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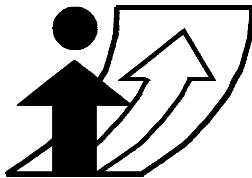
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## **Abstract**

When applying dynamic route guidance to improve the network performance, it is important to balance the interests of the road authorities and the road users. In this paper we will illustrate how bounded rationality and indifference bands can be taken into account in dynamic route guidance to improve the network performance while respecting the interests of road users. The paper elaborates on empirical findings reported in literature to propose a suitable interpretation and utilization of the indifference bands in a control approach. By means of a service level-oriented route guidance control approach we evaluated the potential gain in network performance of different absolute indifference bands. Results from a simulation test case show a reduction in total travel time of 5% compared to user equilibrium, in case of an indifference band of 4 minutes for a trip of approximately 22 minutes. The improvement in network performance increases with an increasing indifferent band, up to 14% in case of an indifference band of 10 minutes.

## **Keywords**

Route guidance, bounded rationality, indifference band, perception error, service levels, network performance

# 1. Introduction

Today's increasing adverse effects of congestion indicate the need to apply dynamic traffic management (DTM) on a network level to improve network performance. However, there exists a well-known conflict between realization of system optimal conditions and user optimal conditions (e.g. Wardrop, 1952, Van Vugt, 1996, Koutsoupias and Papadimitriou, 2009). Hence, to successfully operationalize DTM on a network level, a suitable trade-off between the interests of road authorities and those of drivers needs to be made. The main challenge addressed in this paper is to find and implement a control approach that operationalizes road authorities' traffic management policies and steers the network towards the desired state without seriously violating drivers' interests.

Empirical research in the field of traffic psychology indicates that drivers have difficulty in assessing the quality of their chosen alternative (e.g. Simon, 1955, Ariely, 2009) or are simply not willing to adapt their choice if the benefits of switching are below a certain threshold (e.g. Mahmassani and Chang, 1987, Mahmassani, 1996). This perspective of individual decision-making is known as bounded rationality and contributes to the so-called indifference band. On the basis of a simple example, using the green split of traffic lights as control mechanism, it was already demonstrated that application of indifference bands can successfully steer a system towards its optimal state (Vreeswijk et al., 2012). This paper therefore proposes the use of these psychological constructs to improve the network performance, in such a way that user interests remain respected. To this aim, service level definitions are used to describe the quality of the network elements and the perceived quality from the perspective of the road user. The trade-off between quality of the network elements with respect to network performance and the perceived quality of the road users is operationalized by a service level-oriented route guidance approach.

The control approach should realize network states in line with the policy objectives, i.e. phenomena that decrease the network performance should be prevented in a systematic and comprehensible way without strongly violating the road users' interests (e.g. mode, route, departure time and arrival time). This is a challenge, because it is often acknowledged that road users are generally most concerned with improving their own situation, disregarding the effect of their actions on the network performance and the intentions of traffic management policies. Vice versa this argument also holds; as road authorities develop visions on how their network should function without explicit care for individual drivers.

By means of a simulation test case we will illustrate the use of indifference bands to improve the network performance. The notion of indifference bands (Mahmassani and Chang, 1987) is based on the observation that drivers behave boundedly rational. For example, they make estimation errors that influence their perception of their situation. There is evidence that such errors contribute to an indifference band that represent drivers' insensitivity to varying conditions. In this paper we argue that the network performance can be improved by considering the indifference bands in traffic control while the expectation of individual road users remain protected. Note that although the network state moves from user equilibrium towards system optimal state, drivers are indifferent to this change because their perception of the old and new state is similar. Hence, they won't respond to the change in perceived traffic conditions.

The remainder of this paper will focus on two questions. Firstly, what is the width of the indifference band? This question is concerned with the extent to which road users are insensitive to conditions that are suboptimal from their individual perspective. Secondly, what are the implications for the achievable network performance improvement with application of a service level-oriented route guidance approach?

The following section will give an extensive overview of the background of our work. Bounded rationality, indifference bands, perception error and service level-oriented route guidance will be discussed in detail. Next we will formulate our approach from the theory and empirical evidence that is available. Through application of the approach in a test case we will demonstrate the potential effect on the network performance. The final sections discuss the results and conclude.

## **2. Background**

### **2.1. Bounded rationality**

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 (Avineri and Prashker, 2004, Srinivasan and Mahmassani, 1999). In other words, people presumably make logical and sensible decisions and quickly adopt their choice to changing conditions. In reality, people have limited knowledge and constrained cognitive abilities leading to prejudiced reasoning and certain randomness in behaviour and choice outcomes (Avineri and Prashker, 2004, Chorus and Timmermans, 2009). Behavioural economics draw on the aspects of both (cognitive) psychology and economics, and study the motives and behaviours that explain deviations from rational behaviour (Ariely, 2009, Avineri, 2010). This perspective is known as bounded rationality or satisficing behaviour (Simon, 1955, Simon, 1982), and also found its way into transportation research (e.g. Mahmassani and Chang, 1987, Chang and Mahmassani, 1989, Jayakrishnan et al., 1994). In summary, bounded rationality states that drivers do not necessarily make the most economical (or logical) choice.

### **2.2. Indifference bands**

A well-known mechanism derived from the principles of bounded rationality, which is has been used and validated in the field of transportation, is the notion of indifference bands. According to the theory of indifference bands, drivers will only alter their choice when a change in the transportation system or their trip, for example the travel time, is larger than some individual-situation-specific threshold (Chorus and Timmermans, 2009, Srinivasan and Mahmassani, 1999, Chang and Mahmassani, 1988, Mahmassani and Liu, 1999, Jou et al., 2005). In the field of time psychology this threshold is called the ‘comfort zone’ (Van Hagen, 2011). In addition, drivers are supposed not to update their choice (e.g. route, departure time, mode) when the difference in quality between two routes, for example in travel time, is less than the same threshold.

There are many factors associated with indifference bands which explain why a change in

network performance not necessarily leads to a behavioural response. Examples are limited awareness and disinterest (Vreeswijk et al., 2012). Underlying reasons may be that a driver is not alert to changes due to the formation of habits, that a driver is not able to detect or 'see' the change because it is small or outside the driver's periphery, that the driver is disinterested if the type of change is regarded insignificant, or simply because of a lack of (knowledge of) alternatives.

Multiple studies provide evidence that boundedly rational behaviours are neither random nor senseless; they are systematic, consistent, repetitive, and therefore predictable (Avineri and Prashker, 2004, Ariely, 2009, Tversky and Kahnemann, 1992). As a consequence the indifference band can be estimated too and therefore used as an input variable for DTM. In several studies an attempt was made to estimate the width of the indifference band. All studies acknowledged the existence of the phenomenon, but their estimations vary: 10 minutes (Mahmassani and Chang, 1985), 18 minutes (Van Knippenberg and Van Knippenberg, 1986), 5-10 minutes or 17-22% (Srinivasan and Mahmassani, 1999). From these figures it is clear that no single, generic indifference band can be defined without knowledge of the traffic conditions, trip lengths, etc. The indifference band is clearly situation specific.

### **2.3. Perception error**

In literature there is strong debate about discrepancies between drivers' perception and the existing level of service standards (Washburn et al., 2004). The Highway Capacity Manual (HCM) proposed six levels of service ranging from 'A' very good service to 'F' very poor service which are separated by threshold values of characteristic measures of traffic flow performance, such as traffic density, volume-to-capacity ratio and average speed. However, empirical evidence of below referenced studies show that on average drivers are unable to properly estimate the actual quality of the conditions they experience. Drivers' perceptions of level of service appear widely variable, while usually only two or three levels of traffic conditions are distinguished.

