**Prioritization of Different Road User Groups at Traffic Signals**

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## Introduction

Traffic signals are a very important instrument to manage urban traffic. When designing traffic signal programs, many different goals and road user needs have to be considered. While traffic engineers must ensure the technical planning, implementation and operation of traffic signals, their work must be supported by a clear policy. One of the major questions to be answered within such traffic signal control policy is the prioritization of different road user groups at traffic signals.

Traditionally, transit signal priority is one of the most widely implemented priority strategies at traffic signals. There were a large number of studies on various aspects of this priority strategy. An overview of them is available in Nguyen (2013), Garyfalia *et al.* (2015) and Lin *et al.* (2015). Another widely implemented prioritization is the preemption for emergency vehicles (EVs), which aims to reduce the delay of EVs at traffic signals and their conflicts with other private vehicles (U.S. Department of Transportation, 2006). Some other priority strategies have been proposed in previous research, such as truck signal priority and pedestrian priority (Ramsay and Bunker, 2005; Saunier, Sayed and Lim, 2009; Seaton, 2000). Despite of the studies on priority for a single traffic mode, past research has also dealt with prioritization for a multi-modal traffic signal control, which addresses multiple priority requests from several traffic modes (Zamanipour, Head and Ding, 2014). Recently, also more attention has been paid to consider environmental impacts within traffic signal control (e.g. Diegmann, 2014; Kohoutek, Weinbruch and Boltze, 2012). However, there is still a lack of integrated consideration of the trade-offs between different road users and different objectives under various situations within the framework of prioritization.

This paper proposes a general policy framework for traffic signal control. While modifications may be necessary to adapt to specific local conditions, it may serve as a blueprint for any urban traffic signal control policy.

## 1. General Policy for Traffic Signal Control

(1) Traffic signals are a **very important instrument to manage urban traffic**. Traffic signal control has significant impacts on accessibility and on the quality of traffic flow for the different road user groups, as well as on other aspects such as traffic safety, environmental condition and economical efficiency. Furthermore, also impacts on mode choice must be considered in designing traffic signal control.

(2) The design of traffic signal control shall **consider the various impacts** on the different road user groups as comprehensively as possible. This includes the principles of barrier free mobility and sustainability.

(3) In some cases, the advantages regarding a specific impact or road user group can only be achieved together with disadvantages for other road user groups. In such cases, a **comprehensible consideration** shall be done before decision making. Comprehensibility and transparency are important conditions for the acceptance of decisions by the citizens. Therefore, decisions to design traffic signal control need rules for a fair balance of different impacts, for the treatment of goal conflicts, and therefore for the prioritization of different road user groups.

(4) Traffic signal control should aim for a **situation-responsive prioritization**. It is not just fixed rules that shall be applied, but instead - according to available technical options - the specific current situation shall be considered (e.g. traffic volumes, environmental situation, day of the week, time of day).

(5) **Planning instruments** for traffic signal control shall be developed which allow to determine all major impacts and to reflect them in the course of consideration.

(6) The actual impacts of traffic signal control shall be monitored frequently, as part of a **performance measurement**. Results shall be reported to decision makers in defined cycle or event-driven to allow corrections regarding priorities and rules of consideration.

(7) To allow a differentiated traffic signal control **modern control technologies** shall be applied. Any existing national standard for traffic signal control must be considered. Any discrepancies from rules known as the state of the art need an explanatory statement.

(8) As far as new approaches are promising a more sustainable traffic system, **field trials** and their evaluation shall be supported to improve the state of the art.

## 2. Main goals and relevant parameters

(1) There are four main goals within the framework of traffic management, which are generally relevant for all traffic modes: satisfaction of mobility needs, increase of traffic safety, reduction of environmental pollution, and improvement of economic efficiency (Boltze and Dinter, 1994).

