Signal Control in Mixed Traffic based on Bus Probe Vehicles: Concept and Application

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Abstract: This paper presents an approach and a case study to traffic responsive signal control in mixed traffic conditions. Inductive loop detectors are not likely to be a feasible option in many fast growing cities of developing countries due to heterogeneous, often very congested traffic conditions with no lane discipline. Therefore, the approach used in this paper is based on identifying traffic conditions through bus travel time information obtained through direct vehicle to infrastructure communication. The approach is embedded in the MOSCUE framework (multi-objective signal control in urban areas) which allows the decision maker flexible adjustments of the signal controller to possibly changing policy objectives. The feasibility of the concept is illustrated with a case study from Ho Chi Minh City, Vietnam. It is shown that even if only buses transmit travel time data the controller can achieve some improvements in overall traffic performance.

Key Words: Traffic signal control, fuzzy logic, mixed traffic, bus probe vehicles

1. INTRODUCTION

Many Asian developing cities have been experiencing rapid growth of private mode use. The consequences are well known and include increasing loss of time, money and negative effects on human health and the environment. There are however different patterns of motorization. While in developed countries traffic is dominated mainly by cars, in some Asian developing cities, motorcycles (MC) are the dominant mode. This may be a result of differences in climate, the economic and infrastructure situation, population density as well as culture background (Minh, 2007). In HCMC, currently there are more than 3.5 mil motorcycles carrying around 90% of the trips (HCMC Department of Transport, 2007). Meanwhile, bus is the only public transport mode that was planned to be a main transport mode. Significant investment has been dedicated to develop the bus network in recent years. However, the city’s bus fleet of currently 3208 vehicles is serving only 6.3%. As in many other developing cities, the present road conditions in HCMC do not allow dedicated bus lanes.

Since the buses travel in these mixed unordered traffic conditions, the reliability and low speed
of the bus is a major aspect of the quality of service (Van, 2009). The average travel speed of buses during peak hours in HCMC is around 13 km/h, which is reduced 39% from 6 years ago (Van, 2009). Buses are not only impeded by a great number of motorcycles running around but also influenced much by waiting for traffic lights. The present traffic signal control in HCMC is fixed and can only be manually changed by police. It is therefore expected that a traffic signal control system that can be responsive to the buses could reduce delays and stops for buses as well as private mode users at junctions.

To deal with the increasing traffic congestion and accidents, the government is aiming to improve the quality of buses by a variety of measures. As part of this, by the end of 2007, the HCMC Public Transportation Management and Operation Center, funded by the city government, carried out an installation of in-vehicle GPS devices for 15 buses on 3 routes. Data related to the buses’ trip are recorded and sent back to the center. However, at this trial stage, the application of GIS-GPS to supervise the operation of the buses are mainly limited to preventing violation of traffic rules, e.g., running over the speed limit. Since the price for GPS devices is not so high (at around US $1000/unit), it is expected that installation of the GPS devices could be widely expanded and a bus control center utilizing GIS and GPS technologies to track and control the movement of buses in the network could be built. In addition, presently some transport companies and researchers in HCMC are also working on several projects to integrate GPS devices to vehicles for tracing and supervising their real-time location (e.g. Vinatrack, 2008).

Given the current suboptimal traffic signal control strategies in many developing countries as well as ongoing ITS developments, this study proposes a new framework to control key junctions in cities of developing countries. In contrast to established controllers in this framework the controller obtains its dynamic input information from probe vehicles such as mass transit buses. In the following, Section 2 contains a literature review summarizing problems to control traffic with inductive loop data in mixed traffic conditions. Section 3 explains the main idea of how to use bus probe data for signal control which is implemented into the existing MOSCUE framework. This framework is reviewed and extended in Section 4. Sections 5 then describes an application of the concept to a road corridor in HCMC and Section 6 concludes this paper.