In one study drivers' assessment of motorway traffic conditions, reported while waiting at traffic lights on a freeway exit were compared with actual v/c-ratio from the same time period (Papadimitriou et al., 2010). This study showed that drivers' assessment of level of service is especially variable at moderate traffic conditions within the v/c interval of 0.55-0.70. Besides, only low-tolerance drivers appear to distinguish level of service A and B, and only high-tolerance drivers appear to distinguish level of service D from E. Findings did not differ for driver and vehicle characteristics. Based on these results, three service levels were proposed: one for the highest v/c values, one for medium-high v/c values, and one level for all other v/c ratios. Using video clips taken from cameras on overpasses, another study with 195 individuals from 5 different occupational groups showed similar results (Choocharukul et al., 2004). Likewise, participants of this study seemed to differentiate three levels of freeway traffic conditions. Besides, they had lower tolerance for LOS A, whereas a higher tolerance for worse LOS. For urban commuters similar results were found as they appeared to be primarily concerned about the total trip time and its reliability in order to complete the journey in reasonable time (Hostovsky et al., 2004). As such, fine distinctions between LOS A through D did not seem to matter in the urban context.

Another stream of research investigated the perception of the level of service at signalized

intersections. Study results (see Zhang, 2004 for a review) suggest that also in this case drivers do not perceive level of service in way consistent with the HCM criteria . Generally, two and perhaps three levels of service are generally perceived (Pecheux et al., 2000). Lower levels of service were rated higher than expected, which suggests that drivers may be more tolerant to longer delays (or used to them) than what is usually assumed. On the other hand, high levels of service, i.e. A through C, are perceived as very similar. Using a special and less rigid data clustering technique it was concluded that drivers are able to differentiate six levels of service, but not the existing HCM ones (Fang and Pecheux, 2009). In this study, the service levels A and B were merged for a single level and level F was split into two.

A third stream of research looked at the accuracy of drivers' perception of route alternatives. Most studies observed that driver perceptions become more accurate if the difference between alternative routes increases. It was found that driver perceptions were on average around 60% accurate (Tawfik and Rakha, 2012). Besides, drivers were able to perceive travel speed better than travel time, while perception of travel distance was least accurate. Several revealed preference studies showed that on a substantial percentage of trips drivers do not choose the shortest route (Jan et al., 2000, Beckor et al., 2006, Zhu and Levinson, 2012, Thomas and Tutert, 2010). The number of trips varied from 25% to as much as 84%, depending on the route type (e.g. orbital or centre) and travel time difference between route alternatives. Often the travel time difference is small (e.g. 30 seconds), but a substantial number of non-trivial travel time differences were found, ranging from 2 up to 5 minutes or 8-25% of the average commute time (Thomas and Tutert, 2010, Zhu and Levinson, 2012). Based on the observation that drivers' perception not always correspond with their experiences one could distinguish three types of choice behaviour (Tawfik et al., 2010): (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).

Finally, a recently adopted theory in transportation research worth mentioning is prospect theory. The theory is derived from behaviour economics and relevant in the context of this paper. It is based on the principle that decisions are context-dependent and alternatives are framed in terms of gains and losses relative to some common reference point, while losses weigh twice as much as gains of equivalent size (Kahnemann and Tversky, 1979, Avineri and Bovy, 2008). In line with this theory it is arguable 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. The recently introduced theory or regret minimization also builds upon these principles, i.e. people anticipate and try to avoid the situation where a non-chosen alternative outperforms the chosen one (e.g. Chorus, 2012).

## **2.4. Service level-oriented route guidance**

The approach that we adopt is a recently proposed service level-oriented route guidance approach that is able to systematically improve network outflow by preventing the negative effects of spill back and capacity drop. The control process will be presented, but details on the applied controller, a finite-state machine in combination with feedback control laws, can be found elsewhere (Landman et al., 2012, Landman et al., 2011).

The capacity of road infrastructure drops during the onset of congestion, because the flow out of the queue is smaller than the maximum achievable flow during free flow conditions. Blocking back of queues to upstream road infrastructure can cause hindrance to flows that do not need to pass the bottleneck. Both phenomena realize a decrease in the network outflow (or more total time spent by vehicles in the system) which can be prevented by guiding traffic away from the critical bottleneck towards network elements where it least degrades the network performance.

The dynamic route guidance approach controls the performance of two alternative routes by maintaining predefined target service levels. The critical performance conditions at which spill back occurs within a route are defined in terms of average speed or travel time within the route, based on simulation or empirical data. The performance of the routes is then degraded stepwise towards this critical value by step sizes that remain well within the indifference band of road users (i.e. the performance difference between the routes is not noticeable by the road user). However, once a route reaches its critical value, its performance is stabilized by sending traffic to its alternative. To maximally postpone the occurrence of blocking back, a performance difference is realized that is equal to the maximum value of the indifference band of road users for the specific situation.

Target service levels of a route are degraded and recovered during respectively over- and undersaturated traffic conditions. Oversaturated means that the traffic demand for both routes is larger than their joint capacities, resulting in increasing congestion and decreasing service levels. If the demand for both routes is smaller than this joint capacity, routes are assumed to be undersaturated (even though congestion can still be present), resulting in performance recovery.

In Table 1 it can be seen that the service levels are defined as performance ranges, indicated by an upper boundary  $v_r^{\text{ub}}(l_r(k_c))$  and a lower boundary  $v_r^{\text{lb}}(l_r(k_c))$  of the traffic speed (or travel time), with  $r \in \{1, 2\}$  the route index,  $l_r(k_c)$  the service level index at control interval  $k_c$  of route  $r$ . We assume that the preferred or main route between an origin is indicated with  $r=1$  and its alternative with  $r=2$ . The service level upper boundaries are used as the target values to stabilize the performance of a route by sending traffic to the alternative (i.e. by adjusting the split fraction of the routable flow). Notice from the table that the boundaries of the same service level can be different for the different routes (i.e. any performance regime over the routes can be established), and that the level indices increase when the performance degrades.

Table 1: Service levels with their upper boundaries (ub) and lower boundaries (lb) in terms of speed (km/h)

Levels	Main route		Alternative		
	$l_1(k_c)$	$v_1^{\text{ub}}(l_1(k_c))$	$v_1^{\text{lb}}(l_1(k_c))$	$v_2^{\text{ub}}(l_2(k_c))$	$v_2^{\text{lb}}(l_2(k_c))$
1		80	60	80	50
2		60	40	50	30
3		40	20	30	20
4		20	10	20	10
5		10	0	10	0

### 2.4.1. The degradation and recovery process

The degradation and recovery process is briefly elaborated by means of Figure 1 and the service levels given in Table 1. We assume all routes  $r \in \{1, 2\}$  to initially perform within their first service level  $l_r(0) = 1$  (i.e. both routes are in free flow conditions). During oversaturated conditions the upper boundary of the main route's first service level  $v_1^{ub}(l_1(k_c))$  is maintained and the performance of the alternative  $v_2(k_c)$  is allowed to degrade until its first service level lower boundary  $v_2^{lb}(l_2(k_c))$  in point A. Once this boundary is reached, the alternative's target service level at the current control interval  $k_c$  is increased to  $l_2(k_c) = l_2(k_c - 1) + 1$  and the corresponding upper boundary value  $v_2^{ub}(l_2(k_c))$  maintained. The performance of the main route  $v_1(k_c)$  is subsequently allowed to degrade until its first service level lower boundary  $v_1^{lb}(l_1(k_c))$  in point B. Once reached, the service level of the main route increased to  $l_1(k_c) = l_1(k_c - 1) + 1$  and the corresponding value of the second service level maintained  $v_1^{ub}(l_1(k_c))$ . As long as oversaturated conditions remain, this procedure will degrade the performance stepwise.

