidents.**
	D: ± If the car mode is safer (less safe) than transit/cycling/walking, then there is more/less traffic on the road, less/more traffic on transit, cycling, and waling.
	E: O
5. To maximise capital	A: ± High car/bicycle ownership leads to more/less car traffic and longer/shorter travel times by car.
	B: **--/++ High car/bicycle ownership leads to more/less car traffic and congestion.** **-- Car owners tend to make more trips.**
	C: -/+ High car/bicycle ownership leads to more/less car traffic and accidents.
	D: **--/++ High car/bicycle ownership leads to more/less car traffic and emission.** **-- Car owners tend to make more trips.**
	E: - Car owners tend to make more trips and thus generate more noise. ± People with good/bad health tend to walk and cycle more/less, leading to better/worse personal health.
6. To maximise synergy with normality	A: - No peak avoidance tendency leads to longer travel times during peak hours.
	B: **-- No attempt to avoid peak hours means heavier peak hour congestion.** - Following the default (quickest) route means more congestion on the highway.
	C: - Heavier congestion during peak hours leads to more accident. **++ Compliance with speed limit and traffic rules, as well as less lane change/overtaking, leads to less accidents.**
	D: **-- Heavier congestion means more emission.**

	E: ± People follow their peers in deciding whether or not they shall walk and cycle, leading to better/worse personal health.
7. To maximise identity recognition	A: + More travellers with "tele-working" identity means less road traffic. - No attempt to avoid peak hours means heavier peak hour congestion.
	B: **--/+ Sticking to current behaviour in terms of departure time and mode choice means no endogenous mechanism to mitigate congestion (but higher stability).** **-- No attempt to avoid peak hours means heavier peak hour congestion.** + More travellers with "be green" identity means more traffic on green modes.
	C: + More travellers with "be safe" identity means more safe trips.
	D: **++ "Green" people attempt to produce less emission.** **-- "Motor bikers" normally produce more emission.**
	E: + More travellers with "be social" identity means less noise. **++ "Healthy" people tend to walk and cycle more, enhancing their personal health.**
8. To maximise pleasure	A: O
	B: + Pleasurable routes are usually not congested with commuting traffic. + Flexible departure time means tendency to avoid peak hour.
	C: ± Pleasurable routes are usually more curvy, although they are usually less busy.
	D: - Pleasurable routes are usually longer in distance.
	E: - Pleasure from high speed produces louder noise.

5.1.2 Overview: individual vs. system objectives

This subsection attempt to provide a concise overview of the relationships identified in §5.1.1. This is achieved via the correlation table in Table 5.2. As can be seen, the correlation is not always one-sided. When both positive and negative correlations exist, the more dominating correlation is shown in bold typeface.

Cases with major correlations are highlighted with table cell shading. These correlations will be used in §5.2 for identifying key focus areas of behavioural interventions, which in SUNSET are realised by incentives. Incentives targeting at these focus areas are expected to generate behavioural responses that have effective impacts on the system objectives. In other words, such incentives are more likely to be successful from the policy maker's point of view.

Table 5.2 Overview of relationship between individual and system objectives

Individual objectives	System objectives				
	A. To maximise accessibility	B. To minimise congestion	C. To maximise safety	D. To minimise impact on environment	E. To maximise wellbeing
1. To minimise travel time	-	±/--	+/-	+/--	+/--
2. To minimise scheduling effort	O	±/--	±	±	O
3. To minimise cost	O	++/--	±	++/--	±/-
4. To maximise safety	O	+/±	++	±	O
5. To maximise capital	±	++/--	+/-	++/--	±/-
6. To maximise synergy with normality	-	--	++/-	--	±
7. To maximise identity recognition	+/-	+/--	+	++	++
8. To maximise pleasure	O	+	±	-	-

5.2 Evidences from practice

Individual objectives represent travellers' internal motivation for behaving in certain ways. To study traveller behaviour, field studies often make use of more explicit medium of stimulus, such as incentives. These incentives are usually material related, in contrast to the non-material incentives being researched in SUNSET.

(Material) incentives affect travellers' behaviour either by reshaping a traveller's objectives, or by changing (the values of) certain attributes in one's objectives. Characteristics of the incentive have effect on how travellers react to it. The relevant characteristics concern the scope, design, qualification criteria, and reward delivery of the incentive; they are summarised in Table 5.3.

Various incentive programmes have been field tested in the past to study the traveller response. A meta-analysis on 34 publications that report the effects of incentive programmes for stimulating safety belt use (Hagenzieker et al., 1997) has identified 136 short term and 114 long term effect sizes, with a mean short term increase in safety belt use rate of 20.6% and a mean long term effect of 13.7% (see Table 5.4 for the detailed results). This shows that incentives are an effective means to encourage safety belt use. Besides incentives targeting at safety belt use, a selection of other, more recent incentive programmes is listed in Table 5.5; they are discussed in details in the following subsections.

Table 5.3 Characterisation of (material) incentive programmes

Category	Criteria	Settings
Scope	Duration	Whether the programme is temporary (then how long?) or permanent
	Network	The spatial scope of the programme, from municipalities and regions, to national wide and pan-EU
	Participation	Whether the receiving of rewards depends on individual behaviour, or on the collective behaviour of a group (e.g. company reward); Whether participation in the programme is optional or obligatory; Whether participation in the programme is targeted (e.g. only for professional drivers) or open for the general public
Design	Type	Four categories (Geller, 1982): (a) exchangeable token such as cash or meal coupons, (b) immediate valuable or promotional item such as stickers and T-shirt, (c) chance to win a contest or lottery, and (d) work or society related privilege
	Value	Monetary value of the reward, or the expected value in the case of lottery
	Variation	Whether the programme is dynamic over time (e.g. time of day); Whether the programme is differentiated for drivers (e.g. young drivers get a higher incentive)
Qualification	Fulfilment	Whether the rewarding is based on percentage of fulfilling the required actions, or established only upon complete fulfilment (i.e. following the reward route in whole)
	Probability	The probability that a reward is established once the driver has fulfilled the requirement
Delivery	Contingency	Whether the rewarding is contingent upon the actual fulfilment; example for a non-contingent delivery is when any individual who signed a pledge card to follow the reward routes could get the rewards, and the actual behaviour is not checked
	Immediacy	Whether the establishment of a reward (not necessarily the actual payment) is immediate or delayed; example of a delayed delivery is when the rewards are calculated retrospectively

Source: Hagenzieker et al. (1997); Bie et al. (2011).