(2) Satisfaction of mobility needs
Mobility is a basic need of human beings. The accessibility of a city determines its attractiveness for not only residents but also the economy. Therefore, it is necessary to improve the quality of traffic flow (delay, number of stops, queue length) and to increase the level of comfort while using different traffic modes. To achieve this goal in traffic signal control, particularly the following parameters must be considered:

- delay for vehicles (motorized and not motorized)
- delay for individuals
- number of stops
- queue lengths
- comfort

(3) Increase of traffic safety
While in some developed countries major improvements in traffic safety have already been accomplished in the last decades, many other countries are still suffering from severe traffic safety problems. However, in all countries further efforts are still necessary to reduce the number of traffic accidents, injuries and deaths. To achieve this goal, particularly the following parameters related to traffic signal control must be considered:

- number of traffic accidents
- number of slight injuries
- number of severe injuries
- number of fatalities

(4) Reduction of environmental pollution
To protect human health, the negative impacts of traffic through noise emission and air pollution shall be reduced[1]. Residents should be also assisted to choose the most

[1] For many countries, the number of early deaths due to air pollution seems to be significantly higher than the number of fatalities due to traffic accidents. For example, according to the statistics of German Federal Environment Agency (Umweltbundesamt) the annual number of deaths caused by particulate concentration in Germany is about 47,000 (Kallweit, 2013). Since traffic contributes about 20% of the particulate concentration in Germany, it could be concluded that the traffic related emissions of particulate matter lead to about three times the number of deaths caused by traffic accidents (in Germany 3,400 in 2014). Further severe impacts on human health are caused by other air pollutants (e.g. nitrogen oxides, ozone) and by noise pollution.

environmentally friendly traffic mode with the best impacts on their health. Energy consumption and green house gas emissions are having a close relation and shall be reduced.[2] To achieve this goal, particularly the following parameters related to traffic signal control must be considered:

- emission of air pollutants
- ambient air quality
- noise level
- energy consumption, $CO_2$ emission

(5) Improvement of economic efficiency
The travel time for movements should be reduced. Infrastructure and vehicles should be utilized efficiently. To achieve this goal, particularly the following parameters related to traffic signal control must be considered:

- average travel speed
- saturation degree of green times

(6) Among these goals, the prevention of emissions with adverse health effects and the improvement of traffic safety have the highest weight.

(7) Table 1 shows the relevance of the above mentioned parameters for each traffic mode.

| Goal | Parameter | Walking | Cycling | Public transport | Motorized private transport | Freight transport |
|---|---|---|---|---|---|---|
| Satisfaction of mobility needs | delay for vehicles | | | + | + | + |
| | delay for individuals | + | + | + | + | + |
| | number of stops | o | + | + | + | + |
| | queue length | o | o | o | + | + |
| | comfort | + | + | o | o | o |
| Increase of traffic safety | number of traffic accidents | o | + | + | + | + |
| | number of slight injuries | o | + | + | + | + |
| | number of severe injuries | o | + | + | + | + |
| | number of fatalities | o | + | + | + | + |
| Reduction of environmental pollution | emission of air pollutants | | | o | + | + |
| | ambient air quality | | | o | + | + |
| | noise level | | | + | + | + |
| | energy consumption, $CO_2$ emission | | | + | + | + |
| Improvement of economic efficiency | average travel speed | + | + | + | + | + |
| | saturation degree of green times | o | o | + | + | + |

+ relevant o usually not significantly relevant

**Table 1:** Relevant parameters for each traffic mode

## 3. Prioritization of traffic modes and influencing mode choice

(1) All kinds of traffic modes are available for citizens: walking, cycling, public transport and motorized private transport[3]. Furthermore, the freight transport, especially heavy vehicle traffic, requires special examinations.

[2] In special cases, traffic signal control may also influence land consumption, which is not specifically considered in this paper.

[3] Depending on local conditions, further modes may need specific consideration, e.g. motorcycles in the case of Vietnam.

(2) Due to their general advantages regarding environmental compatibility, walking, cycling and public transport shall be promoted[4]. However, any absolute priority for one single traffic mode is not appropriate. Instead, in each case, the overall impacts of measures at traffic signals must be considered to avoid inadequate negative impacts on other traffic modes and other relevant parameters.

(3) Mode choice has a significant impact on the sustainability of the overall transport system. Therefore, besides the direct impacts of traffic signal control measures, indirect impacts influencing the medium- and long-term mode choice behavior must be considered, as well.

