Multimodal Assessment of Signalized Intersections Considering the Number of Travellers

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ABSTRACT

The purpose of transportation networks is the efficient and sustainable movement of people and goods. However, established evaluation procedures commonly assess the *traffic* quality instead of the *transport* quality, i.e. they focus on vehicles instead of goods and travellers. Furthermore, the existing methodologies evaluate the quality of each transport mode separately and often neglect the role of bicycles and pedestrians. Recently, several methods have been proposed to consider transport networks from a multimodal perspective, which is an important step towards the transport quality evaluation in the context of sustainability. A transparent and objective evaluation methodology is needed which comprehensively considers all transport modes. The procedure introduced in this article is limited to the assessment of signalized intersections, but goes one step beyond the existing methods: the multimodal assessment considers the number of travellers of the different modes. A route importance factor is introduced to reflect the differing significance of the transport modes. A case study underlines the strengths of the procedure.

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INTRODUCTION

Motivation

The overall goal of traffic facilities is to enable the movement of people and goods. With the increasing transport demand and consequently the increasing negative impacts of traffic, the focus shifts from the predominantly traffic quality oriented assessment of traffic facilities towards an assessment of efficiency, which will also serve the sustainability of transport facilities (in all three dimensions: environment, economy, and social equity). The discussion on climate change and local pollutants (PM, NO_X) further fosters this shift.

When considering signalized intersections, the existing assessment procedures impede the consideration of sustainability factors. To take two prominent examples, the United States Highway Capacity Manual (HCM) and the German Highway Capacity Manual (HBS), both assess the traffic quality separately for each transport mode by using the respective vehicle volumes (*1*, *2*). Thus, the mobility of people is not adequately considered. A direct comparison of the achieved transport quality, i.e. the quality of transport for all travellers, for different scenarios is not easily achieved.

A procedure to assess the transport quality of traffic facilities from a multimodal perspective is missing so far. Either a unique LOS (level of service) should be defined, which incorporates all transport modes, or at least a direct comparison of the quality for different modes should be supported. While in the past, procedures have been developed to estimate a multimodal level of service for transport corridors, a particular model focussing on signalized intersections and going beyond the assessment of delay of vehicles or pedestrians is still missing.

State of the art

The National Cooperative Highway Research Program (NCHRP) Report 616 presents one of the most comprehensive projects to develop a procedure for a multimodal assessment of urban streets (*3*). Several of the findings from NCHRP 616 have been integrated in the upcoming HCM 2010. The influence of signalized intersections on the modal LOS is incorporated in the automobile mode by considering the number of stops per mile. The transit mode indirectly uses the control delay as it affects the average vehicle speed. Control delay plays no role in the bicycle level of service and it plays a minor role in the pedestrian mode. Both non-motorized modal models focus on safety perceptions rather than only intersection delay. The report explicitly does not define a combined multimodal LOS. It, therefore, does not take the number of travellers of the different modes into account. Furthermore, the method is not intended for the design of signal control.

In Switzerland, Simon (2001) developed a method to measure the multimodal performance of signalized intersections, and, thus, allow for signal control optimizations (*4*). The Intermodal Quality Index (IQI), which measures the total person-delay, was defined. A time weighting factor and transit demand elasticity factor were added to the IQI calculation. However, the project only focused on motorized modes and explicitly did not consider bicyclists or pedestrians. Furthermore, the method is suitable for the ranking of multiple scenarios, but does not support calculating a multimodal level of service.

The Florida Department of Transportation released their second version of their multimodal level of service handbook (*5*). It considers the interrelationships between the LOS of the different modes at the section and facility levels. That is, a higher automobile travel speed increases the automobile LOS but has a negative effect on the bicycle LOS. New quality models from Landis are used for the bicycle and pedestrian modes (*6*, *7*). The models are not specific to signalized intersections.

Outline

This article introduces a methodology for assessing the transport quality at signalized intersections. The methodology takes the number of travelers of all transport modes into account. The procedure has to be seen as a framework, which can be adjusted and further improved. It is particularly useful for comparing different signal control settings and intersection layouts. The function of routes for specific modes, changes in traveller volumes, and modal shifts can be assessed. The model utilizes some new ways of determining levels of service to reflect recent research findings. These LOS definitions may be adjusted without changing the rationale behind the model.