Table 5.4 Effects of incentives on safety belt use: results from a meta-analysis

Characterisation	Category	Short term effect (%)		Long term effect (%)	
		Mean	*s.d.*	Mean	*s.d.*
Mandatory safety belt use law	Yes	12.0	*2.2*	13.6	*2.3*
	No	22.5	*1.4*	13.6	*1.0*
Type of population	Community	13.4	*1.7*	9.1	*1.5*
	Company	20.0	*1.8*	11.9	*1.1*
	University	17.4	*2.7*	9.7	*2.3*
	Elementary school	36.5	*2.9*	21.6	*2.0*
	Other	13.3	*3.1*	15.5	*3.5*
Control group	No	21.8	*1.4*	14.6	*1.0*
	Yes	14.1	*2.8*	8.9	*1.8*
Group and/or individual reward	Individual	17.5	*1.1*	12.4	*1.0*
	Group	32.5	*4.0*	17.9	*1.9*
	Group and individual	38.8	*8.3*	16.8	*2.2*
Delivery of reward	Immediate	22.2	*1.6*	19.0	*1.8*
	Delayed	14.2	*1.3*	8.7	*0.9*
	Immediate and delayed	30.2	*3.7*	16.4	*1.7*
Promotional item	No	17.8	*1.3*	9.6	*0.9*
	Yes	24.9	*2.3*	18.5	*1.4*

Source: Hagenzieker et al. (1997).

Table 5.5 Characterisation of field tested incentive programmes

Category	Criteria	Incentive programmes			
		BOB	**Belonitor**	**Spitsmijden**	**Transumo-IV**
Scope	Duration	Random days	Temporary	Temporary	Permanent
	Network	Region	Corridor	Corridor	Region
	Participation	Individual Optional Public	Individual Optional Targeted	Individual Optional Targeted	Individual Obligatory Targeted
Design	Type	Item	Token	Token	Token
	Value	~€0.50	Points	€3~7	€2~5
	Variation	Random Uniform	Any time Uniform	Peak hours Uniform	Any time Uniform
Qualification	Fulfilment	Complete	Complete	Complete	Percentage
	Probability	Random	~100%	~100%	~100%
Delivery	Contingency	Contingent	Contingent	Contingent	Contingent
	Immediacy	Immediate	Immediate	Immediate	Immediate

Source: see the references listed in §5.2.1~§5.2.4.

5.2.1 Bob campaign

The Bob campaign originated in Belgium in 1995 (BIVV, 1995). It was a collaboration between several governmental departments (incl. the police) and the Belgian beer brewing industry.

The aim of the campaign is to raise awareness of the danger of driving under the influence. Road safety statistics have shown that drivers with high blood alcohol content are at an increased risk of accident and injuries. High awareness and high compliance with no-drink-and-drive rules are therefore expected to improve road safety.

The concept
Bob stands for "Bewust Onbeschonken Bestuurder" (Dutch for "Conscious Non-Drunk Driver") and the campaign follows the "designated driver" approach. The designated driver is the person who abstains from alcohol on a social occasion, in order to drive their companions home safely.

During the Bob champagne, police surveillance is put into place and breath tests are carried out with (randomly) selected drivers. The designated driver who is tested non-positive of blood alcohol content is then awarded a promotional item (e.g. Bob-keychain).

The impact
In Belgium, Bob has become the symbol against drink-and-drive. To date, more than 90% of the Belgian population knows about the campaign. More than 37% of all drivers in Belgium claim to have offered to be a designated driver. 34% have actually been a designated driver at least once, and 46% have ever been driven home safely by their designated driver.

Recent results (BIVV, 2012) show that drunk-driving rate has been dropping gradually since the campaign started in 1995; during the campaign year 2011-2012 (which ran between 2 December 2011 and 16 January 2012) a record low rate of 3.3% has been observed (Table 5.6).

The Dutch version
The same concept has been picked up in the Netherlands (VVN, 2001). under the brand name "Bob jij of Bob ik?" (Should you be Bob or should I?). Similar trends as in Belgium have been reported.

Table 5.6 Recent results of the Bob campaign in Belgium

Campaign year	2010-2011		2011-2012	
	Number	%	Number	%
Drivers tested	–	*100*	263085	*100*
Drivers positive (BAC: 0.05~0.08%)	2503	*1.2*	2891	*1.1*
Drivers positive (BAC: >0.08%)	5224	*2.4*	5854	*2.2*
Total positive	7727	*3.6*	8745	*3.3*

Source: BIVV (2012).

5.2.2 Belonitor

Belonitor (Belonitor, 2005) was a Dutch practical test for improving the driving behaviour by rewarding the driver. A total of 62 lease car drivers were chosen for the test, which ran from January to June 2005. On-board units (OBU) measure and assess the vehicle's speed and headway with the front vehicle on a continuous basis. A green icon is displayed when the driver behaviour is good, otherwise a yellow icon is displayed. With good behaviour drivers earn points with which gifts can be redeemed.

The Belonitor test was run on an ABA basis:

- A before period without rewards (points);
- A test period with rewards;
- A withdrawal period without reward

At all three stages the green/yellow displays remains fully operational. The observed driver behaviour pattern is summarised in Table 5.7.

As can be seen, the rewards have significant impacts on encouraging safe driving behaviour. However, after withdrawal, there is very little remnant effects. The test further shows that:

- Fuel consumption during the test was on average 5.5% lower than in the four months before the test.
- A large-scale application of Belonitor can result in:
  - 15% fewer deaths and serious casualties;
  - 9% fewer injuries per year; and
  - 1.2% fewer random traffic jams.

Table 5.7 Belonitor: drivers' speed and headway behaviour

Period	Before test	During test	After test
Kilometres driven within the speed limit (%)	66%	86%	70%
Kilometres driven with sufficient distance to the front vehicle (%)	58%	77%	61%

Source: Belonitor (2005).

5.2.3 Spitsmijden

The Spitsmijden (Spitsmijden, 2009) is a series of tests on peak hour avoidance carried out in the Netherlands.

The first test took place in 2007 on the A12 highway from Zoetermeer to The Hague. The test lasted 50 days and a total of 340 drivers participated in the test. A participant received a reward each time they avoided the morning peak traffic period (defined as the 2-hour period between 07:30 and 09:30). Three award schemes were tested:

- Scheme 1: 7 euro reward for avoiding 07:30-09:30;
- Scheme 2: 3 euro reward for avoiding 07:30-09:30;
- Scheme 3: 7 euro reward for avoiding 07:30-09:30, otherwise 3 euro reward for avoiding 08:00-09:00.

The test results are shown in Table 5.8. Similar to Belonitor, significant behaviour adaptation is observed during the test but most driver resume their original behaviour after the rewards are withdrawn. Follow-up Spitsmijden tests have shown similar results.

Table 5.8 Spitsmijden: drivers' departure time choice

Departure time	Before test	During test			After test
		Scheme 1	Scheme 2	Scheme 3	
Before 07:30	20.1%	33.0%	38.5%	37.8%	20.7%
During 07:30-08:00	17.8%	8.9%	6.0%	7.4%	19.1%
During 08:00-09:00	27.4%	15.1%	10.9%	9.9%	24.3%
During 09:00-09:30	4.8%	2.4%	2.2%	2.4%	3.8%
After 09:30	10.3%	16.0%	15.1%	15.9%	12.0%

Note: percentages do not add up to 100% because of other options such as switching to public transport or working at home.
Source: Spitsmijden (2009).

5.2.4 TRANSUMO Intelligent Vehicles

In the Intelligent vehicles project of the TRANSUMO programme, a computer-aided driving simulation study (Bie et al., 2011) has been carried out. It studies the effect of monetary awards on drivers' route choice behaviour.