2. LIMITATION OF SIGNAL CONTROL WITH LOOP DETECTOR

There is a long-standing research history in traffic signal control showing that effective settings can significantly influence the traffic network performance. Initial single junction fixed time control systems have been improved to area wide systems and adaptive signal control systems. The aim of adaptive systems is to take variations in flow into account to minimize the overall delay on all approaches. These systems are now widespread and indeed have been shown to be successful with numerous case studies in mostly developed countries (see for example the SCOOT (2008) and SCATS (Tyco, 2008) pages for reviews). For adaptive signal control the quality of the input data is crucial. In all major applications input data are primarily based on (inductive) loop-detectors. In traffic conditions such as prevailing in most developed countries, loop detectors are an efficient, reliable and relatively inexpensive way of collecting traffic data. Inductive loop detectors measure occupancy which is then used as a proxy for the traffic density. Further double inductive loops allow an approximate calculation of vehicle speeds. Density and speed can then be used to adjust priorities at junctions to maximize the throughput
dynamically. To base the signal control on inductive loop detector data only does however have a number of shortcomings. Firstly, Middleton et al (2002) point out that priorities in transport policy are nowadays changing away from throughput maximization to consideration of multiple objectives including pedestrian, bicycle and environmental issues. To allow a more flexible approach considering changing objectives Schmöcker et al (2008) hence propose a framework titled “MOSCUE: Multi-objective Signal Control in Urban Environments”. In order to reflect these changing objectives new developments often supplement loop detector data with other data sources, namely short range communication, GPS data or video detection. These systems have been used to priorities more sustainable modes of transportation such as buses and trams as well as non-motorized road users (Carsten et al, 1998).

Further, Hossain (2001) pointed out that in traffic without lane discipline and with numerous vehicle classes saturation flows of junctions are depending on a large number of factors and Trabia et al (1999) noted that loop detectors are less effective in very congested traffic. A second problem of inductive loop detector based systems is therefore that these do not perform as well in congested mixed traffic conditions prevailing for example in South-East Asian countries. Thirdly, there is often not enough available budget to install (and maintain) large scale signal control systems based on loop detectors. In many cities, it is therefore unrealistic to assume that inductive loop detectors will be installed in the near future. It is more realistic to assume that a large number of buses and/or taxis become equipped with GPS devices which will be used for a variety of purposes such as security, dispatching as well as passenger information. Recently cost-effective GPS equipped probe vehicles could further be used to estimate traffic conditions on road corridors as well as in larger networks (e.g. Liu et al, 2008).

3. SIGNAL CONTROL INPUT BY BUS TRAVEL TIME

As discussed above the idea to apply traffic responsive signal control to mixed traffic in developing cities meets an obstruction as it is difficult and costly to count cars and motorcycles in disordered traffic by using loop detectors. This study therefore proposes that the signal control input data are collected by an advanced ITS system transferring single vehicle data directly to the signal controller. The main idea is illustrated in Figure 1. The time a bus passes a position $S$ located upstream of the junction and a position $E$ located shortly downstream of the junction’s stop line are recorded and transferred to the signal controller. The cloud symbolizes the various technological possibilities for this vehicle to infrastructure communication. As argued above for example GPS systems combined with mobile phone technologies are becoming more popular in developed as well as developing countries and are a data source that is already widely applied for numerous vehicle tracking applications (e.g. Dessouky et al., 1999, Turksma, 2000). In particular equipping buses with GPS transponders appears to be an efficient solution as the data can be used for a variety of purposes such as route performance monitoring (Bullock et al., 2005) and pedestrian countdown information as well as junction priorities as currently being implemented in London (Transport for London, 2008). Alternatively also other vehicle to infrastructure communication systems could be applied such as wireless local networks, dedicated short range microwave or infrared communication. The large ongoing CVIS initiative investigates technologically feasible solutions and their wide range of possible applications (CVIS, 2008).

The time difference between the two multiple recordings $t_{Si}$ and $t_{Ei}$ are presumed to give an estimate of the traffic conditions on the road corridor and the hence optimal signal timings.
Obviously, the more individual data recordings and the more recording points are available to the signal controller, the better the signal timings can be optimized. To illustrate the feasibility of the proposed concept it is proposed that all fixed route buses passing through the corridor transmit information. If taxis and other commercial or private vehicles would also be equipped to transmit information it is expected that the feasibility of the concept would further be improved.

![Figure 1 Concept of bus probe data based signal control of a road corridor](image)

Before the signal timings are newly updated the controller should have received sufficient new information from the probe vehicles. The updating interval should hence consider the frequency of probe vehicle arrivals as well as possible irregularities due to congestion. In the case study described in the following, it was for example determined that an updating interval of every four cycles is feasible. During this time duration always several probe vehicles transmit their travel time.