After a discussion of performance indices for the four major transport modes automobile, public transport, bicycle traffic, and pedestrian traffic, the multimodal assessment model is derived from its objectives, and its strengths and limitations are discussed. A case study exemplifies the application of the procedure. The methodology is described in more detail in (*8*).

DISCUSSION OF PERFORMANCE INDICES

General issues

How the performance of transport facilities should best be assessed has long since been disputed. Two viewpoints usually compete with each other: the engineer's perspective focusing on measureable parameters; and the user's perspective, which is dominated by subjective factors. While engineers commonly try to realize a system optimum, the travellers are only interested in their personal experience. Another issue is the difference between the average performance and the best or worst performance (i.e. the variation of the performance for different travellers).

Following the aim of transporting people, it is apparent, that the traveller's perspective has to be a major focus of a performance assessment. The more the perspectives of the different travellers vary, however, the more the system perspective or the performance of the transport network for all travellers comes into focus. Signal control can usually perform well from the engineering and the traveller's perspective at the same time, because delay is important for both. But particularly for the non-motorized modes, delay falls short of an adequate transport quality measure from the traveller viewpoint. This is particularly apparent in assessments which do not consider the number of travellers of the different modes. This deficiency can be highlighted by public transport priority measures which do not depend on the occupancy of vehicles.

In the following subsections the determination of a level of service is discussed for the four dominant transport modes in industrialized countries (auto, public transport, bicycle, and pedestrians). The focus is placed on the U.S. and the German Highway Capacity Manuals, due to their widespread use, their established history, and the professional backgrounds of the authors. Particularly for developing countries, the considered transport modes would have to be extended, for instance, by motorcycles or paratransit. The modal levels of service will be the basis for a multimodal assessment, which will be discussed in the subsequent section.

Modal discussion

Motorized vehicles

The current methodologies for determining the automobile quality at signalized intersections in the American and German Highway Capacity Manuals use control delay as the performance measure. The underlying queuing delay theory is similar in both, although different values and variables are utilized in the calculations. Engineers defined the LOS delay classes, and these values differ in both manuals, which reflect differing modal priorities and user expectations. The Canadian manual continues to utilize the saturation level as the performance measure. In Germany, coordinated corridors are treated differently, because the number of vehicles in a platoon being able to pass without stopping in these situations is commonly seen as more important than the total delay.

The current manuals, in particular the Canadian manual, are designed from the engineer's viewpoint. Newer methodologies have been developed that reflect the road user's viewpoint.

Zhang and Prevedouros (2004) investigated the quality of service from the user perspective using a web survey (*9*). It was found that delay was not ranked as the most important measure. Rather, signal responsiveness, only one cycle delay and exclusive lanes for protected left turn movements were ranked the highest.

Lee et al. (2007) used fuzzy aggregation and cultural consensus to rate signalized intersections (*10*). Through a literature review, they selected six key factors that affect intersection quality: traffic signal waiting time (delay), length of gaps in the traffic of the cross-street, signal operation (efficiency), signal visibility (physical aspects), information guidance systems (physical aspects) and physical features of the intersection (physical aspects). They determined that a three-level LOS would be more practical for users than the current six-level system.

It is apparent that so far no unique performance measure could be agreed upon. It is also apparent that control delay as the only performance measure does not satisfy the user perspective. Among engineers the control delay or some related measure (e.g. saturation degree) has proven to be a universal meaningful measure. On the other hand the number of stops gains increasing attention, not only in the context of coordination, but also for its environmental benefits, e.g., reductions in vehicle emissions and fuel consumption.

Public Transport

For the determination of the quality of public transport, the American HCM defers to the Transit Capacity and Quality of Service Manual, which does not define quality evaluations at the intersection level (*11*). In contrast, the German HBS defines a control delay-based quality measure, similar to the automobile mode. Besides the lower LOS delay classes, the main difference in the public transport quality assessment is the queue model, which assumes a dedicated transit lane and hence no queue build-up.