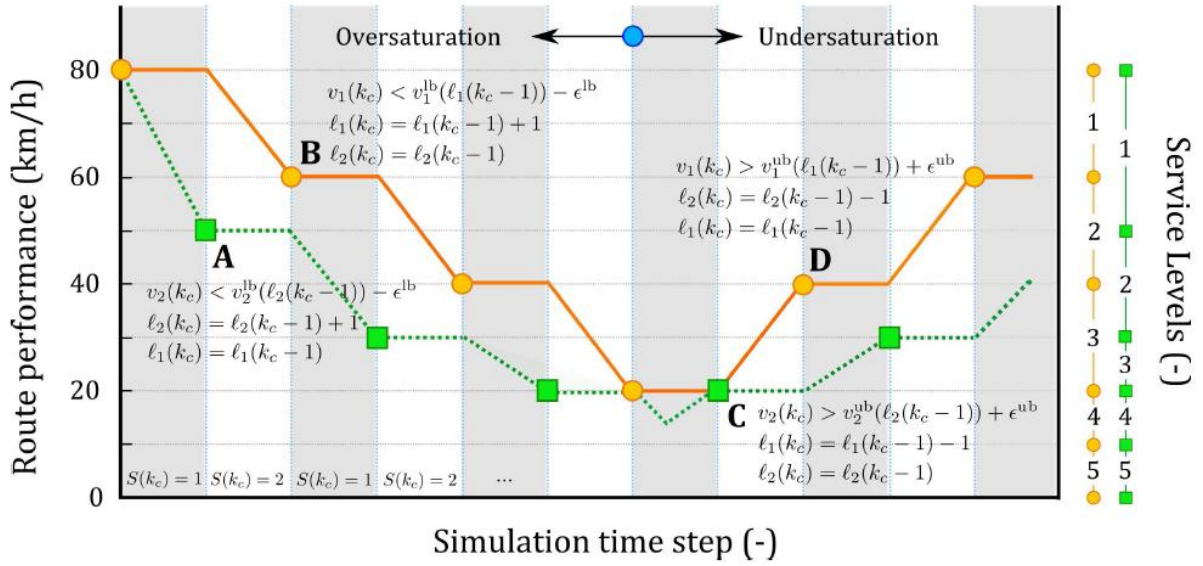


Figure 1: Process of degrading and recovering target service levels.

When the situation becomes undersaturated, the route that is not kept at constant performance will recover until its active service level upper boundary  $v_r^{ub}(l_r(k_c))$  is reached as can be seen in point C. Here, the performance of the alternative crosses its active performance upper boundary, hence the target service level of the main route is decreased to  $l_1(k_c) = l_1(k_c - 1) - 1$  and the active upper boundary  $v_2^{ub}(l_2(k_c))$  of the alternative maintained, so that the main route will further recover. If the main route crosses its performance upper boundary, the target service level of the alternative is decreased to  $l_2(k_c) = l_2(k_c - 1) - 1$  and the upper boundary of the main route maintained, so that the alternative will recover.

The mechanism is designed such that the preferred route recovers before the alternative does, and that the target service levels of the routes never differ more than one service level index.



With respect to the adoption of the psychological constructs the following aspects of the service level definitions are important:

- The maximum performance difference between two routes per service level is determined by  $\Delta v_{1,2}(l(k_c)) = v_2^{\text{lb}}(l(k_c)) - v_1^{\text{ub}}(l(k_c))$
- The degradation step size within a service level of a route is determined by  $\Delta v_r(l(k_c)) = v_r^{\text{lb}}(l(k_c)) - v_r^{\text{ub}}(l(k_c))$

When maintaining route service levels, the boundary values are always translated into travel times, because this prevents unrealistic and unfair travel time differences between route alternatives from realized and maintained (i.e. small variations in low speeds result in much larger travel time differences than small variations in high speeds).

The aim of service level-oriented route guidance approach is to guide traffic instead of to inform drivers about delays in the network. Much research has been devoted to choice modelling, driver compliance and the influence of information, for reviews see (Prato, 2009, Bonsall, 1992, Chorus et al., 2009, Chorus et al., 2006, Han et al., 2007). We acknowledge that these are relevant aspects of route guidance. Clearly, the proposed control approach can only have an impact if there is the size of the controllable flow and the compliance rate are large enough. In this paper we will leave this topic out of consideration and focus on the application of indifference bands in the service-level control approach. We believe that if a control approach is designed to respect the expectations of drivers it will be successful. In the remainder of this paper, when we refer to route guidance we refer to Variable Message Signs (VMS) that inform drivers about the preferred route to a certain destination. No travel times or delays are shown, nor do the drivers receive any form of compensation or incentive to use the preferred route.

### 3. Approach

As mentioned before, we believe that the indifference band is a great opportunity for Dynamic Traffic Management as it provides road authorities with certain freedom to improve the network performance. Although we focus on route guidance in this paper, we consider this approach suitable for any DTM system that influences the network performance in terms of travel times, delay times, traffic density, average speed, etc. For example, traffic lights, variable message signs, ramp metering, lane management, etc. This approach does not consider the use of incentive schemes, for example, based on monetary rewards and penalties. As such, the amount of freedom road authorities have is directly related to the indifference band, i.e. the wider the indifference band, the more freedom road authorities have to achieve network performance improvements. As long as the indifference band is respected, driver response is assumed to be limited even if their situation declines. Vice versa, if road authorities aim to change route choice, the effect of their measures should exceed the indifference band. Either way, the effectiveness of DTM is likely to increase when drivers' expectations are considered by means of the indifference band.

*EXAMPLE: Blocking back within a route can be prevented (queue stabilized) by sending traffic to the alternative route. If no redundant capacity is available in that alternative, its quality will degrade (travel times increase). The indifference band indicates the maximum acceptable travel time difference between both routes that is acceptable (i.e. non-observable)*

*and/or non-interested) from a user perspective. This in turn defines the achievable gain in network performance with respect to the user equilibrium situation and the situation in which no prescriptive route guidance is given.*

To obtain route guidance signals that are ‘acceptable’ from the average driver’s point of view, the indifference band will define the following input parameters of the control approach:

- The difference between the upper and lower boundaries within the service levels of a route.
- The maximal performance difference between two route alternatives.

With regard to the width of the indifference band the following observations can be made based on the literature discussed earlier:

- The indifference band is situation specific, subject to traffic conditions, trip length, etc.
- In absolute sense, widths of 5-18 minutes (average 10 minutes) have been suggested.
- In relative sense, indifference band of 17-22% have been suggested.
- Travel time differences between best and chosen routes of 2-5 minutes or 8-25% were found.
- Usually only two or three levels of traffic conditions are clearly distinguished (see Table 2).
- Drivers are more tolerant to longer delays than traditionally anticipated (see Table 2).
- Loss aversion: losses are valued twice as much as a same-sized gain.