In this study, drivers are rewarded for the percentage of the safest route (by distance) they follow. It focuses on the dynamic route choice behaviour of drivers. The results are shown in Table 5.9.

As indicated by the results, the incentive is effective in motivating drivers to follow the safest route.

Table 5.9 TRANSUMO-IV: the effect of safety incentives on en-route route choice

Occasions/intersections where the driver choose a following link	Without incentives		With incentives	
	Count	%	Count	%
Which is on both the safest and quickest route	168	40.6%	212	57.9%
Which is on the quickest route but not the safest route	175	42.3%	104	28.4%
Which is on the safest route but not the quickest route	25	6.0	29	7.9%
Which is neither on the safest route nor on the quickest route	46	11.1%	21	5.7%

Source: Bie et al. (2011).

5.3 Implications for incentive design

This section addresses Obj8 Assess the impact of given changes in behaviour (incentives) on system objectives. This deliverable focuses on the potentially effective incentives based on the relationship between individual objectives and system objectives. A follow-up deliverable (D3.4) will continue this subject by quantitatively assessing the impact of behaviour changes (identified in D3.3) on the system objectives.

5.3.1 Key focuses of incentives

Based on the overview in §5.1.2, the key areas of focus for design effective incentives are identified in Table 5.10. These areas are recognised as the combinations of individual and system objectives where the correlation is major and (overwhelmingly) one-sided.

Within these key focus areas, the incentives discussed in §5.2 can be categorised as below:

- Safety belt use: C4;
- Bob campaign: C4;
- Belonitor: C4;
- Spitsmijden approach: B2, B6;
- Transumo-IV: C4.

Incentives should be designed with respect to these focus areas. Examples of such incentives are discussed in details in Table 5.11. An incentive which is successful in achieving one system objective may be also successful in fulfilling other system objective(s): it is expected that

- Incentives which succeed in reducing congestion (Objective B) will also have a positive effect in maximising accessibility (Objective A), because less congestion leads to more trips being made within satisfactory travel time;
- Incentives which succeed in reducing environmental impact (Objective D) will also have a positive effect in maximising citizens' wellbeing (Objective E), due to the reduction of traffic noise and the benefit on personal health of switching to walking and cycling.

Table 5.10 Key focus areas of effective incentive design

Individual objectives	System objectives				
	A. To maximise accessibility	B. To minimise congestion	C. To maximise safety	D. To minimise impact on environment	E. To maximise wellbeing
1. To minimise travel time		B1		D1	E1
2. To minimise scheduling effort		B2			
3. To minimise cost					
4. To maximise safety			C4		
5. To maximise capital					
6. To maximise synergy with normality		B6	C6	D6	
7. To maximise identity recognition		B7		D7	E7
8. To maximise pleasure					

Table 5.11 Suggestions for effective incentive design

Focus areas	Target of incentive	Examples
B1, D1, E1	Travel time	Compensation for extra travel time when choosing a non-car mode Information feed on the environmental/health benefit of choosing a non-car mode
B2	Planning tool	User-friendly tool/information on alternative departure time, mode, or route
C4	Safe driving	Reward for obeying the speed limit and maintaining sufficient headway
B6, C6, D6	Synergy	Start a “movement” of flexible working hours; Create a culture of obeying the speed limit
B7, D7, E7	Identity	Promote “identity” self-recognition based on personal mobility profile

5.3.2 Travel time oriented incentives

Travel time oriented incentives should target the difference in travel time between different modes. For shorter trips, the car mode is usually the quickest and public transport is often (much) slower. Walking is always an alternative but not all people enjoy walking; cycling is also an option provided that the facilities are available.

The incentives should try to compensate the extra travel time with the non-car mode, either via monetary means (bonus) or information-related rewards (such as fuel savings, calorie burnings, CO2 footprint).

For longer trips, car mode is not always quicker but it may be considered hassle free compared to transit mode or P+R. This is an area where planning tool oriented incentives can play a role (§5.3.3).

Characterisation
A monetary incentive will have to be implemented for the long term, as remnant effects are known to be low after withdrawal of the incentive. Temporary incentives can have a long term effect if they contribute to trend forming. For example, a monetary reward that is accumulated towards the purchase of a bicycle, may form a habit of cycling in the traveller with the earned ownership of the bicycle.

Incentives presented in the form of information feeds should also be implemented for the long term, unless they are believed to contribute to trend forming in the incentive receivers.

Such an incentive should target a local/regional level and for travellers who are frequent car users.

Impact
The major impact would be on congestion and emission. Congestion is expected to have a more significant than linear reduction after people switch to non-car modes. A linear reduction rate on emission is expected. Some gain on personal wellbeing is also expected due to noise reduction and health benefit.

5.3.3 Planning tool oriented incentives

The planning tool can provide information that the user is normally unaware of and/or alternatives that the user has not thought of. A user-friendly planning tool can come up with suggestions that is useful and personalised to the user.

Many people are unaware of the transit possibilities connecting their origin and destination. The knowledge and assurances of such possibilities motivate the traveller to take public transport. Other information on e.g. productive time gain, attraction sites along the route, provides extra motivation for using the transit service.

Characterisation
Such an incentive should target long trip and therefore cover a large region, e.g. a national planning tool. Participation should be open to the public. The reward can be materialised in the form of the chance to win a contest or lottery.

Impact
The major impact is on congestion, esp. congestion on the highway, which is expected to drop linearly with the reduction of car traffic.

An important requirement for the long-term success of such an incentive is to make the planning tool accurate and up-to-date. Accuracy is generally no longer an issue but maintenance also requires the information update from various operators. This may become an obstacle at countries where the transit service are operated by multiple companies.

5.3.4 Safety oriented incentives

Safety oriented incentives have been repeated tested in practice. With monetary rewarding, they proved to be quite effective in the short term, but they do not contribute to long term behavioural adaptation. It is also an ethical argument that people should not be rewarded with monetary incentives for what they are supposed to be doing (i.e. driving safely, obeying the rules). Therefore, non-monetary rewards (such as status recognition within a social network) are more suitable in this case although they may be less effective.

Characterisation
Such an incentive should have specific targets, either geographically or demographically. Geographical incentives focus on a local area. Demographical target means a certain type of travellers. For example, new drivers are less experience with driving; elderly drivers may be particularly interested in safety-related information, instruction, and advices.

Impact
The major impact would be on safety but it may be difficult to validate this. Safety is manifested by accidents which are rare events. So evaluation has to cover a longer period of time in order to draw reliable conclusions.

5.3.5 Synergy and identity oriented incentives

Synergy and identity are similar in the sense that they both relate to the "role" a traveller intends to plan. Synergy is closed connected with other travellers, whereas identity mainly relates to the traveller him-/herself.

Characterisation
The synergy oriented incentives should target all travellers within a selected geographical and/or demographical context (i.e. with a high penetration level). The identity oriented incentives can focus on subgroups of travellers (e.g. high mileage drivers) and promote identities (e.g. "green", awareness of personal carbon footprint) among the group.

Given their broad scope, the synergy oriented incentives should focus on non-monetary rewarding, otherwise the programme may become financially unviable.