No research into perception-based, intersection level quality measures was found in the literature.

Bicycle traffic

Both the HCM and HBS utilize control delay as the quality measure for cyclists. The models are the same except they define differing saturation flow rates for a bike lane. Both models assume no queue build-ups, either due to the low number of cyclists, or because it is implied that cyclists find alternative routes if queue accumulation occurs. These assumptions will hold true in countries or cities where bicycle use is comparably low.

New research has shown that control delay does not accurately portray the quality of service perceived by cyclists, which is reflected in NCHRP 616. Many of the new models indicate that safety and comfort are the dominating factors in perceived quality. Landis et al. (2003) performed an empirical study and found that lane widths, vehicle volumes and crossing widths play a determining role in user perception (*12*). This differs from the web-based survey findings by Stinson and Bhat (2003) of bicycle commuters, in which travel time was the most significant factor in route choice (*13*). However, the survey was route-based and not intersection-based and the respondents were commuters and not the general cycling public.

It is seen that control delay alone does not sufficiently represent perceived intersection qualities and that an empirically-based model similar to Landis' is needed. A great difficulty in assessing user perception of cyclists and pedestrians has to be seen in the weather dependability of these travellers. The question has to be raised how this effect can be incorporated into performance measures. The solution will highly depend on the respective regions and their climates.

Pedestrians

The current quality models in the HCM and HBS utilize control delay as the performance measure to determine the quality of service. The HCM also defines a time-space measurement for LOS measurements, which reflects the pedestrian crowding of the crosswalk and waiting area.

Research has shown that pedestrian safety and comfort also need to be included in the perceived quality level. Petritsch et al. (2005) developed an empirical-based model that incorporated both the aspects of comfort and safety, and delay (*14*). They determined the critical factors to be: permitted turning vehicles, cross street traffic volumes and speeds, lanes crossed and control delay. Hubbard et al. (2007) found that the additional delay incurred by pedestrians due to permitted turning vehicles also needs to be considered (*15*). Ni (2010) recently reviewed the specific requirements of pedestrians with respect to their safety, underlining the importance of turning traffic on pedestrian compliance (*16*). Alhajyaseen (2010) looked at the density dependent requirements of pedestrians, which is of importance in crowded areas of central business districts not only in Asian cities (*17*). The heterogeneous behaviour, derived from the differing characteristics of pedestrians attracts increasing interest in the endeavor to model pedestrian behaviour. An overview on these efforts is given in Matsumoto et al. (2010) (*18*).

TOWARDS A BASIC MULTIMODAL ASSESSMENT TOOL

Objectives

To improve the efficiency of transport it is important to consider the movement of travellers in the first place, instead of looking at the movement of vehicles only. Consequently we need a multimodal assessment, which derives one level of service (in this case for an intersection) and takes all transport modes into account. The efficiency of the different transport modes should be assessed with respect to the number of travellers transported. Thus, modal shifts and changes in traveller volumes can easily be evaluated.

Since the number of travellers can differ largely between transport modes, the danger arises to neglect a very poor quality of a minor mode. This could conflict with the provision of a basic service to all travellers. Another aim is, hence, to give disproportionately high significance to poor levels of service.

Because intersections may be part of a dedicated network for specific transport modes, the assigned importance of transport modes at a particular intersection should be incorporated into the model. If an intersection, for instance, is part of a bus rapid transit corridor, public transport should receive higher priority than other modes. The same applies to pedestrians, if the intersection belongs to a school route, or to motorized vehicles, if it is a major arterial etc.

The objectives of the model can be summarized as follows:

1. Based on travellers
2. Higher significance for poor levels of service
3. Accounting for functional classification of intersections

Development

Approach

To derive a single level of service for an intersection, a performance index has to be used which is suitable for all transport modes. As has been outlined before, this is only possible if the four individual modal levels of service are used. The prevailing performance indices for motorized and public transport, e.g. delay or number of stops, do not suit the needs of cyclists. Pedestrians have even different requirements. The multimodal model is, hence, based on modal levels of service and developed following the above outlined objectives. Thus the model is developed in four steps:

1. A LOS is defined for each mode and converted to a numeric value (e.g. 1-6).
2. The modal LOS are weighted according to the number of travellers.
3. Poor LOS receive higher significance by squaring the LOS.
4. The modal LOS are further weighted by a factor accounting for the intersection function.