(4) To deteriorate traffic flow for motorized private vehicles in urban areas is not an appropriate means to control mode choice. Inappropriate restraints for motorized traffic will not only lead to congestion and delays for drivers, but also harm human health significantly by avoidable emissions of noise and air pollutants, specifically for local residents, pedestrians and cyclists.

The aim at improving traffic flow explicitly does not lower the intention to influence mode choice in favor of pedestrian traffic, cycle traffic and public transport. However, to control mode choice measures without negative environmental impact shall be applied, such as demand-oriented measures of mobility management, regulatory and financial measures of parking management, road pricing, improvements of the bicycle network, and many others.

## 4. Comprehensive consideration and fair balance between multiple impacts

(1) The design of traffic signal control shall consider the various impacts on different road user groups comprehensively.

(2) In many cases in the design of traffic signal control, contrary requirements and goal conflicts cannot be avoided. As far as significant negative impacts are recognized, they should be verified technically, elaborated transparently and considered carefully by comparing with the advantages of the measure.

For measures which would promote one traffic mode, besides the positive impact on this specific mode also the negative impacts on other traffic modes should be displayed and quantified, where possible.

(3) For **measures to promote pedestrian and cycle traffic**, specifically the following parameters must be considered:

- Delay, number of stops and queue lengths in motorized individual traffic
- Delay for public transport
- Noise level and emission of air pollutants by motorized private transport and heavy vehicles (where possible also ambient air quality)
- Fuel consumption and $CO_2$ emissions by motorized private transport and heavy vehicles

(4) For **measures to promote public transport**, specifically the following parameters must be considered:

- Delay, number of stops and queue lengths in motorized individual traffic
- Average and maximum delay for pedestrians and cyclists
- Noise level and emission of air pollutants by motorized private transport and heavy vehicles (where possible also ambient air quality)

[4] As an example, many countries have established an urban road user hierarchy that gives the highest priority to walking, cycling and public transport, which would be reflected in decisions about transportation policy, planning, design, operations, and maintenance (Fischer *et al.*, 2010).

- Fuel consumption and $CO_2$ emissions by motorized private transport and heavy vehicles

(5) For **measures to promote motorized private transport and heavy vehicles**, specifically the following parameters must be considered:
- Average and maximum delay for pedestrians and cyclists
- Delay for public transport
- Impacts on mode choice

(6) To achieve a multimodal impact assessment, the same parameters regarding different traffic modes should be aggregated. Under consideration of the physical fundamentals, most of them can be aggregated without further adjustments (e.g. emissions).

For the evaluation of average delay, a person-related aggregation would be appropriate. Based on the average vehicle occupancy, the overall average delay for all road users at the intersection could be calculated (Hunter, Wolfermann and Boltze, 2011).

Different weights could be assigned to the delay at different traffic modes in order to consider the political preferences and comfort aspects for each individual traffic mode (e.g. differences in comfort or weather protection).[5]

(7) Generally, it is difficult to aggregate the impacts on different goals and parameters. However, finally it is necessary to find a fair balance of – for example – delay for different road users, number of traffic accidents and health impacts of air pollution and noise.

Necessary quantitative weights may be concluded from relevant literature (e.g. Bickel et al., 2006; FGSV, 1997). However, the rates used for monetarization are often controversial and they are always reflecting political preferences.[6]

Therefore, to allow a comprehensive assessment of traffic signal control measures a concept to combine and weight all the objectives and criteria should be developed and politically approved.

## 5. Situation-responsive prioritization

(1) Traffic signal control shall be situation-responsive. It is not just fixed rules to be applied, but instead – according to available technologies – the specific current situation shall be considered (e.g. traffic volumes, environmental situation, day of the week, time of day).

(2) Variations in traffic volumes are already considered, if an adaptive traffic signal program is implemented which changes according to time and traffic volumes, and if the above mentioned suggestions for performance measurement and fair balance are applied.

(3) Prioritization of transit vehicles aims to consider the occupancy of the transit vehicle and its position compared with the schedule. Priority can be given to transit vehicles which are behind schedule, but not to early vehicles.