Impact
The impact would be distributed non-linearly over time: in the beginning little or even no effects may be observed. But over time it will grow (exponentially). For this reason the incentive should be implemented for a long term or permanently.

5.3.6 Incentive design in SUNSET

The preceding subsections have discussed a selection of incentives that are most likely to be effective, based on the identified relationship between individual and system objectives. These incentives are recommended for practical implementations in general. The characterisation of such incentives are highlighted in Table 5.12. When practical limitations restrict the applicability of certain (features of) incentives, a sub-selection of effective incentives should then be made.

Table 5.12 Incentive programmes: general recommendations

Category	Criteria	Target area of incentive			
		Travel time	Planning tool	Safety	Synergy & identity
Scope	Duration	Long or short term	Long term	Long term	Long term
	Network	Local or regional	National	Local	Local
	Participation	Target group	Public	Target group	Public or target
Design	Type	Monetary/info	Information /advice	Information /advice	Information
	Value	Compensate time loss			
	Variation	Focus on peak hours		Focus on e.g. the elderly	
Qualification	Fulfilment			Percentage	Percentage
	Probability		~100%	~100%	
Delivery	Contingency	Contingent	Non-contingent	Contingent	
	Immediacy		Immediate reward		Retrospective

For the SUNSET incentives, some general characteristics are already known, due to practical/technical constraints and/or strategic decisions. These general characteristics are listed in Table 5.13. Since the SUNSET service will not provide a trip planning tool on the national level, the planning tool is not recommended as a potential incentive in SUNSET. The remaining three types of incentives are discussed in details below relative to SUNSET.

Travel time oriented incentives should focus on motivating people to choose non-car mode for their trips. These incentives will provide rewards in the form of information feeds (therefore no monetary reward). Such information should include three components:

- The differences in travel time (between the modes);
- The contribution to environment;
- The contribution to personal wellbeing.

Safety oriented incentives target car drivers and reward them for safe behaviour while driving, such as maintaining a safe speed profile. A safe speed profile is typically steady in speed over time and under the speed limit. Further investigation is needed on the technical applicability of such incentives in SUNSET.

Synergy and identity oriented incentives aim to promote identity recognition, either individually or within a social group. The recommended identities are

- The 'green' identity: raising awareness of the personal emission and carbon footprint;
- The 'being fit' identity: raising awareness on the healthy benefit of cycling and walking;
- The 'safe' identity: promoting compliance with traffic rules and safe driving styles;
- The 'slow living' identity: promoting peak hour avoidance and the choice of "more-relaxed" modes (such as walking).

Individual recognition can be realised by a personal mobility tracker, which registers a traveller's mobility profile and then feed the traveller with status information with respect to these identities. Within-group recognition can be implemented by utilising social networks and comparing the status of travellers to their peers.

Table 5.13 Incentive programmes: recommendations for SUNSET

Category	Criteria	SUNSET in general	Recommended incentive programmes		
			Travel time	Safety	Synergy & identity
Scope	Duration	Long term			
	Network	Local or regional	Local or regional	Local (e.g. hotspot)	Local community
	Participation		Target group	Targeted	Public or targeted
Design	Type		Information	Information	Information & status
	Variation		Focus on peak hours	Focus on car drivers	
Qualification	Fulfilment			Percentage	Percentage
	Probability	~100%			
Delivery	Contingency	Non-contingent			
	Immediacy	Almost immediate	Immediate	Immediate	Retrospective

6. CONCLUSIONS

This research has established the relationship between travellers' individual objectives and the network-level policy goals. The methodologies are behaviour modelling and network modelling. Behaviour modelling is applied to identify the behavioural consequences of individual objectives, while network modelling aggregate the individual behaviour to the system-level measurement equivalent to the policy goals.

The major results are summarised in §6.1. Based on these results, recommendations are drawn in §6.2 on the design of effective incentives, which shall prove useful for the other tasks and work packages in SUNSET.

6.1 Summary: system vs. individual objectives

Relationship is identified in terms of correlations. A positive correction between an individual object and a system objective means that, if more people follow this individual objective, a positive outcome (increase for maximisation, decrease for minimisation) is expected for the system objective. The major results are summarised in Table 6.1. This table is colour-coded:

- Positive correlations are indicated in green;
- Negative correlations are indicated in red.

The correlations are established by linking the objectives with behavioural indicators. The most significant behaviour aspects are:

- Mode choice, mainly car versus other modes;
- Timing choice, especially departure time choice;
- Driving behaviour, including longitudinal control of vehicles and compliance with traffic rules.

Overall the results appear as expected.

Congestion is strongly related to several personal objectives. In particular:

- To minimise scheduling effort means that the driver does not actively avoid the peak hour or the congested route, resulting in heavier congestion. This implies that a user friendly planning tool can be of great use in congestion mitigation. In particular, the P+R mode has not been well accommodated in most up-to-date planning tools and should be a focus area for future enhancement.
- To maximise capital means that car owners will try to use the car as much as possible. This leads to more road traffic and maybe also more (unnecessary) trips. A countermeasure would be to promote the ownership of bicycles and the provision/improvement of cycling/walking infrastructure.

Emission has an almost linear relationship with the amount of car traffic. Most personal objectives make the car mode preferable than other modes (including transit, cycling, walking, and P+R), resulting in greater environmental impact. Measures for emission reduction should focus on the modal shift from private mode (car) to public mode (transit), alternative mode (walking, cycling), and combined mode (P+R).

Personal wellbeing of citizens shares a positive correlation with emission reduction. The active modes, i.e. walking and cycling, contribute to the personal health of travellers and reduce emission due to the reduction in car traffic.

Table 6.1 Individual objectives vs. policy goals: major correlations

Individual objectives	System objectives				
	A. To maximise accessibility	B. To minimise congestion	C. To maximise safety	D. To minimise env. impact	E. To maximise wellbeing
1. To minimise travel time		More car traffic (instead of transit) leads to heavier congestion on the road.		More car traffic (instead of transit) leads to more emission.	Driving generates noise and is less healthy.
2. To minimise scheduling effort		Following departure timetables (blindly) means no attempt to avoid peak hours or congested route.			
3. To minimise cost		Travelling off peak is usually cheaper, leading to less congestion during peak hours.		Less peak traffic means lower emission spikes.	
4. To maximise safety			Lower speed and longer headway lead to less (severe) accidents.		
5. To maximise capital		Car owners tend to make more car trips.		Car owners tend to make more car trips.	
6. To maximise synergy with normality		No attempt to avoid peak hours means heavier peak hour congestion.	Compliance with traffic rules leads to less accidents.	Heavier (peak) hour congestion means more emission.	
7. To maximise identity recognition		No attempt to avoid peak hours means heavier congestion in peak hours.		"Green" people attempt to produce less emission.	"Healthy" people walk & cycle more often.
8. To maximise pleasure					

The impact of synergy/identity related objectives is multifold:

- Certain identities play a positive role for the system objectives, while other identities lead to negative impact of the system objectives. For policy makers, positive identities should be promoted and negative identities discouraged. Various means exist, including advertisement, publicity campaign, and even legislation.