4. THE MOSCUE FRAMEWORK

MOSCUE presents an approach to multi-objective signal control using fuzzy logic. The framework is based on Ahuja and Bell (2006) and is illustrated in below figure. Previous to the online application the controller is offline optimised with the help of a microsimulation model of the road corridor. The traffic engineer specifies acceptability thresholds for key traffic performance variables such as delays, queue sizes or emissions which can be estimated with the micro simulator. Various signals timings are tested and optimised with the help of genetic algorithms. The fit of a particular solution is evaluated with the help of the \textit{minimax} principle, also referred to as Bellman-Zadeh evaluation (Bellman and Zadeh, 1970). The idea is to maximise the minimum satisfaction among all (competing) objectives. A simple maximisation of the sum of the satisfactions with all objectives would leave the engineer with the problem of having to choose weights for each objectives. Similarly, creating the Pareto optimal front of solutions leaves the engineer with the choice of which solution to choose. Further, instead of directly optimising the green times of the junction the GA optimises the fuzzy logic membership functions which then determine the green times. In the online application of the framework, the optimised membership functions are then used to dynamically control the junction based on the input data.
The offline optimisation can therefore be summarised as follows. The satisfaction $D(x)$ with a particular set of signal timings determined by $x$ is the one that maximises the minimum satisfaction $C(x)$ of each key performance indicator $i \in n$ (Eq. 1) subject to safety constraints and maximum length on the stage durations and cycle length.

$$\text{Max } x \quad D(x) = \min \{ C_i(x), \ldots, C_n(x) \}$$

(1)

The satisfaction of each key performance indicator (KPI) is evaluated according to the simulation output $y_i(x)$ as well as the acceptability and unacceptability thresholds defined by the traffic engineer. In Eq(2) $y_i^F$ is defined as the value that is deemed fully acceptable and $y_i^0$ as the value that is defined as unacceptable. Any performance of the traffic corridor in between these two values satisfies the engineer to some degree.

$$C_i \left( y_i \left( x \right) \right) = \max \left\{ 0, \min \left\{ 1, \frac{y_i^0 - y_i \left( x \right)}{y_i^F - y_i^0} \right\} \right\}$$

(2)

In existing case studies, the framework has only been applied to optimize single junctions. In this paper, the framework is extended by coordinating the control of several adjacent junctions. A second improvement compared to previous case studies is that not only the stage durations but also the cycle length is optimized. As the junctions are in close distance it is assumed that a common cycle time is optimal which allows keeping the offset between junctions constant in order to allow green waves for traffic on the main corridor.

In the extended framework $x$ contains the fuzzy membership functions for all stage durations $g_i$ as well as the cycle length $l$. Clearly, $x$ influences the traffic performance $y$. Let $t = t_E - t_S$ be defined as the set of bus travel time used for signal control observation. Using these bus probe data for signal optimization further makes the assumption that the input data $t$ varies as $y$ changes. The exact relationship between these variables is, however, difficult to define. Therefore, a global search algorithm, such as GA, offers a convenient solution with the disadvantage that convergence to the global optimum is not guaranteed.

Figure 2 The MOSCUE framework as in Schmöcker et al (2008) where ‘Sensor data’ are to be replaced by ‘bus probe data’ in this paper
In Schmöcker et al (2008) the basic framework, including the fuzzy logic controller and optimisation with GA, is described in detail and has been further applied with a case study of a road corridor in Central London. A corridor consisting of six junctions was modelled of which the first junction was optimised with the proposed framework. Results show that MOSCUE can reproduce performances achieved with the currently installed SCOOT system with the additional advantage of easy adaptability to new control strategies.

5. CASE STUDY

5.1 Description of the site

Figure 3 shows the approximately 1400m long section of the Truong Chinh Street from Tan Hai Road to Xuan Hong Road selected for the case study. The main road is an undivided four-lane street for through traffic in north-south direction connecting the city centre with suburbs. This corridor is a typical major urban road in central HCMC, served by 11 bus routes but dominated by private road users, in particular motorcycles. Field observations show that more than 95% of the vehicles were motorcycles while less than 5% were cars. The routes and headways of the bus services are shown in Table 1 below referring to the network and lettering of network entrance and exit points in Figure 3. The study section of the corridor intersects with seven roads out of which the first six (from left of Figure 3) are signal controlled. In this study, the control of the central three of them, marked and numbered I to III in Figure 3, are modeled to be controlled traffic responsively.