Table 2: perception of level of service at freeways and controlled intersections versus level of service definitions of the Highway Capacity Manual (HCM)

	HCM Freeway LoS (pc/mi/ln)	Perceived Freeway LoS (pc/mi/ln) (Choocharukul et al., 2004)	HCM Freeway (v/c)	Perceived LoS (v/c) (Papadimitriou et al., 2010)	HCM LoS intersection (sec.)	Perceived Intersection LoS (sec.) (Fang and Pecheux, 2009)
A	0-11	0-7	0.00-0.35	0.00-0.55	0-5.0	0-15.0
B	>11-18	>7-21	0.35-0.55		5.1-15.0	10.0-27.5
C	>18-26	>21-34	0.55-0.77	0.55-0.70	15.1-25.0	22.5-40.0
D	>26-35	>34-49	0.77-0.92		25.1-40.0	35.0-57.5
E	>35-45	>49-82	0.92-1.00	>0.70	40.1-60.0	51.0-82.0
F	>45	>82	>1.00		>60.0	>82.0

To define a service level table for our test case we base our design decision on the following conclusions. First of all, drivers may perceive the travel time of a route (PTT) differently than the actual travel time (ATT) as shown in Figure 2. The dashed center line represents the case of no perception error and equal PTT and ATT. In reality, drivers tend to overestimate (top-left) and underestimate (bottom-right) travel times depending on individual-situation specific factors. There doesn’t seem to be general rule in literature for drivers’ overestimation and underestimation of travel times, probably because perception of travel time varies substantially between routes depending on the route characteristics. To illustrate, a solid linear line is plotted for route x for which drivers systematically underestimate the travel time. From the viewpoint of the driver there is no difference between the travel times of both routes, while in reality there is. In practice, driver perception of travel time can be far more complex

than a simple linear relation. An example is provided for route y by means of the dotted line for which low and high travel times are overestimated while moderate travel times are underestimated.

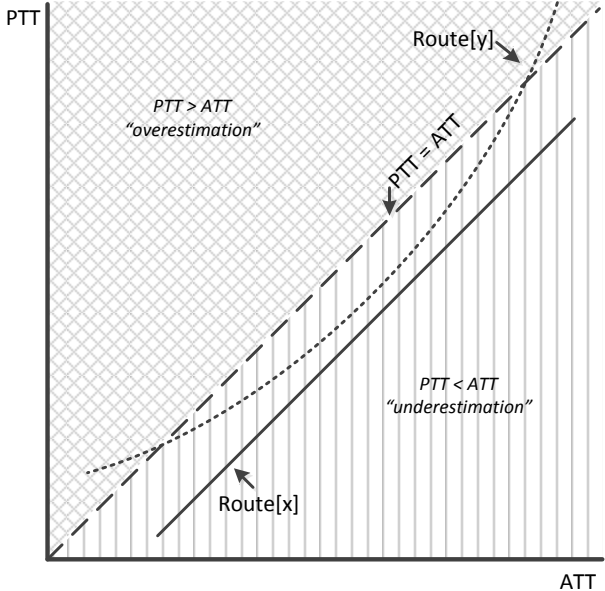


Figure 2: perceived travel time (PTT) versus actual travel time (ATT)

Perception errors based on the difference between perception and reality are a helpful indicator for the indifference band. This is shown in Figure 3. For the purpose of illustration we continue with the linear relation between PTT and ATT. In this example travel times of route y are systematically underestimated, while travel time of route x are generally overestimated. These perception errors are indicated by PE[y] and PE[x] respectively. However, what matters most to estimate the indifference band, is the perception of route x relative to the perception of route y, indicated by PE[x-y]. In Figure 3, the indifference band is the difference between the actual travel time of route x (ATT[x]) and the actual travel time of route y (ATT[y]), for which drivers perceive equal travel times (PTT[x,y]).

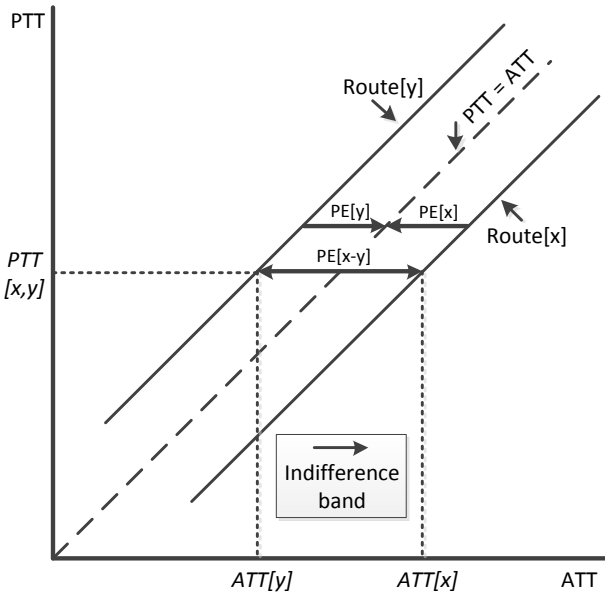


Figure 3: perception errors (PE) and the indifference band

Looking at service levels, the literature findings suggest that driver have more difficulty perceiving differences in low (i.e. A-B) and high level of service (i.e. E-F) regimes than in moderate levels of service. Hence, it is reasonable to assume that the indifference band is wider for high and low levels of service than for moderate levels of service. Figure 4 shows the level of service of route x versus the level of service of route y. On the dashed center line the level of service of both routes is the same. Building upon Figure 3, we assume again that due to perception errors, route x is generally perceived as being better than route y even though they are equal in reality. The perceived difference in level of service between both routes ( $\Delta LoS$ ) is plotted as the solid line with the suggested width for the three regimes low, medium and high. Like in Figure 3, the horizontal lines represent the indifference band. Based on literature, an appropriate width of the indifference band seems to be at least in the range of 2 minutes while in certain circumstances, like in low and high levels of service, this width could increase to approximately 10 minutes.

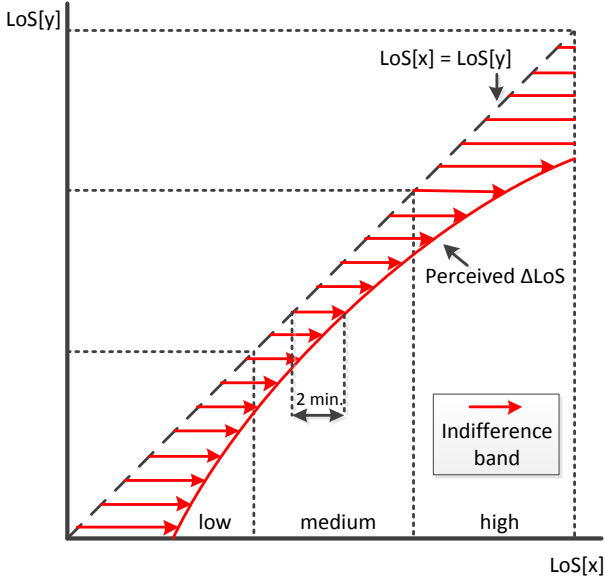


Figure 4: level of service of route y ( $LoS[y]$ ) versus level of service of route x ( $LoS[x]$ )

It was mentioned that the indifference band is situation specific, i.e. subject to route attributes important in route choice that may influence drivers' perception. These attributes may vary over routes and their exact influence on route choice may be hard to determine. Examples of route attributes are: directness, number of intersections, weather, information, congestion, presence of trees, etc. Due to the lack of situation-specific knowledge it might not be possible to estimate the width of the indifference band in the kind of detail suggested in Figure 4 or line C in the figure below. One alternative is to assume that the indifference band can be represented by an absolute value which is equal for all regimes. Another alternative is to express the indifference band as a percentage of the actual travel time. Hence, in absolute sense the indifference band increases with increasing travel times. Both cases are shown in Figure 5 by the dotted lines A and B respectively.