– Synergy is a double edged sword. To promote an identity within a community may meet with resistance in the beginning, due to the low penetration level of such identity in the community. However, as the promotion goes on, synergy would bring the snowball effect along and lead to an accelerating growth of recognition, until the majority of the community start to share this identity.

6.2 Recommendation for designing incentives in SUNSET

Within SUNSET, incentives will be tested for their effectiveness on promoting more sustainable travel behaviour. Based on the relationship between individual and system objectives, a selection of potentially successful incentives

Based on their applicability in SUNSET, this deliverable recommends the following incentives for further investigation in SUNSET:

- Intermodal information provision;
- Identity promotion within individual travellers;
- Identity and status recognition among a group of travellers.

The intermodal information provision is motivated by the travel time difference between the difference modes. The information should highlight the gains of the sustainable modes on environment protection and personal health.

With the personal mobility tracking service, identity promotion focuses on the “green” identity by encouraging travellers to travel in more sustainable ways.

Utilising social networks, within-group status recognition is the most prominent feature of SUNSET. Status is establishing by classifying the personal identity within the group context.

The detailed design of incentives will be presented in the SUNSET Deliverable 3.4 “Feasible and potentially successful incentives”. These incentives will then be tested in the SUNSET living labs.

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Appendix A. Bounded rationality and regulation flexibility

This appendix discusses the concept of bounded rationality in individual choices and its implications for traffic management (referred to as "regulation flexibility"). An earlier version of this appendix has appeared in the format of a journal paper (Vreeswijk et al., 2012).

Most existing research focus on intrinsic choice behaviour, i.e. elementary choice based on the characteristics of multiple choice alternatives (e.g. Prato, 2009; Bonsall, 1992; Chorus et al., 2009; Chorus et al. 2006; Han et al., 2007). Alternatively, we can also study behaviour by examining drivers' response when the characteristics of the choice alternatives (slightly) change, due to e.g. dynamic traffic management (DTM) measures (Vreeswijk et al., 2010), or ITS application and services (Vreeswijk et al., 2012). DTM measures refer to systems that influence the network performance in terms of travel times, delay times, traffic density, average speed, etc. Examples include route guidance and traffic lights. Driver responses are manifested in the changes in their route choice (e.g. rat run), departure time, mode choice, driving behaviour (e.g. red light violation), etc.

The predictability of choice behaviour and behavioural response is a key topic in traffic modelling. Most available traffic models combine demand (i.e. drivers' trips and travel choice behaviour) and supply (i.e. infrastructure and DTM). By means of traffic assignment this determines the performance of the transportation system. Often, these models assume a fixed supply and an elastic demand which anticipates to changes in the system performance. However, to include driver response the question is how demand alters when e.g. DTM change supply.

Many assumptions in conventional traffic modelling have been derived from standard economics. It is often assumed that drivers are rational decision makers and above all perfectly informed about the available choice alternatives. Moreover, that they can calculate the value of the different options available, that they are able to derive the optimal choice, and that they are cognitively unhindered in weighting the implications of each potential choice (Srinivasan & Mahmassani, 1999; Avineri & Prashker, 2004). In other words, people presumably make logical and sensible decisions and quickly adopt their choice to changing conditions.

Obviously these assumptions are debatable.

In reality, people have limited knowledge and constrained cognitive abilities leading to prejudiced reasoning and certain randomness in behaviour and choice outcomes (Avineri & Prashker, 2004; Chorus & Timmermans, 2009). It is not just the behaviour (i.e. choice outcome) that is of interest, but also the decision-making process behind such behaviour. Behavioural economics draw on the aspects of both (cognitive) psychology and economics, and studies the motives and behaviours that explain deviations from rational behaviour (Ariely, 2009; Avineri, 2010). This perspective of individual decision-making is known as bounded rationality or satisficing behaviour (Simon, 1955; Simon, 1982). Bounded rationality is expanding itself into transport researches (e.g. Mahmassani & Chang, 1987; Jayakrishnan et al., 1994).

Although in some cases, like random utility theory modelling, a random variable or error term is considered to somehow weaken the assumptions of perfect rationality, many models fall short in considering imperfections in drivers' choice behaviour. The development of better descriptive models of choice behaviour and empirical validation of theories derived from behavioural economics is on-going (Chorus & Timmermans, 2009; Vreeswijk et al., 2011).

A useful bounded rationality mechanism is the notion of indifference bands. That is, travellers will only alter their choice when a change in the transportation system or their trip, for example the travel time, surpasses some individual-situation-specific threshold (Chang & Mahmassani, 1988; Mahmassani & Liu, 1999; Jou et al., 2005; Chorus & Timmermans, 2009). There are many factors associated with bounded rationality which explain why a change in network performance not necessarily leads to a behavioural response. For example: due to the formation of habits a driver is not alert to changes; a driver may be unaware of a change if the change is small or not within the driver's periphery; drivers may be disinterested in a change if they regard it insignificant, or there is simply a lack of (knowledge of) alternatives.

> ***Example*** *(used figures are imaginary): at a controlled intersection, increases in waiting time up to 5 seconds may largely go unnoticed and hardly invoke response. Presumably, this is because drivers are unable to notice the change. Increases between 5 and 10 seconds are more likely to be detected by drivers, but still may invoke little response. Presumably, this is because the change is not important enough relative to drivers' reference point and alternatives. However, when the increases in waiting time are higher than 10 seconds (exceeds the indifference band threshold), they may increasingly invoke substantial response. Presumably, this is because drivers do detect such changes and find them 'disturbing' enough to favour alternatives. The same example can be applied to cases of travel time, arrival time, level of service, etc.*

It becomes obvious that basic knowledge of many factors is needed to determine the indifference band for a specific traveller-situation. Examples are: how drivers cognitively and affectively experience (waiting/travel) time, how accurately drivers are able to estimate time intervals, drivers' ability to detect changes and value them correctly, the existence of alternatives and drivers' awareness of these alternatives.

Indifference band provides road operators with certain freedom to move the performance of their network towards a state that minimises the total travel time in the network. Multiple studies have shown that boundedly rational behaviour is neither random nor senseless; rather, they are systematic, consistent, repetitive, and therefore predictable (Tversky & Kahnemann, 1992; Avineri & Prashker, 2004; Ariely, 2009).

Network-favoured measures do not necessarily improve the situation of all drivers. However, undesirable and disproportionate behavioural response of drivers whose situation declines may be limited or even absent, if the indifference band is respected. Hence the feasible region of DTM expands compared to the case of perfect rationality; DTM becomes more effective and the network performance benefits. In addition, the indifference band also indicates the minimum required effect of DTM to ensure driver response and likewise increase the effectiveness of the measure.

The feasible region provides extra opportunities to DTM: 'regulation flexibility'. 'Regulation' means the adjustment of control variables of traffic management and traffic control measures to optimise the network performance (e.g. green split at controlled intersection). 'Flexibility' is derived from the notion of indifference bands and symbolises a road operator's freedom to 'regulate' without unintended behavioural response effects. Clearly, the central question is the dimension of the indifference band and its threshold values in particular.