Table 1 Bus routes passing through the network and their service frequency

<table>
<thead>
<tr>
<th>Bus route (Route number)</th>
<th>Services per hour</th>
<th>Bus route (Route Number)</th>
<th>Services per hour</th>
<th>Bus route (Route Number)</th>
<th>Services per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>A ↔ I (13)</td>
<td>11~18</td>
<td>A ↔ I (94)</td>
<td>8</td>
<td>D ↔ G (52)</td>
<td>10</td>
</tr>
<tr>
<td>A ↔ I (48)</td>
<td>7~15</td>
<td>A ↔ E (41)</td>
<td>13~18</td>
<td>G ↔ L (23)</td>
<td>8</td>
</tr>
<tr>
<td>A ↔ I (65)</td>
<td>7</td>
<td>A ↔ E (64)</td>
<td>10~18</td>
<td>E → A (51)</td>
<td>10~15</td>
</tr>
<tr>
<td>A ↔ I (66)</td>
<td>6</td>
<td>A ↔ H (30)</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The geometry and the alignment of the roads in the model were obtained from the aerial map of Google Earth® with additional field measurements carried out to determine the road widths. Further, traffic surveys at both peak and non-peak hours were conducted to obtain motorcycle and car volumes for the modeled network. Note that trucks are banned from the city centre during daytime. Bus frequencies were taken from their schedules. Further, the fixed time traffic signal settings were recorded including the offset between the junctions. It should be noted that each signal group is operated with two stages without any all red between stage changes, so the conflicts between left-turning and straight-ahead traveling vehicles remain. The stages and stage durations of the three junctions under fixed time control which are changed to be fuzzy-controlled are shown in Figure 4.

To estimate the condition of this network, five performance indicators were measured, including, average travel time of bus passengers, average travel time of motorcycle users, average travel time of all passengers, maximum queue length in the main corridor and maximum queue length in the branch streets. Table 2 presents the key performance indicators and definitions of acceptability in for two example policies. Under policy 1, the decision maker for example accepts that an average travel time of bus passengers of less than 275 sec must be considered as fully acceptable. Under policy 2, the decision maker is not fully satisfied with such a result but aims to find signal settings that result in bus passenger’s travel times of less than 225. In the optimization, this will lead to a lower overall satisfaction as one of the four objectives is likely to be less satisfied as a result.

Table 2 Key performance indicators and definitions of acceptability in policies to be tested

<table>
<thead>
<tr>
<th>Key performance indicators</th>
<th>Policy 1: Balance</th>
<th>Policy 2: Prioritizing bus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full acceptable ((y^F))</td>
<td>Not acceptable ((y^o))</td>
</tr>
<tr>
<td>Obj1: Mean travel time of bus passengers</td>
<td>275</td>
<td>375</td>
</tr>
<tr>
<td>Obj2: Mean time of MC users</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>Obj3: Mean travel time of all travelers</td>
<td>250</td>
<td>375</td>
</tr>
<tr>
<td>Obj4: Maximum of queue on the corridor</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>Obj5: Maximum of queue on the branch streets</td>
<td>5</td>
<td>20</td>
</tr>
</tbody>
</table>
5.2 The Micro Simulation Model

VISSIM was chosen as the micro simulation software tool as it allows to model fuzzy controlled junctions, can be embedded in the MOSCUE framework and is known to be flexible enough to model two-wheelers, complicated bus routes and is able to analyze non-signalized and signalized intersections (Trueblood and Dale, 2003; Bared and Adara, 2005; Schroeder et al., 2006).

Most parameters of motorcycle behavior were calibrated using the data of Minh (2007). He recorded and analyzed the traffic in Hanoi where the condition and the behavior of drivers are quite similar to those of HCMC. Some additional parameters required in VISSIM such as minimum lateral distance, and average standstill distance were the results of our field observation and some remaining such as deceleration rates ($1\text{m/s}^2$ per distance) had to be assumed. For car and bus, in mixed traffic during peak time condition, the distribution of desired speeds of these four wheelers in the models is assumed to be similar to that of motorcycles, but with less variation. More information on the model set up as well as the traffic flows are provided in Van (2009).

The model was validated by comparing simulated travel times to field observations. Two probe motorcycles were used to measure the time to travel through the corridor before the peak hours. The measurements included the stop time caused by intersection signals. Totally, 10 measurements were taken with a mean of 273.6 sec ($\text{SD} = 1.9$ sec). The mean value generated by the model was 278.4s ($\text{SD} = 1.2$ sec) which is 1.8 % larger than the observed one. Based on this assessment, it is assumed that the model reflects the real traffic well.

Note however that the VISSIM model had difficulties simulating traffic flow under several congested situations such as often occurring during peak times. The gridlocks occurring frequently at junctions are normally solved by some co-operative behavior between drivers which the model could not simulate. To avoid unrealistic simulation outcomes due to mixed and especially high traffic conditions, this study used traffic data at non-peak hours instead of peak hour, as a preliminary step to test the operation of the extended MOSCUE framework.