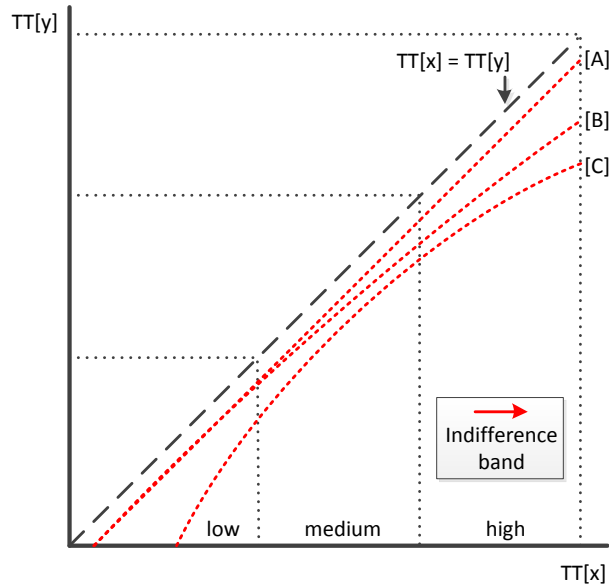


Figure 5: width of the indifference band: [A] absolute value, [B] percentage, [C] continuous

Finally, the notion of loss aversion implies that the service levels should have a different definition in case of degradation compared to recovery of service levels. This would require a specific service level table like Table 1 for both the degradation and the recovery process. Roughly, the difference between upper and lower boundaries, route alternatives and service levels for the degradation process would become half these differences of the recovery process. However, to limit complexity we won't consider asymmetry effects due to loss aversion in this paper. Instead, the reader may consult (Bie et al., 2012) for several numerical examples.

## 4. Test case

By means of a simulation test case the potential to improve the network performance while respecting the threshold values of the indifference band is illustrated. To this aim, different indifferent bands are applied within the control approach to evaluate the corresponding network performance. It is also shown how the indifference band is adopted into the service level-based control approach. Moreover, a comparison is made with system optimal route guidance that is realized by model predictive control (MPC) and user optimal route guidance realized by a predictive feedback control approach. Details on these control approaches can also be found in (Hegyi, 2004, Wang et al., 2003).

### 4.1. Applied traffic flow model

The macroscopic first-order multi-class cell-based traffic flow model Fastlane (Van Lint et al., 2008) has been used for the process simulation, the state predictions of the finite-state-machine and the optimization procedure within the Model Predictive Control approach. Fastlane propagates traffic flows destination dependent through the network, enabling correct manipulation of flows by means of route guidance between an origin and destination pair. This also allows for proper simulation of the onset and dissolving of congestion including the negative effects of the blocking back phenomenon.

## 4.2. Performance Indicators

The different control methodologies are evaluated based on the network performance indicator: the total time that vehicles have spent in the network (TTS). The time spent by  $N(k)$  vehicles in one time step  $k$  is  $TN(k)$  and the total time that the vehicles spend in the network over a period  $k = \{0, 1, \dots, K\}$  with  $K$  the total number of simulation time steps becomes

$$J_{TTS} = T \sum_{k=1}^K \sum_{m \in M} \sum_{c \in C_m} \rho_{m,c}(k) \lambda_{m,c} \quad (1)$$

with  $\rho_{m,c}(k)$  the vehicle densities over the cells  $c \in C_m$  of all links  $m \in M$  in the network and  $\lambda_{m,c}$  the corresponding cell lengths.

## 4.3. Test case layout

The applied traffic network and its characteristics are shown in Figure 3. The VMS to distribute traffic is located in the north. Traffic moves from origin  $O_1$  towards destinations  $D_1$  in the east and  $D_2$  in the south. Destination  $D_2$  can be reached by a preferred route (main route) on the east side or the alternative on the west side. The main route is considered more important since a considerable part consists of a freeway section that is also used by other large traffic flows traveling towards destination  $D_1$ . Within each route a bottleneck is located with fixed capacity of 800 veh/h (e.g. representing an intersection) to realize congestion. Traffic is loaded into the network at origin  $O_1$  over a three hour simulation period. The inflow at simulation time  $kT$  is interpolated from the pattern given in Table 3. From the total demand, 50% travels towards destination  $D_1$  and 50% towards destination  $D_2$ . The compliance rate  $\gamma$  of traffic to a given advice is assumed to be 30% and the nominal split fraction  $\beta_n^{N,d}(k_c)$  at the node  $n$  downstream the VMS towards destination  $D_2$  over the main route is 50%.

Table 3: Demand  $Q$  loaded at origin  $O_1$

Time (hh:mm)	8:00	8:30	9:00	9:30	10:00	10:30	11:00	11:30	12:00
Demand (veh/h)	2000	4000	4000	3500	2500	2500	0	0	0

### 4.3.1 Service level definition

The policy behind the test case is to increase the network production, with the restriction that the travel time difference over the routes should be less than the prevailing indifference band (IB). The applied target service levels are given in Table 4. The critical travel time at which the congestion in the main route spills back to the freeway is approximately 1100 seconds. This means that this critical value is maintained once the main route degraded to service level 5. The indifference band that holds for the specific situation then determines the maximum acceptable travel time difference over the routes (i.e. the achievable gain in network performance without user interests being violated). In the test case we study the potential gain in network performance by evaluating different absolute indifference bands (i.e.  $IB = \{120, 240, 360, 480, 600, 720, 840\}$  seconds).