The process is illustrated in FIGURE 1 and formalized in Eqn. 1.

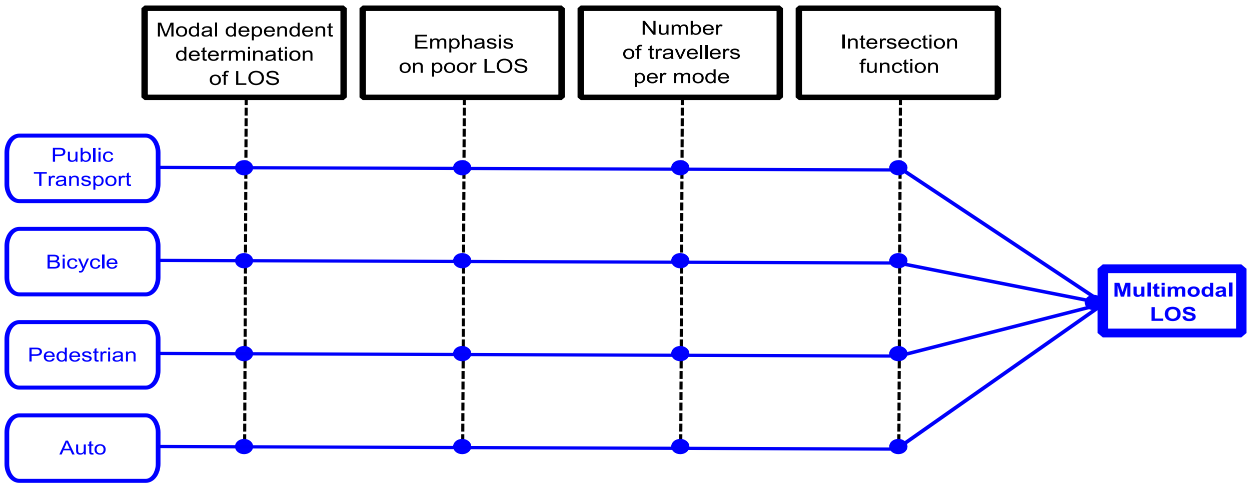

FIGURE 1 Illustration of multimodal LOS determination.

$$LOS = \frac{\sum RI_i \times T_i \times LOS_i^2}{\sum RI_i \times T_i \times LOS_i} \qquad \text{Eqn. 1}$$

Where:

LOS_i	=	Level of Service of mode i (as numerical value)	[-]
T_i	=	Number of travellers of mode i	[-]
RI_i	=	Route Importance factor of mode i	[-]

Individual Modal LOS Model

The multimodal model is modularly built and the state or nationally defined individual modal LOS models can be used. For example, in Germany, the four control delay-based quality models of the HBS could be used.

Intersection classification

Intersections are nodes connecting links. The function of the link (or street) must be considered in the intersection multimodal quality, in order to reflect user expectations and to support the engineering goals of the traffic networks. This relates to the principal and minor arterial definitions in Exhibit 10-3 of the HCM or the route classification in the German Guidelines for the Integrated Network Design (RIN) (*19*).

The multimodal model defines the factor Route Importance (RI) for each mode, which is intended to weight specific modes higher or lower based on the intersection function for each mode. These factors should be large enough to affect the multimodal quality but small enough that they do not cause undue influence in the model. The factors are defined in this paper range from 0.9 to 1.1. However, further investigation is needed into the range of these factors and the clear definition of them. To avoid unnecessary bias in the multimodal assessment model, these factors should be generally agreed upon and fixed in standards like the HCM. It remains a political question to define the intersection function, but the model thus remains transparent and objective.