All KPIs defined in the previous section could be observed from VISSIM. Travel time was measured for vehicles running straight, from one end to the other end of the corridor. The travel time of the passengers were then computed based on occupancies of each type of vehicles. The occupancy of bus, car and motorcycle were presumed to be 30, 1.4 and 1.2 respectively. Maximum queue lengths are defined as the maximum values of all queues at the three studied junctions on the main corridor and on the branch street. In the model, queuing was defined as having a speed of less than 1.5 km/h. The duration of the VISSIM simulation was limited to 2100s. The first 1000 sec were taken as warm-up period so that the measures of the KPIs were computed only from the 1000th onwards.

5.3. Implementation of GPS Control in VISSIM

In VISSIM, for offline optimization of the fuzzy control rules, it is also possible to measure the travel time of a type of vehicle between two sections using detectors based on first-in first-out rule. In this rule, once a bus enters the first section, the simulation second then will be stacked up in an array; and when a bus exits the second section, the travel time of that bus is calculated by subtracting the current simulation second by the first item in the storage array. Note that
this way of measuring travel time may be erroneous if the buses overtake another in between the two sections. However, the error would be acceptably small if the distance overtaken by another bus is small. In fact, within the areas near the stop line, traffic is usually high, and if there is no bus stop, it is expected that overtaking by far-distance may not occur.

5.4. Fuzzy Membership Optimization Based on Bus Probe Data

As the three junctions are adjacent to each other and do not differ much in traffic volumes, the same fuzzy logic rule base was used for all (Table 3). For each two-stage signalized junction, Stage 1, the green time for vehicles going straight on the corridor, is controlled by these fuzzy logic rules, whose membership function were to be optimized. The optimization was carried out based on two input parameters for each junction. One is the average travel time of the buses on the corridor and the other is the average travel time of the buses on the branch street. The bus travel times were measured over a distance of 50m upstream of the stop line. Taking this relatively short distance ensured that no bus stop was located in between the two measurement points disturbing the travel time measurements.

The input parameter to determine the cycle length is the average travel time of the buses on the main corridor through the three junctions, i.e. the average of the three inputs used for the three stage controls. For simplicity, the same cycle time for all junctions was assumed. (Figure 4 shows that in the original fixed time control the cycle times between the junctions slightly differ.) The fuzzy rule base for the cycle length control can be seen in Table 4. The rule defines that a longer average travel time of buses on the main corridor yields longer cycle time. This rule coincides with the rule to control the stage, that is, the green time for the main directions will be increased if it takes longer for buses to travel through the three junctions on the main corridor.

Although there are 11 bus lines passing through the network operating at frequencies of 5-15 min, there may be some cases that no bus passes a junction in a cycle time. This is especially in the branch streets, which are served by less bus routes (see Table 1). To overcome this problem, the stage durations and cycle length are updated only after every four cycles and the travel time of the buses observed during this time interval is averaged.

Table 3 Fuzzy rule base controlling the duration of the stage 1 of the three junctions

<table>
<thead>
<tr>
<th>Green time of SGI / SGII / SGIII \ Average travel time of buses through \ Junction I / II / III on branch streets</th>
<th>\ Short</th>
<th>\ Medium</th>
<th>\ Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average travel time of buses through junction I / II / III on main corridor</td>
<td><strong>Short</strong></td>
<td><strong>Medium</strong></td>
<td><strong>Medium</strong></td>
</tr>
<tr>
<td>\ Short</td>
<td>\ Medium</td>
<td>\ Medium</td>
<td>\ Short</td>
</tr>
<tr>
<td>\ Medium</td>
<td>\ High</td>
<td>\ Medium</td>
<td>\ Medium</td>
</tr>
<tr>
<td>\ Long</td>
<td>\ High</td>
<td>\ High</td>
<td>\ Medium</td>
</tr>
</tbody>
</table>

Table 4 Fuzzy rule base for controlling cycle length

<table>
<thead>
<tr>
<th>Average travel time of buses through junction I &amp; II &amp; III on the corridor</th>
<th><strong>Short</strong></th>
<th><strong>Medium</strong></th>
<th><strong>Long</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle length \ (h)</td>
<td>Short</td>
<td>Medium</td>
<td>Long</td>
</tr>
</tbody>
</table>

Based on the rules in above tables, there are 7 input and 4 output functions to be optimized. As each fuzzy rule consisted of three levels, short-medium-high, there are three membership function points to be optimized for each input function. For the output function an additional
fourth point determines the maximum stage duration or cycle length respectively. Thus in total, $7 	imes 3 + 4 	imes 4 = 37$ values have to optimized by GA. The definition of chromosomes and the GA settings follows the approach proposed in Schmöcker et al (2008).