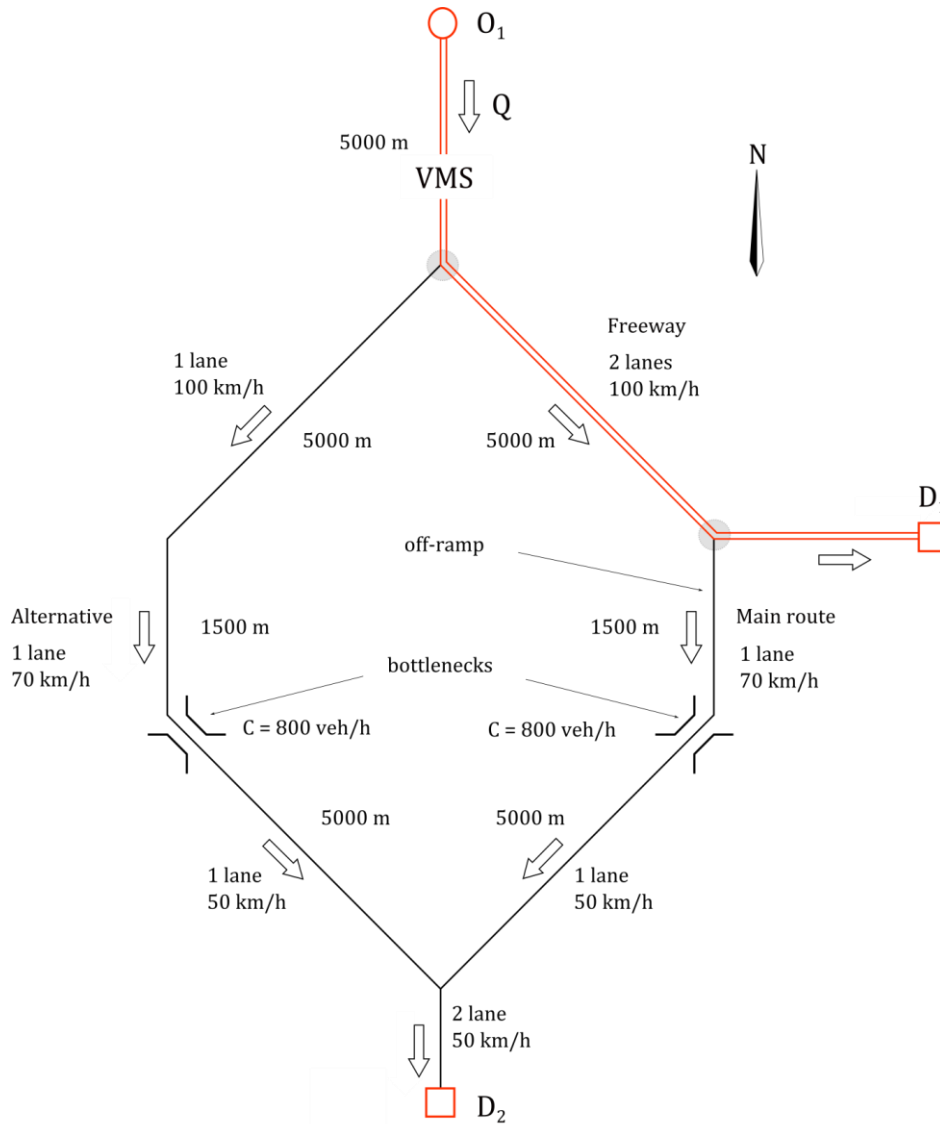


Figure 6: test case network

In this paragraph the set-up of the service level table is presented including the adoption of indifference bands. The table is illustrated for the situation in which the maximum value of the indifference band is assumed 600 seconds. The degradation step size of service levels 1 to 4 is chosen 120 seconds, resulting in a maximum performance difference of 120 seconds over the routes (i.e.  $\Delta\tau_{1,2}(l(k_c)) = \tau_2^{lb}(l(k_c)) - \tau_1^{ub}(l(k_c)) = 120$  for  $l(k_c) = \{1, 2, 3, 4\}$ ). Once the main route is degraded to service level 5, the critical performance value of 1110 seconds is maintained and the alternative accepted to degrade until a travel time difference is established of 600 (i.e.  $\Delta\tau_{1,2}(l(k_c)) = \tau_2^{lb}(l(k_c)) - \tau_1^{ub}(l(k_c)) = 600$  for  $l(k_c) \geq 5$ ).

Table 4: Service level table for the test case with the 1<sup>st</sup> and 2<sup>nd</sup> column of a route indicating the service level upper boundary (ub) and lower boundary (lb) in terms of travel time (s)

Levels	Main route		Alternative		
	$l(k_c)$	$\tau_1^{ub}(l_1(k_c))$	$\tau_1^{lb}(l_1(k_c))$	$\tau_2^{ub}(l_2(k_c))$	$\tau_2^{lb}(l_2(k_c))$
1		630	750	630	750
2		750	870	750	870
3		870	990	870	990
4		990	1110	990	1110
5		<b>1110</b>	1230	1110	1710
6		1230	1350	1710	1830
7		1350	1470	1830	1950
...		...	...	...	...

Hence, when the alternative degrades to service level 6, blocking back is no longer prevented due to the indifference band constraint. To conclude, the tuning parameters of the controller are chosen in line with the settings used in Landman et al., 2012.

## 5. Results

### 5.1. Travel times and queue lengths

In Figure 7 the travel times and corresponding queue lengths are given for the different control approaches per route. To realize system optimality in the test case, the MPC approach makes sure that the bottlenecks in the main route and alternative become active and released at the exact same time and that the off-ramp queue does not spill back over upstream bifurcation point. As long as both bottlenecks are active and no other flows are hindered by spill back, it does not matter where the queues are located. In that respect the MPC approach accepts a large travel time difference (i.e. larger than indifference band) over the main route and alternative to prevent spill back of the off-ramp queue to the upstream bifurcation.

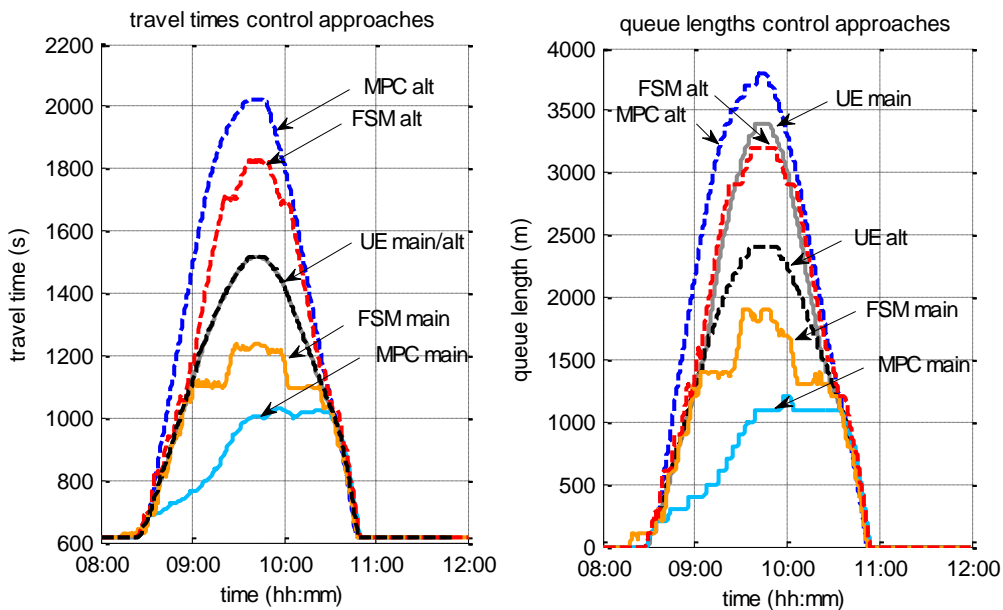


Figure 7: a) the travel times and b) the queue lengths resulting from the control approaches



For the user optimal solution the travel times remain the same, however, the corresponding queue lengths indicate the disadvantage of this approach. As can be seen in Figure 7b by the gray continuous line, the queue of the main route spills back over the upstream bifurcation in an early stage, causing hindrance to the ongoing flow and hence decreased network performance.

Service level-oriented control realized by the Finite-state machine (FSM) degrades the performance of the main route and alternative stepwise according the target service levels given in Table 4. At  $t=1110$  seconds the performance is stabilized and the alternative allowed to degrade until a travel time difference is realized of 600 seconds (i.e. the assumed indifference band). As can be seen by the orange continuous line in Figure 7b, spill back is not completely prevented within the main route, since the queue length exceeds the off-ramp length of 1500 m. This result indicates that a travel time difference larger than 600 seconds is needed to completely prevent spill back from happening. Shorter travel time differences will allow the main route queue to spill back over the bifurcation node in an earlier stage.

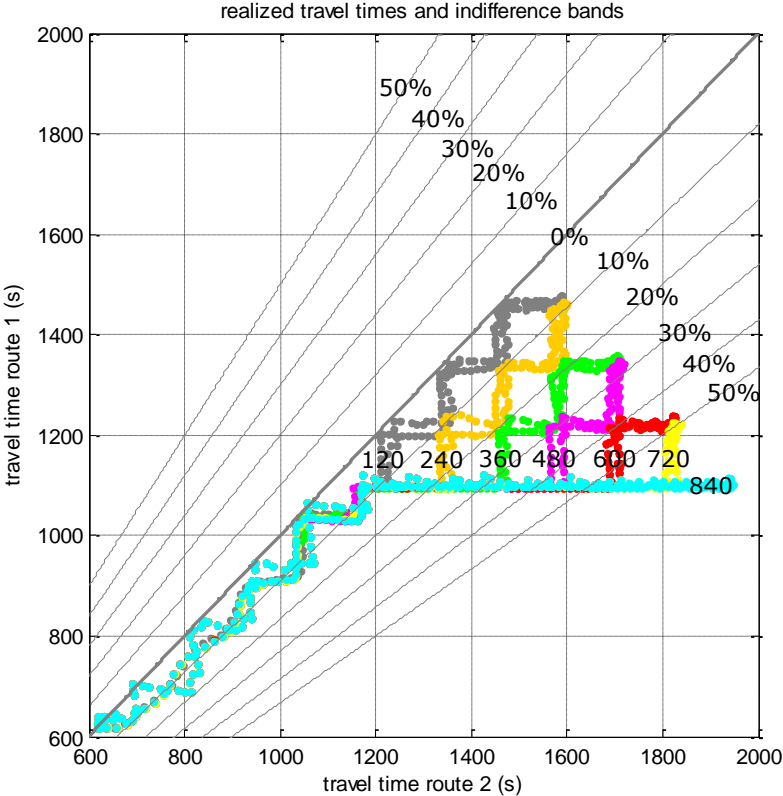


Figure 8: realized travel times on main route and alternative due to the service level oriented control approach with adopted absolute IB values  $IB=\{120, 240, 360, 480, 600, 720, 840\}$ . The diagonal lines additionally illustrate perceived IB boundaries in relative terms.