(4) In situations with critical air pollution levels (impending or already existing exceedance of threshold values), signal programs should be applied which particularly reduce emissions of air pollutants. However, in uncritical situations, signal programs could be used which give lower weight to these environmental criteria. To detect the critical

[5] As an example, the following weights could be used:
- Person-related delay for walkers and cyclists, factor 3
- Person-related delay for public transport users, factor 2
- Person-related delay for users of motorized private vehicles, factor 1

The consequences of these or other weights shall be investigated in ostensive scenarios to support political decision-making on such concept of values.

[6] For example, the rate to value deaths in traffic accidents in Switzerland is four times that much in Germany. This would make the measures to improve traffic safety much more efficient in cost-efficiency calculation in Switzerland.

environmental situation either local measurement stations or estimated values based on regional indicators could be used (Breser and Jiang, 2014).

To reduce emissions, also innovative measures should be tested and implemented, for example the green time adjustment to avoid stops of heavy vehicles.

(5) At places and times with special demand for noise protection (e.g. at hospitals or at night in residential areas), signal programs should be applied which particularly prevent noise emissions. In such situations, green waves and other measures to avoid stops and start-ups of vehicles have to be combined with further measures to influence route and speed choice.

(6) A concept for an active utilization of traffic signal control to reduce noise and air pollution shall be developed and implemented. Examples for traffic signal control measures which should be considered in critical environmental situations are access metering for critical parts of the network, adaptation of signal coordination (green waves) to further reduce the number of stops, reducing the degree of prioritization for transit vehicles, dynamic green time adaption to avoid heavy vehicle stops, and others. Some of these measures should be combined with other traffic control measures, such as regulations for driving directions, route recommendations or speed limits. As mentioned before, the impacts of these measures on other road users must be considered comprehensively.

## 6. Impact estimation before implementation

(1) On the one hand, impact estimation should be conducted before the implementation of any traffic signal control measure in order to evaluate the potential impacts comprehensively and to optimize the measure as possible. On the other hand, it is also necessary to monitor the impacts of traffic signal control measures during the operation in order to verify the effectiveness of the measures continuously (as illustrated in section 7).

(2) Preferred methods for impact estimation are traffic engineering calculations and models.

Simple tasks without significant goal conflicts or repeated tasks can be solved based on the very good knowledge and experience of traffic engineers. For traffic control measures which lead to major goal conflicts the various impacts should be quantified and the trade-offs between different traffic modes and multiple goals should be demonstrated transparently.

(3) The planning instruments for traffic signal control shall be further developed to allow the estimation of all major impacts and their consideration in the case of goal conflicts. A detailed concept for the impact estimation within the different tasks to design traffic signal control shall be elaborated based on this paper and under consideration of available resources.

An appropriate instrument to estimate the impacts of traffic signal control measures is the microscopic traffic flow simulation combined with an associated emission modelling module. Model development and maintenance are a permanent task which is not related to a specific project and which needs sufficient human resources.

(4) Parameters related to the goal **“satisfaction of mobility needs”** (delay for vehicles and individuals, number of stops and queue length) could be calculated by using methods defined in the respective national Highway Capacity Manual. In complex situations, they could also be determined by using a microscopic traffic flow simulation model.

Usually, the comfort aspects can only be estimated qualitatively or – with more efforts – they can be evaluated by road user surveys.

(5) The parameters related to the goal “**increase of traffic safety**”, specifically the accident occurrence due to modifications in traffic signal control, usually can just be estimated based on empirical values from similar situations. The empirical values could be

obtained from either a traffic accident data base or previous research projects. Sometimes also auxiliary quantities can be used in the evaluation procedure.[7]

(6) With regard to the goal “**reduction of environmental pollution**”, the emissions of air pollutants can be determined by a microscopic traffic flow model combined with an integrated emission module. The ambient air quality is strongly influenced by other circumstance factors (buildings, weather, background concentration, etc.), and modelling needs large efforts, so far. Simplifying statistical models (e.g. Kohoutek, Weinbruch and Boltze, 2012) which are sufficiently calibrated for a specific situation offer approaches to estimate the impacts of traffic signal control measures on ambient air quality, at least for hotspots.