The RI factor is split into two categories: high and low. For the automobile mode, principal arterials, as defined in the HCM, are defined as high RI and minor arterials are defined as low RI. Similarly, high RI roads in the German environment can be classified, according to RIN, as roads of the functional categories 0 through III (*19*).

The transit mode is classified similarly to Simon 2001 (*4*). Roads that are transit corridors and have transit lines with short headways of ten minutes or less in the peak times or multiple less frequent transit lines, bus rapid transit corridors, and tramway corridors are categorized as high RI. The remaining roads are classified as low RI.

The classification for bicycles can be done based on the defined bike network. If the street is part of the bike network, then the road is considered as high RI.

The pedestrian RI factor is defined similar to the bike mode. However, special consideration must also be paid to particular pedestrian flows, such as, school children, who use the designated school route and require higher safety, as well as, quality levels.

Discussion of the multimodal model

On the limits of transparency and objectivity

A model fulfilling the objectives established before provides a relatively transparent and objective way of assessing intersections for all transport modes in one step. Subjective influences could be introduced by the definition of the modal levels of service and the setting of the route importance factors. This dilemma can be forestalled by defining these modal levels of service and the route classification levels in general standards. As the modal levels of service are already defined in, for instance, the U.S. Highway Capacity Manual, these definitions should be extended accordingly.

Another advantage of the model is the opportunity to assess changes in modal shift. If, for instance, more travellers are attracted to public transport and the modal shift changes, this will have an impact on the overall transport quality at the intersection. Until now, this change has been difficult to assess. By defining scenarios of different modal splits (with reference to the number of travellers), the transport quality can easily be assessed with the proposed model.

There is still an ongoing debate on the drawbacks of a multimodal LOS. The arguments raised, for instance by (*5*), are mostly addressed by the proposed procedure: the weighting of the modes is objectively achieved by using the number of travellers. The route classification still needs some attention, but can be based on the concepts of HCM or the German RIN (*19*). The travel purpose is not considered, but neither is it considered in the existing modal LOS.

Beyond transport quality: assessing sustainability

One of the aims of the model is to foster the assessment of the sustainability of transport. Because the environmental impacts of signalized intersection can be significantly influenced by intersection design and signal control, it could be desirable to incorporate the environmental impacts of the different transport modes in the model. Environmental impacts can be defined by land use (space requirements of transport modes), emissions (e.g. CO_2, NO_X, PM), and separation effects, to name the most important ones for urban traffic.

Two reasons speak against this incorporation: transport quality and environmental impacts would be mixed. The model would lose transparency. The political weighting of transport quality and environmental impacts would have to be integrated into the model. The objectivity would be reduced. Furthermore, it is quite difficult to assess the environmental impacts of transport modes at the intersection level. What is the *additional* space requirement of a vehicle at an intersection? How can one evaluate space requirements of vehicles sharing the same lane?

It appears, thus, to be advisable to assess environmental impacts on a higher level, and strictly separate the assessment of environmental impacts and transport quality. The same applies to economical and social impacts of intersections.

However, the model supports the assessment of the sustainability by focussing on travellers instead of vehicles. It incorporates the non-motorized modes equally and reflects the route importance of the intersections for all modes. The effects arising from an improvement of one mode on the other modes are transparently exposed.

A CASE STUDY

Introduction

To support the strengths and the applicability of the proposed model, it has been applied to an intersection in the City of Darmstadt, Germany. The base case scenario is evaluated with surveyed traffic counts, average private vehicle occupancies and public transport vehicle occupancies taken from German literature. The base case is followed by a public transport priority scenario and a scenario with increased traffic volumes in the automobile and bicycle modes. The layout of the intersection is shown in FIGURE 2. Both intersecting roads are arterials with several public transport services, particularly in the east-west direction. The intersection control parameters were determined based on the German standards for signalized intersections (RiLSA 1992 and HBS 2005) using a three phase program.