6. RESULTS

From the GA optimization, the membership functions for the two policies are obtained. For brevity all membership functions are shown in the appendix. Interestingly both policies result in fairly similar membership functions giving some confidence in the stability of the results.

![Figure 5 Key performance indicators of the two policies](image)

Figure 5 presents the result of the five performance indicators for both policies and a comparison with the values obtained by simulating the currently used fixed time control. The graph shows the means and the variance as indicated by error bars. The variances are the result of retesting the signal control using 5 different random seeds which determine the starting time of the simulation. The optimization of the three stages and duration length led to an improvement of the performance, not only to buses, but also to motorcycles. For the “balanced” policy, improvements of around 5% in travel time of bus passengers and motorcycle users were achieved due to the application of the optimized fuzzy control rules. The maximum queue length in the corridor and in the branch streets were also reduced by 16 to 32%. For the “prioritizing bus” policy travel time of bus passengers could be reduced by more than 7 % while at the same time motorcycle users could also benefit from smoother movement through this corridor. However, the maximum queue length on the branch streets was found to increase by around 20% in this scenario.
Figure 6 Acceptability over the optimization process for policy 2

Figure 6 shows the improvement of the acceptability over the GA generations. The satisfaction increased fast within the first 10 generations. In subsequent generations, the fitness level increased gradually. After 73 generation, a solution was found with a satisfaction of 0.39 which could not be improved afterwards. The green and pink line refer to average and std deviation between the ten best chromosomes found. A lower std deviation and an average satisfaction closer to the maximum found indicates a higher robustness of the solution as the performance of the best solution can be matched by similar signal settings. Given the low deviation between results found and that no better solutions were found since generation 73 the optimization was terminated after 100 generations.

7. CONCLUSION

This study showed the feasibility of controlling a set of junctions in mixed traffic conditions such as prevailing in many South-East Asian countries dynamically with a fuzzy logic based controller. In particular it was shown, installation of detector loops is not required but input data reflecting the traffic condition of the network are solely obtained from bus travel time measurements. The case study of a corridor in Ho Chi Minh City showed that some key performance indicators of the study network were improved, though only slightly, as the result of applying traffic responsive control. The improvements are expected to increase if the number of probe observations could be further increased to more accurately reflect the traffic conditions. This could be achieved through an increase in bus frequency or through inclusion of other vehicles, such as taxis, into the probe fleet. The sensitivity of the controller to the probe vehicle density remains a topic for further research.

Further research should also confirm whether the improvements are larger in peak hour traffic compared to the non-peak modeled in this case study. This might be expected because during non-peak condition, the travel times of buses through the junction do not differ much between the main corridor and its branch streets. Thus, the fuzzy control inputs are similar across updated time intervals and the traffic control may not be as ‘dynamic’ as in congested situations. Modeling severely congested traffic congestion in mixed traffic conditions is however still a challenge for micro simulation models. In the case study presented here, only the observed travel times during off-peak hours could be validated with those simulated.
REFERENCES


Appendix A1 Optimized fuzzy membership functions for the “balanced” policy

Appendices

Input 1: Bus’s travel time Main-I (s)

Value of membership function
Low
Med
High

Input 2: Bus’s travel time Branch-I (s)

Value of membership function
Low
Med
High

Input 3: Bus’s travel time Main-II (s)

Value of membership function
Low
Med
High

Input 4: Bus’s travel time Branch-II (s)

Value of membership function
Low
Med
High

Input 5: Bus’s travel time Main-III (s)

Value of membership function
Low
Med
High

Input 6: Bus’s travel time Branch-III (s)

Value of membership function
Low
Med
High

Input 7: Average bus’s travel time through I, II & III (s)

Value of membership function
Low
Med
High

Output 1: Stage 1 duration of junction I (s)

Value of membership function
Low
Med
High

Output 2: Stage 1 duration of junction II (s)

Value of membership function
Low
Med
High

Output 3: Stage 1 duration of junction III (s)

Value of membership function
Low
Med
High

Output 4: Cycle length of junctions I, II & III (s)

Value of membership function
Low
Med
High
Appendix A2 Optimized fuzzy membership functions for the “prioritizing-bus” policy

![Optimized fuzzy membership functions for the “prioritizing-bus” policy](image-url)