### 5.2. Travel times versus indifference bands

In Figure 8 the realized travel times over the main route and alternative are given for the Finite-state machine approach maintaining various predefined absolute indifference bands. The steps in the travel time data indicate the stepwise degradation and recovery of the route performance. The middle diagonal illustrates the user equilibrium situation and the other

diagonals the acceptable relative deviation of the equilibrium situation (i.e. indifference bands in relative terms). Acceptable travel times over both routes therefore need to stay between the 0% diagonal and the formulated maximum indifference band definition (i.e. defined in either in relative or absolute terms).

The target service levels for degrading the main route to its critical performance value of 1110 seconds is for all IB settings the same. This can be seen by the strong overlap of data points until the travel time of 1110 seconds is realized within the main route. At this critical performance, the chosen absolute value of the indifference band (i.e.  $IB = \{120, 240, 360, 480, 600, 720, 840\}$ ) is defined by the maximum deviation from the 0% diagonal. The applied absolute indifference bands directly determine the achievable network performance gain with respect to user equilibrium conditions. Note that relative indifference bands can be used as well to determine the maximum absolute acceptable travel time difference that can be maintained by the controller. Moreover, this type of plot can be used to assess if the resulting travel times from a route guidance approach satisfy the defined indifference bands.

### 5.3. Network performance

In Table 5 the network performance of the user optimal approach, the system optimal approach and the service level-oriented approach that corresponds with the different IB settings are given. Both the user optimal and system optimal realize the lowest TTS of traffic towards destination 2. The reason is that the optimal controller is able to determine the control signals that realize activation and release of the bottlenecks in the main route and alternative at the same time. The user optimal solution in this specific case does the same by keeping travel times equal, since both routes have the same characteristics (length, speed). The service level-oriented approach realizes little underutilization (increase 0.6%  $TTS_{D_2}$ ) in the undersaturated phase when the bottleneck within the main route is released and the alternative still has to recover from the lower bound performance of its first service level to free flow conditions. However, the total time spent of potentially hindered traffic to  $D_1$  is of real interests, since hindrance to this flow strongly influences the network performance. The decrease of TTS to  $D_2$  is therefore given in column 4.

Table 5: Network performance in TTS resulting from the UE, MPC and FSM-IB approach

	$TTS_{D_1}$	$TTS_{D_2}$	$TTS_{TOT}$	decrease $TTS_{D_1}$
	(h)	(h)	(h)	
UE	787	1999	2784	--
MPC	661	1998	2660	16.0
FSM-IB-120	774	2011	2785	1.7
FSM-IB-240	748	2011	2759	5.0
FSM-IB-360	716	2011	2727	9.0
FSM-IB-480	699	2011	2710	11.2
FSM-IB-600	675	2011	2686	14.2
FSM-IB-720	668	2011	2679	15.1
FSM-IB-840	661	2011	2672	16.0

The table shows for instance that an absolute indifference band of 4 minutes reduces the TTS of traffic that does not need to pass the bottleneck by 5%, whereas an indifference band of 10 minutes even realizes a 14% decrease of TTS to ongoing traffic.

## 6. Conclusions

Road users have difficulty in assessing the quality of their chosen alternative. Building upon the notion of indifference bands, we have introduced a service level-oriented route guidance approach that utilizes this inability to improve the network performance, without road user interests being violated.

Estimating the width of the indifference band is not trivial. It is situation specific and subject to drivers' perception of a route relative to drivers' perception of another route as well as reality. In case of insufficient knowledge to estimate the indifference band in great detail, we illustrated several other ways for interpretation and quantification of the indifference band. In this paper the effect on the network performance of application of indifference bands in the route guidance approach was explored by means of a simulation test case. By applying absolute indifference bands ranging from 2 to 10 minutes, the test case showed network performance gains between 2 to 14%.

The indifference bands are easily adopted in applied service level-oriented route guidance approach. The approach properly degrades and restores the performance of the controlled routes according the defined target service levels (including the indifference bands). Hence, the behavior of the control approach is comprehensible. As long as monetary incentives are not given to road users to make system optimal route decisions, the utilization of indifference bands offers an acceptable trade-off between policy objectives of road authorities and the interests of individual road user.

Finally, we would like to recommend several avenues for further research we were unable to capture within this paper. First of all, it would be interesting to assess the effects of day-to-day dynamics and driver learning on the performance of the control approach, especially on the long term. Secondly, the route guidance signal to drivers (e.g. travel time information, route advice) should be optimized to achieve high levels of compliance. In addition, in this study we assumed fixed driver compliance which in reality may vary and yield a different outcome in certain situations. Finally, more empirical material is needed to estimate the width of the indifference band. At best, such estimate should provide a minimum width that is common for all cases and some direction for additional width in specific circumstances. It is particularly needed to understand what a realistic indifference band in any context is. For example, an indifference of 10 minutes for a trip of about 22 minutes as in this study seems unrealistic. However, from a different viewpoint drivers in this network were used to 15 minutes of delay in comparison to free flow traffic in case of user equilibrium. With that in mind, an indifference band of 10 minutes, let alone one of 4 minutes seems very reasonable.