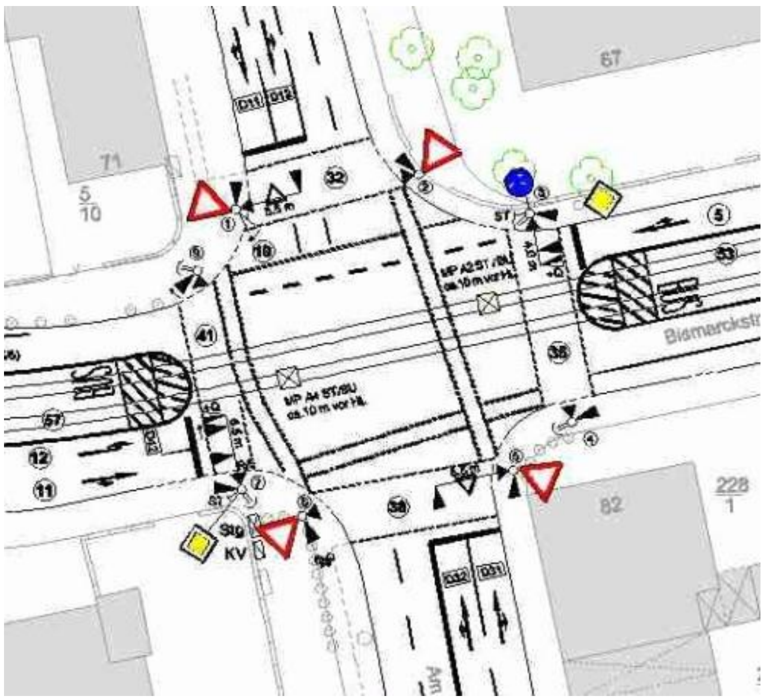

FIGURE 2 Intersection layout.
(Source: Wissenschaftsstadt Darmstadt, Straßenverkehrs- und Tiefbauamt)

Model Parameters

The traveller volumes have been determined from the vehicle occupancies and traffic volumes. The automobile occupancy used is an average value from the literature of 1.25 persons/vehicle (*20*, *21*). The public transport (PT) occupancy is a daily average for buses of 16 persons/bus (*21*). It is noted that both modal values are daily averages and not peak hour specific. If more detailed data would be available, the assessment could be adjusted accordingly. This would put even more emphasis on public transport. The traffic volumes are summarized in TABLE 1.

TABLE 1 Case study traffic volumes and occupancies.

Mode	Vehicles or Pedestrians / hour	Occupancy (Persons / Vehicle)
Auto	1598	1.25
Bicycle	35	1
Pedestrian	120	1
PT	59	16

The intersection must be classified in order to select the route importance factors. The route importance is determined as significant for all modes, except for the bicycle mode (TABLE 2).

Scenario assessment

Base case

The base case is designed based on the German HBS to determine the optimal cycle and phase lengths for the vehicular traffic. The cycle time for this scenario is 65 s and each intergreen time is 8 s. TABLE 2 shows the resulting quality of this intersection.

TABLE 2 Input data and overall LOS for base case.

Mode	Volume	Occ	Persons	LOS	RI	Weighting
Auto	1598	1.25	1998	1	1.1	2197
Bike	35	1	35	2	1	140
Pedestrian	120	1	120	2	1.1	528
PT	59	16	944	4	1.1	16614
∑	1812		3097	Overall LOS		C - 2.9

The resulting overall LOS is C (2.9). Despite the public transport modal split of only 30 %, its poor quality of D significantly lowers the overall LOS.

Scenario 1: Public Transport Priority

In the public transport priority scenario, the buses and trams travelling along the east-west corridor receive a soft signal prioritization by a combination of green time extension, green time curtailment, and phase skipping. This represents a common procedure in Germany.

The prioritization resulted in a reduction of the public transport delay along the east-west direction by nearly 100 %, but an increase by more than 50 % on the south-approach. The overall public transport traveller delay decreased by 80% (24,000 to 4,400 person-seconds, equal to a 20 second/person delay reduction). However, the vehicular traffic was also negatively affected on the north-south corridor due to phase skipping.

The prioritization resulted in the LOS improving to B (TABLE 3). This was accompanied by the public transport LOS improving to A and the automobile LOS worsening to B. The multimodal model objectively evaluates the changes in the individual LOS's and allows for a direct comparison with the base case scenario.