In the example given earlier, the indifference band was 10 seconds, while several of the aforementioned studies suggested indifference bands for the travel time of a route ranging from 10 minutes to 22%. However, it is easy to recognise that such figures strongly depend on the context. To our best knowledge no research has been done that systematically describes the relations and weights of the factors underlying and cumulatively contributing to the indifference band phenomenon.

A summary and visualization of the general framework of the regulation flexibility philosophy is shown in Figure A.1. It is important to distinguish that this figure is descriptive and not conclusively scaled based on quantitative data. Besides, the figure is not restricted to one specific context and DTM measure. On the horizontal axis is the time-effect of a DTM, such as a change in waiting time or travel time expressed in gains or losses. The vertical axis represents the value judgement of drivers ranging from positive to negative. The value function is taken from prospect theory. In the context of difference bands this function describes the two-sided driver response probability subject to the time-effect, reference point and asymmetry of gains versus losses. The reference point is marked by the dot in the centre of the figure.

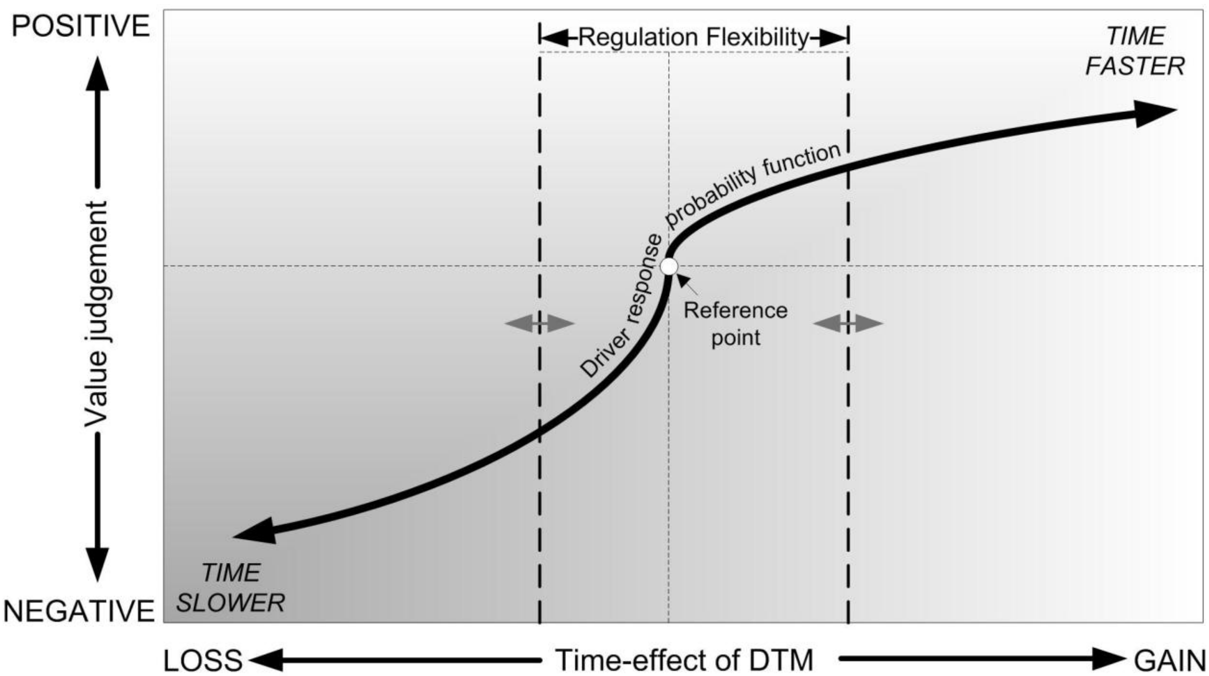

Figure A.1 Theoretical framework of regulation flexibility

Similar to prospect theory, it is assumed that drivers are more likely to notice and respond to changes involving losses than changes involving gains, while the effect of additional gains or losses decreases. For example, waits at traffic lights which increase by 10 seconds have a higher impact than waits which decrease by 10 seconds. In addition, the marginal impact of the 10^{th} second is larger than the marginal impact of the 11^{th} second. Evidence from time psychology research (van Hagen, 2011) adds to this framework that time feels as moving faster with gains and positive value judgments, and slower with losses and negative value judgments. Accordingly, regulation flexibility is defined as an asymmetrical band around the reference point; its thresholds indicated by the dashed lines. Within this band travellers are assumed to be indifferent to time-effects of DTM for reasons mentioned earlier.

Regulation flexibility typically applies to day-to-day scenarios as it is strongly related to between-day decision making. Generally the experiences of the previous day and the current day are known to be dominant determinants for decision making of the next day (Bogers et al., 2005). Moreover, when a traveller notices a time-effect of DTM larger than the regulation flexibility, then it is assumed likely that the next day this traveller responds in one way or another. Though, this is only relevant if the traveller regards the change as a loss. Where gains are concerned it only makes sense for a traveller to adapt its behaviour if due to that gain an alternative has become more attractive. How drivers can become aware of improvements of non-chosen alternatives is another topic (Chorus & Timmermans, 2009) outside the scope of this research.

Due to the stochastic variability of the traffic system a traveller may not notice a change instantly, but requires several days to do so. If the network topology allows, only in rare cases travellers will be able to adjust their behaviour, for example their route, within a day. Empirical evidence is needed for validation and quantification of this framework. Figure A.2 provides a schematic framework of regulation flexibility based on the three-stage decision making process discussed in §3.1.4. For reasons of comprehensiveness and readability, notable factors such as attitude, learning, perception, expectation, motivation, information and personality have been omitted in the figure.