There are several calculation methods and models provided to estimate noise emissions and noise levels.

Energy consumption and $CO_2$ emissions can be derived from microscopic traffic flow models, for example.

(7) The parameters relevant to the goal “**improvement of economic efficiency**” (average speed, saturation of green time) can be calculated or be derived from a microscopic traffic flow model.

(8) The mid-term or long-term **effects on mode choice** usually cannot be related to a single traffic signal control measure. Instead, they are caused by a sum of individual road user perceptions and by a bunch of measures which are only partly related to traffic signal control. Therefore, it is almost not possible to quantify the impact of an individual traffic signal measure on mode choice.

Instead, the parameters which are quantifiable and relevant to each traffic mode (e.g. delay) should be utilized to generally demonstrate in which direction the measure may influence the mode choice. Comprehensive quantification of this issue is only possible on a larger scale.

## 7. Impact assessment during operation

(1) The actual impacts of traffic signal control should be frequently measured. A systematic impact assessment during operation is necessary in order to ensure a stable and high quality of traffic control (compare FGSV, 2010). The aim is to identify deficiencies at an early stage, to verify the effectiveness of implemented measures and at last to allocate the available resources to where they allow the most benefits. The impact assessment (or performance measurement) should not be a one-time activity, but rather a continuous task.

(2) For the impact assessment during operation the following data may be used: traffic accident data, process data from control devices, operation and disruption data as well as information from previous experience and from observations at the traffic signal (FGSV, 2010). Sometimes, information from other systems can also be useful, such as speed profiles from the transit operation system or data obtained from suppliers of navigation systems.

(3) Based on existing standards for the quality management of traffic signals – e.g. in Germany RiLSA (FGSV, 2010) and H QML (FGSV, 2014) – a concept for the continuous impact assessment during operation should be developed, optimizing the efforts for data collection.

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[7] For example, the maximum delay for pedestrians and cyclists can provide clues for accident risks. Or disruptions of a vehicle platoon observed in the simulation may be caused by changes in the coordination and could indicate the risk of rear-end collisions.

(4) Results of the impact assessment shall be reported to decision makers in defined cycle or event-driven to allow corrections regarding priorities and rules of consideration.

## 8. Future technical developments

(1) To allow a differentiated traffic signal control, modern control techniques and planning instruments shall be applied. The current condition of the devices and the foreseeable demand for renovation and replacements should be frequently reported.

(2) There are many current policies implemented to reduce the vehicle emissions, such as promotion of electrical cars, regulation policies (e.g. low emission zone), and others. The changes in the local vehicle fleet should be taken into consideration when calculating the environmental impacts of traffic signal control measures.

(3) In the next years, the general framework for the design of traffic signal control may be significantly influenced by the so-called cooperative systems (car-to-car and car-to-infrastructure communication). This development should be supported as long as it complies with the above mentioned main objectives. Adjustments in traffic signal control may be necessary in order to maintain safe traffic operations (e.g. adjustment of intergreen time once drivers are informed about the start time of green).

## Conclusions and policy implications

Traffic signal control is one of the most important instruments to shape urban traffic. This paper presents the basic outline of an advanced traffic signal control policy which considers the manifold needs of all road users. It calls for a transparent impact assessment and for a holistic view on all impacts of traffic signal control, contributing to overcome the conflicts arising day-to-day in our political bodies in discussions about traffic signal control measures. Parameters and methods for the impact assessment are proposed. The concept of a situation-responsive prioritization is introduced, paying attention not only to traffic-related but also to environment-related conditions. Besides comprehensive impact estimation prior to the implementation of traffic signal control measures, the importance of a continuous quality management during operation (i.e. performance measurement) is highlighted.

In many aspects such ideal traffic signal control policy may need additional efforts within the responsible institutions. However, the benefits for our society arising from well-designed traffic signal control are very substantial. And innovations and investments in this field must not only address advanced technology and advanced planning instruments but – maybe most important – also an advanced policy.

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