TABLE 3 Input data and overall LOS for public transport priority.

Mode	Volume	Occ	Persons	LOS	RI	Weighting
Auto	1598	1.25	1998	2	1.1	8789
Bike	35	1	35	2	1	140
Pedestrian	120	1	120	2	1.1	528
PT	59	16	944	1	1.1	1038
∑	1812		3097		Overall LOS	B - 1.8

Scenario 2: Modal Volume Increases

The multimodal model can also be used to evaluate the quality for different modal splits, as well as, changing traffic volumes. This scenario considers an additional 1000 travellers added to one mode: 1000 automobile travellers (Scenario 2a) and 1000 bicyclists (Scenario 2b).

The results of the volume increases are summarized in TABLE 4. The LOS cannot be maintained with increasing vehicular volumes, when only signal control parameters are modified. [1] However, up to a certain volume, the intersection can easily accommodate a greater number of cyclists. The LOS is consequently constant as additional cyclists are added to the intersection.

TABLE 4 Input data and overall LOS for modal volume increases.

	Base Case[2]	Scenario 2a Auto +1000	Scenario 2b Bike +1000
Auto [Person]	1998	2996	1998
Bike [Person]	35	35	1050
Pedestrian [Person]	120	120	120
Public Transport [Person]	944	944	944
Total [Person]	3097	4095	4112
Chosen Cycle length [s]	60	90	60
Calculated Cycle length [s]	65	99	65
Auto LOS	1	2	1
Bike LOS	2	2	2
Pedestrian LOS	2	2	2
Public Transport LOS	3	4	3
Overall	2.2	2.7	2.1
Overall LOS	B	C	B

[1] The individual modal LOS are given as the average of all approaches. The worst level is naturally lower than the average, supporting the statement.

[2] A reduced cycle time of 60s was used due to better results for all modes.

CONCLUSIONS AND OUTLOOK

Two trends can be observed in transport, which are relevant for the quality assessment of transport systems: an increasing linkage between different transport modes and the requirement of sustainability covering not only the economic, but also the environmental and the social dimension. These trends have to be reflected in the performance measurement of the transport system. While the prevailing standards and manuals offer a wealth of procedures to assess the quality separately for the major transport modes, the multimodal aspect has just started to enter the common practice.

A major gap has to be seen in the neglect of the travellers in the assessment procedures. The motorized modes are still assessed with the focus on vehicles, while it is the travellers we want to transport. The assessment of the transport quality from the viewpoint of travellers, particularly the non-motorized ones, is much more complicated, because many aspects, in addition to the commonly used performance measure delay, play a role for their quality perception. A more comprehensive definition of levels of service for these modes would be desirable.

The research presented here focuses on signalized intersections. Not only because intersections are most important for the overall quality of transport networks, but also because the current procedures for the generation of signal timing parameters and intersection layout are still focused on vehicles, followed by a separate assessment of different modes (if all modes are considered at all). Furthermore, they commonly neglect the interrelation of modal qualities on each other. The effect of public transport priority measures, for instance, on the overall quality of an intersection is usually not directly assessed.

The main features of the proposed procedure for the assessment of the transport quality at signalized intersections are:

- The evaluation is based on the number of travellers (it considers the occupancy of vehicles).
- Levels of service for all transport modes are combined into an overall quality level.
- The route importance of the intersection is taken into account with respect to the individual transport modes.
- The procedure is transparent and, thus, as objective as possible.

The determination of the modal levels of service described in this article are only suggestions, which have to be fitted to local needs and can be improved by further research findings. The same applies to the factors for the intersection function.

A simple field study highlighted the potential of the methodology. The effects arising from improvements for one mode on the other modes can easily be highlighted. Even the effect of changes in the modal split on the overall transport quality at the intersection can be evaluated.

To date, the methodology is limited to fixed time traffic control. It is a good starting point for further research on traffic actuated control, where intermodal effects are even more important (e.g. due to dynamic prioritization of certain modes). The procedure is not intended as a tool for the overall evaluation of street networks, but it could contribute to this evaluation. In the first place, it is intended as a tool supporting the design and operation of signalized intersections.

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