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## References

- Ariely, D. (2009). *Predictably Irrational - Revised and expanded edition*, London, HarperCollingsPublishers.
- Avineri, E. (2010). 'Choice Architecture' and the Design of Advanced Traveler Information Systems (ATIS). *Proceedings of the 13th IEEE - ITS Conference - Workshop on Traffic Behavior, Modeling and Optimization*. Madeira
- Avineri, E. & Bovy, P. H. L. (2008). Identification of parameters for a prospect theory model for travel choice analysis. *Transportation Research Record*, **No. 2082**, 141-147.
- Avineri, E. & Prashker, J. N. (2004). Violations of expected utility theory in route-choice stated preferences. *Transportation Research Record*, **No. 1894**, 222-229.
- Beckor, S., Ben-Akiva, M. E. & Ramming, M. S. (2006). Evaluation of choice set generation algorithms for route choice models. *Annals of Operation Research*, **144**, 235-247.
- Bie, J., Vreeswijk, J. & Van Berkum, E. (2012). Adopting Prospect Theory for Modeling Day-to-Day Traffic Dynamics: risk aversion and equilibrium stability. *In: 4th International Symposium on Dynamic Traffic Assignment*, Martha's Vineyard, Massachusetts, USA.
- Bonsall, P. (1992). The influence of route guidance advice on route choice in urban networks. *Transportation*, **19**, 1-23.
- Chang, G-L. & Mahmassani, H. S. (1988). Travel time prediction and departure time adjustment behaviour dynamics in a traffic system. *Transportation Research*, **22B**, 217-232.
- Chang, G-L. & Mahmassani, H. S. (1989). The dynamics of decision behavior in urban transportation network. *In: BEHAVIOUR, I. A. F. T. (ed.) Travel Behaviour Research*. Aldershot,: Gower Publishing.
- Choocharukul, K., Sinha, K. C. & Mannering, F. L. (2004). User perceptions and engineering definitions of highway level of service: an exploratory statistical comparison. *Transportation Research Part A: Policy and Practice*, **38**, 677-689.
- Chorus, C. (2012). Regret theory based on route choices and traffic equilibria. *Transportmetrica*, **8**, 291-305.
- Chorus, C. G., Arentze, T. A. & Timmermans, H. J. P. (2009). Traveler compliance with advice: A Bayesian utilitarian perspective. *Transportation Research Part E: Logistics and Transportation Review*, **45**, 486-500.
- Chorus, C. G., Molin, E. J. E. & Van Wee, B. (2006). Use and effects of Advanced Traveller Information Services (ATIS): A review of the literature. *Transport Reviews*, **26**, 127-149.
- Chorus, C. G. & Timmermans, H. J. P. (2009). Measuring user benefits of changes in the transport system when traveler awareness is limited. *Transportation Research Part A: Policy and Practice*, **43**, 536-547.
- Fang, F. C. & Pecheux, K. K. (2009). Fuzzy data mining approach for quantifying signalized intersection level of services based on user perceptions. *Journal of Transportation Engineering*, **135**, 349-358.
- Han, Q., Dellaert, B., Van Raaij, F. & Timmermans, H. (2007). Modelling strategic behaviour in anticipation of congestion. *Transportmetrica*, **3**, 119-138.
- Hegy, A. (2004). *Model predictive control for integrating traffic control measures*. TRAIL thesis, series, PhD-thesis, Delft University of Technology.
- Hostovsky, C., Wakefield, S. & Hall, F. L. (2004). Freeway users' perceptions of quality of service: Comparison of three groups.

- Jan, O., Horowitz, A. J. & Peng, Z. R. (2000). Using global positioning system data to understand variations in path choice. *Transportation Research Record*, **1725**, 37-44.
- Jayakrishnan, R., Mahmassani, H. S. & Hu, T. Y. (1994). An evaluation tool for advanced traffic information and management systems in urban networks. *Transportation Research Part C*, **2**, 129-147.
- Jou, R.-C., Lam, S.-H., Liu, Y.-H. & Chen, K.-H. (2005). Route switching behavior on freeways with the provision of different types of real-time traffic information. *Transportation Research Part A: Policy and Practice*, **39**, 445-461.
- Kahnemann, D. & Tversky, A. (1979). Prospect theory: an analysis of decision under risk. *Econometrica* **47**, no. **2**, 263-291.
- Koutsoupias, E. & Papadimitriou, C. (2009). Worst-case equilibria. *Computer Science Review*, **3**, 65-69.
- Landman, R., Schreiter, T., Hegyi, A., Van Lint, H. & Hoogendoorn, S. (2012). Policy-based, service level-oriented, route guidance in road networks: a comparison with system and user optimal route guidance. *Transportation Research Record*, **in press**.
- Landman, R. L., Hegyi, A. & Hoogendoorn, S. P. (2011). Service level-oriented route guidance in road traffic networks. *In: Proceedings of the 14th International IEEE - ITS Conference, Washington D.C.*
- Mahmassani, H. S. (1996). Dynamics of commuter behavior: recent research and continuing challenges. *In: LEE-GOSSELIN, M. & STOPHER, P. (eds.) Understanding travel behavior in an era of change.* New York: Pergamonn Press.
- Mahmassani, H. S. & Chang, G.-L. (1985). Dynamic aspects of departure-time choice behavior in a commuting system: theoretical framework and experimental analysis. *Transportation Research Record*, 88-101.
- Mahmassani, H. S. & Chang, G.-L. (1987). On boundedly rational user equilibrium in transportation networks. *Transportation Science*, **21**, 89-99.
- Mahmassani, H. S. & Liu, Y. H. (1999). Dynamics of commuting decision behaviour under Advanced Traveller Information Systems. *Transportation Research Part C: Emerging Technologies*, **7**, 91-107.
- Papadimitriou, E., Mylona, V. & Golias, J. (2010). Perceived level of service, driver, and traffic characteristics: Piecewise linear model. *Journal of Transportation Engineering*, **136**, 887-894.
- Pecheux, K. K., Pietrucha, M. T. & Jovanis, P. P. (2000). User perception of level of service at signalized intersections. *In: 79th Annual Meeting of the Transportation Research Board, Washington D.C.*
- Prato, C. G. (2009). Route choice modeling: past, present and future research directions. *Journal of Choice Modelling*, **2**, 65-100.
- Simon, H. A. (1955). A behavioural model of rational choice. *Quarterly Journal of Economics*, **69**, 99-118.
- Simon, H. A. (1982). *Models of bounded rationality: behavioral economics and business organization*, Cambridge, The MIT Press.
- Srinivasan, K. K. & Mahmassani, H. S. (1999). Role of congestion and information in trip-makers' dynamic decision processes experimental investigation. *Transportation Research Record*, 44-52.
- Tawfik, A. & Rakha, H. (2012). Network route-choice evolution in real-life experiment: necessary shift from network- to driver-oriented modeling. *Transportation Research Record*, (**in print**).
- Tawfik, A., Rakha, H. & Miller, S. (2010). Examining drivers experiences, perceptions, and

- choices in route choice behavior. *In: Proceedings of the 13th IEEE - ITS Conference - Workshop on Traffic Behavior, Modeling and Optimization, Madeira.*
- Thomas, T. & Tutert, S. I. A. (2010). Route choice behavior based on license plate observations in the Dutch city of Enschede. *In: BIERLAIRE, M. & OSORIO, C., eds. Seventh Triennial Symposium on Transportation Analysis: Tristan VII, Tristan, Norway.*
- Tversky, A. & Kahnemann, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty*, **vol. 9**, pp. 195-230.
- Van Hagen, M. (2011). *Waiting experience at train stations*. PhD-Thesis, University of Twente.
- Van Knippenberg, C. & Van Knippenberg, A. (1986). Measurement of arrival times; a discussion of Mahmassani et al., 1985. *Transportation Research Record*, **1085**, 47-49.
- Van Lint, H., Hoogendoorn, S. & Schreuder, M. (2008). Fastlane: new multiclass first-order traffic flow model. *Transportation Research Record*, **2088**, 177-187.
- Van Vugt, M. (1996). *Social dilemmas and transportation decisions*. PhD-thesis, Rijksuniversiteit Limburg.
- Vreeswijk, J. D., Bie, J., Van Berkum, E. C. & Van Arem, B. (2012). Effective traffic management based on bounded rationality and indifference bands. *IET Intelligent Transport Systems - Special issue on Models and Technologies for ITS*, (*in print*).
- Wang, Y., Papageorgiou, M. & Messmer, A. (2003). Predictive feedback routing control strategy for freeway network traffic. *Transportation Research Record*, **1856**, 62-73.
- Wardrop, J. G. (1952). Some theoretical aspects of road traffic research. *Proceedings of the institute of civil engineers*, **1**, pages 325-378.
- Washburn, S. S., Ramlackhan, K. & Mcleod, D. S. (2004). Quality-of-service perceptions by rural freeway travelers: Exploratory analysis.
- Zhang, L. (2004). *Signalized intersection Level-of-Service that accounts for user perceptions*. PhD-thesis, University of Hawaii.
- Zhu, S. & Levinson, D. (2012). Do people use the shortest path? An empirical test of Wardrop's first principle. *91th annual meeting of the Transportation Research Board*. Washington D.C.