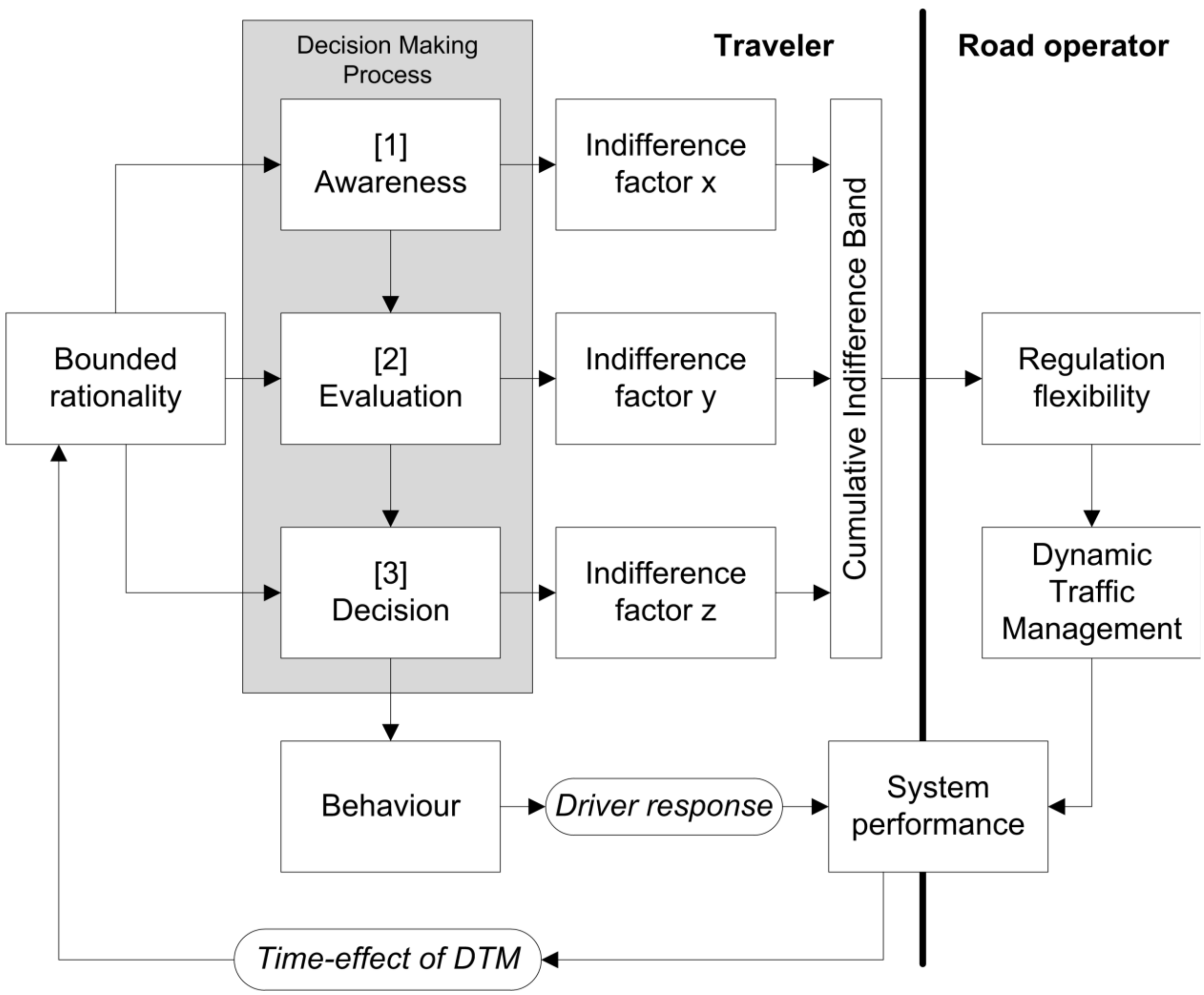

Figure A.2 Conceptual framework of choice behaviour and regulation flexibility

Awareness

Research on the impact of learning shows that the awareness among drivers of changes in the transport system is limited and grows over time as a result of direct experience and indirect learning (Chorus & Timmermans, 2009). A change could involve an improvement or degradation in the current option or an existing alternative, or the introduction of a new alternative. It concerns for example the waiting time at traffic lights, the average speed or the travel time. In general, the larger, the more expectable the more important and the more negative a change, the sooner a traveller is expected to notice the change (Tawfik et al., 2010a). Take the waiting time at traffic lights as an example: several surveys showed that drivers' estimates of waiting times, on average, are fairly accurate, but widely variable, as are their perceptions (Pechaux et al., 2000; van der Bijl et al., 2011).

When a change is within the natural variation of a traffic situation with respect to an average, it seems unlikely that drivers are capable of detecting the change at all. For example, if the waiting time at a traffic light has an average of 30 seconds and a variation of 15 seconds, it means that measures shifting the average within the range of 15 to 45 seconds are hardly distinguishable from the natural variation.

Similar findings were found in studies on user perceived level of services at signalised intersections and motorways. These studies showed that drivers are unable to perceive fine differences and only distinguish two or three levels of service rather than the six provided by the Highway Capacity Manual (Choocharukul et al., 2004). Interestingly, this suggests that drivers' quality perception is nearly binary with only the level 'good' and 'not good'.

Derived from cognitive sciences, change blindness is the inability to detect and report changes to objects from one instant to the next that are obvious once pointed out (Martens, 2011). Experiments have shown that participants are surprisingly bad at detecting even large changes, sometimes leading to change blindness in 88.5% of all cases. For drivers, change blindness increases when the changed item is not relevant for the task, when the magnitude of the change decreases, and when the change is further outside the visual periphery.

Evaluation

When travellers have been able to detect a change, the central question in the evaluation state is whether they value it properly or not? In a rational way, people have little feeling of how much things are worth. They focus on the relative advantage of one thing over another rather than the absolute difference, compare them locally to the available alternative, and estimate value accordingly.

Different studies confirm that the decisions and actions of drivers do not always correspond with their (perceived) observations. In one study only 12% of the drivers was able to correctly perceive their experienced travel times, and reversely, 12% perceived the opposite of their experience (Tawfik et al., 2010a). Similar and even larger figures were found with varying traffic volume and timing of traffic lights (Vreeswijk et al., 2011). This led to three types of behaviour:

1) logical behaviour that reflects drivers choosing better perceived routes (perceive route A better and choose route A),
2) cognitive behaviour reflecting drivers choosing a route in spite of not perceiving a difference between both routes; to reduce mental working load (perceive no different, choose any route), and
3) irrational behaviour that reflects drivers choosing worse perceived routes (perceive route A better and choose route B).

For the last type, cognitive scientists use the term 'choice blindness' to explain such failures to detect mismatches between intention and outcome of a simple task (Johansson et al., 2006).

Most surprisingly, in a choice blindness paradigm, participants are still able to offer arguments why their choice was the most logical. For drivers an interesting insight on this aspect is that drivers are better in perceiving travel speeds than travel times; perceived travel speeds seem to influence choice outcomes more than perceived travel time (Tawfik et al., 2010).

Previous experiences are known to serve as an anchor in the memory of drivers and strongly affect choice behaviour, in particular when bad experiences are involved (Ariely, 2009). Loss aversion refers to the fact that people treat gains and losses differently as they tend to be more sensitive to decreases in wealth than increases, while people become less sensitive for every marginal gain or loss. In general, bad experiences involving loss, weigh two times a similar size good experience involving a gain. Figuratively, good experiences create a certain 'acceptability-buffer', which may be emptied again by far less bad experiences (e.g. unacceptable DTM measures). Clearly, the reference point in the mind of the driver determines to a large extent how things are valued. Earlier research concluded that the perception of the reference point in the mind of the driver is vague and fuzzy rather than crisp; they may not necessarily consider their actual experience to be the reference point.

To value a choice option or a change in any of its attributes, the option and/or its attributes need to be within the area of interest of an individual. As a result of driver's bounded rationality there are multiple factors which narrow this area of interest and make drivers appear indifferent concerning the evaluation of alternatives. For example habitual behaviour, which evolves in trips that are often repeated and causes cognitive processes to reach automaticity and eventually result in making choices in a more or less mindless fashion. Besides, drivers tend to be near-sighted which means that experiences of the previous day as well as short-term gains dominate choice processes.

Satisfying behaviour, stating that people are happy with a good solution instead of finding the best solution, is regarded as another major cause for drivers' indifference. It means that humans tend to minimise their cognitive efforts, and follow simple heuristics to reach decisions which are both satisfactory and sufficient, especially under uncertainty and time constraints. Empirical research on the indifference band showed that drivers may be uninterested in other choice options until their current situation worsens by 22% (e.g. extra travel time), or a choice alternative improves by 22% [8].

Decision

Changes in traffic conditions may be observed and correctly valued or not, but do they provide sufficient motive to affect the decision outcome? Generally, studies on decision behaviour focus on decision outcomes, apart from few exceptions which shifted interest to the analysis of underlying cognitive mechanisms. Such studies for example showed that drivers think much more strategically than usually presumed (Senk, 2010; Razo & Gao, 2010). Based on the analysis of verbal reports, at least four decision strategies can be considered:

1) the comparison strategy,
2) the exploitation strategy,
3) the exploration strategy, and
4) the anticipation strategy.

The great diversity in applied strategies proves that a certain level of awareness and acceptance of changes affect choice decisions.

For route choice, a study showed that route switching occurs more frequently when the traffic conditions fluctuate randomly than when they are stable (Srinivasan & Mahmassani, 1999). This type of behaviour is largely influenced by risk attitude (i.e. risk aversion and risk seeking), which determines the amount of risk somebody is willing to take. Many factors such as travel purpose, length of the trip and preferred arrival time have a big impact on a driver's risk attitude and choice outcomes. In terms of choice outcomes, roughly four route choice patterns (Tawfik et al., 2010b) can be distinguished:

1) fixed choice,
2) single trial,
3) preferred switching, and
4) random switching.

Appendix B. Penetration level and ITS deployment

This appendix follows the discussion on penetration level in §4.1.3. It illustrates the benefit of governmental subsidies on ITS deployment, which may bring a win-win situation to the stakeholders. An earlier version of this appendix has appeared in the format of a conference paper (Bie & van Berkum, 2012).

Retail price versus penetration level

Drivers' decision of whether to purchase an ITS application mainly depends on its retail price and the potential utility of using it. The price, P, is set by the manufacturer, subject to various objectives and potential constraints. The potential utility of using the application is related to B. If the potential utility is evaluated as B_{100} regardless of the actual penetration level, then the number of purchase, hereby directly linked to Q, is a function of P, i.e.

$$Q = g(P). \qquad (12.1)$$

Figure B.1 shows a typical P-Q curve: purchase decreases with higher prices. On the other hand, if utility is evaluated at the actual penetration level, then an iterative process evolves: $B^{(n)} = f(Q^{(n)})$, $Q^{(n+1)} = g(P, B^{(n)})$, converging at an equilibrium defined by $Q^{\square} = g(P, f(Q^{\square}))$.

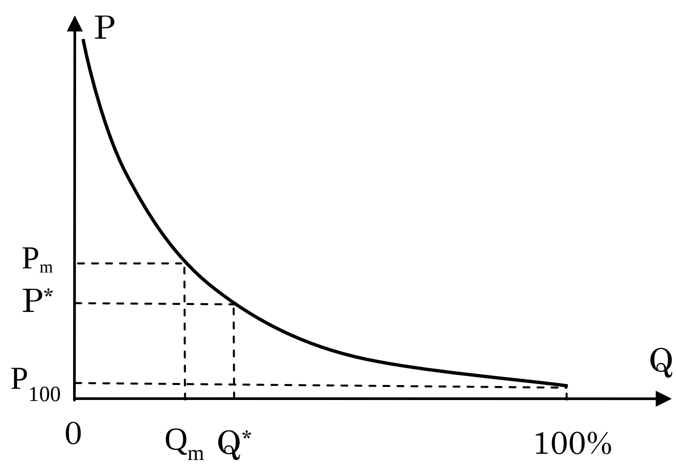

Figure B.1 Retail price (P) **vs. penetration level** (Q)

The revenue generated through the sales of ITS application is $Pg(P)\kappa$, where κ is the population of drivers. Under the objective of revenue maximisation, the optimal price can be derived by solving

$$\begin{aligned} &\max\ Pg(P)\kappa \\ &s.t.\quad P \geq 0 \end{aligned} \qquad (12.2)$$

The solution is equivalent to the solution of $g(P) + P\dot{g}(P) = 0$, represented by P_m in Figure B.1.

The existence of Q^* (cf. Figure 4.1) implies that, if the price is set too high, the penetration level will be low and the impact on traffic could be negative. The maximum price in order to achieve a positive impact is given as $P^* = g^{-1}(Q^*)$. For the case illustrated by Figure B.1, P_m would be too high and result in negative impact on the traffic system.

Win-win situation

While the manufacturer tries to maximise revenue, $Pg(P)\kappa$, by setting the price at P_m, the traffic operator (or the government) wants to maximise traffic benefit, $f(g(P))\kappa$. If the price can be lowered from P_m to $P_m-\Delta P$, then the traffic benefit will increase from $f(g(P_m))\kappa$ to $f(g(P_m-\Delta P))\kappa$ but the revenue would drop from $P_m g(P_m)\kappa$ to $(P_m-\Delta P)g(P_m-\Delta P)\kappa$. The increase in benefit is given by

$$\Delta B = f(g(P_m-\Delta P))\kappa - f(g(P_m))\kappa. \tag{12.3}$$

The decrease in revenue is

$$\Delta R = P_m g(P_m)\kappa - (P_m-\Delta P)g(P_m-\Delta P)\kappa. \tag{12.4}$$

The following theorem (Bie & van Berkum, 2012) states that under certain conditions the increase in benefit outweighs the decrease in revenue.

> _Theorem:_ *If* $\dot{g}(P_m)<0$ *and* $\dot{f}(g(P_m))>0$*, then there always exists small enough* ΔP *'s (* $\Delta P>0$*) such that* $\Delta B-\Delta R>0$.

The first requirement, $\dot{g}(P_m)<0$, states that penetration level decreases strictly monotone with retail price at the retail price of P_m. The second requirement, $\dot{f}(g(P_m))>0$, states that traffic benefit increases strictly monotone with penetration level at the penetration level of $g(P_m)$. Both conditions are reasonable and easily satisfied (as in Figure B.1).

For big ΔP 's, consider the ultimate case of lowering the price to P_{00}, revenue would decrease to $P_{100}\kappa$ while benefit increases to $B_{100}\kappa$. The corresponding requirements would be $P_{100}+E_{100}>P_m g(P_m)+f(g(P_m))$, not unlikely to be true judging from Figure 4.1 and Figure B.1Figure B..

This implies that a win-win situation can be achieved: the government subsidies the manufacturer for it to lower the price of the ITS application; the reward is in the form of increased traffic benefit (due to higher penetration levels). The amount of subsidy, S, is determined such that

$$\Delta R < S < \Delta B. \tag{12.5}$$

Compared to the case without subsidies, the gain by the manufacturer is $S-\Delta R$, and the gain by the government is $\Delta B - S$. Therefore a win-win situation arises.

In conclusion, if the traffic impact (or benefit) of an ITS application on an individual driver level has a strictly monotone relationship with the penetration rate, then government subsidies should be provided in order to lower retail price, increase penetration level and increase traffic benefit. Such type of ITS applications are most likely to be cooperative systems, where a high equipment rate is essential.