Bus Prioritisation in Motorcycle Dependent Cities

M.Sc. Nguyen Van Nam
from Hanoi, Vietnam

TECHNISCHE UNIVERSITÄT DARMSTADT

Chair of Transport Planning and Traffic Engineering

Prof. Dr.-Ing. Manfred Boltze

A dissertation submitted in fulfilment of the requirements for the Degree of Doktor-Ingenieur (Dr.-Ing.) of the Department of Civil Engineering and Geodesy, Technische Universität Darmstadt

Supervisor: Prof. Dr.-Ing. Manfred Boltze
Co-supervisor: Assoc. Prof. Dr. Bhargab Maitra

Date of submission: 10. 04. 2013 Date of oral examination: 23. 05. 2013

D 17 Darmstadt 2013

Herausgeber:

Technische Universität Darmstadt
Fachgebiet Verkehrsplanung und Verkehrstechnik
Petersenstraße 30
64287 Darmstadt

www.tu-darmstadt.de/verkehr
fgvv@verkehr.tu-darmstadt.de

Schriftenreihe des Instituts für Verkehr
Fachgebiet Verkehrsplanung und Verkehrstechnik
Heft V 29

ISSN 1613-8317

Darmstadt 2013

Abstract

In many cities of developing countries, buses are the backbone of public transport. However, most of them are operating in mixed traffic conditions without priority measures and with a number of problems at bus stops, on travel ways, and at traffic signals. Illustrative examples for this situation are motorcycle dependent cities (MDCs) such as Hanoi and Ho Chi Minh City. A lack of bus prioritisation for many years is one of the main causes leading to the poor quality of bus services and the rapid growth of individual motorised traffic in these cities. Consequently, MDCs are facing critical transport problems in terms of traffic accidents, environmental pollution, traffic congestion, and economic loss.

To solve that problematic situation, this study presents an integrated approach for prioritising buses in MDCs. The important role of bus services and the necessity of bus prioritisation were justified at first. Then the principle approaches of bus prioritisation were consolidated based on the experience of developed countries. As a subsequent part, existing problems for buses at bus stops, on travel ways, and at traffic signals were determined, and the concept of bus prioritisation was introduced to MDCs. Thereafter, corresponding measures were developed and formulated to solve the mentioned problems. The fundamental effect of the most potential measures was estimated, based on the principles of traffic engineering. To identify the level of effects of promising measures, sensitivity analyses were conducted.

The location of on-line bus stops in mixed traffic conditions was identified to have noticeable influences on traffic flow quality of both buses and other vehicles as well as on capacities of intersection approaches involved. For this reason, a significant amount of vehicular delays can be saved and a considerable amount of capacity can be added if the bus stop location is properly selected. This study identified that the impact of a bus stop on capacity and traffic flow quality varies at different positions of the stop, and it is critical within certain ranges close to traffic signals. Outside those ranges, the impact reduces to modest or insignificant levels. Thereby, the determination of those ranges contributes to select a proper bus stop position with respect to the requirements of capacity and traffic flow quality at traffic signals. Based on the results of the sensitivity analysis, a position of bus stops with a distance further than 60 metres from the stop line (for near-side stops) or from the beginning of the downstream intersection (for far-side stops) is recommended for general traffic situation in MDCs.

Regarding priority measures for bus travel ways, it is concluded that most of the existing measures such as exclusive bus lanes, bus lanes shared with other modes, and queue jump lanes will be hardly applied to current roadways of MDCs if supportive measures (e.g. traffic rerouting and infrastructure measures) are not given. Thereby, a provision of additional options which enable to prioritise buses on their travel ways will be significant for these cities. From the practical essentials, this study developed two new measures including discontinuous bus lanes and partial dynamic bus lanes. On the one hand, these bus lanes will result in positive effects for buses; on the other hand, their side effects on general traffic will be kept at permissible levels.

The sensitivity analysis indicated that these lanes provided the following advantages under heavily loaded traffic conditions:

- About 40% of bus delay was reduced in the range of the intersection,
- Over 20% of total person delay was saved for the subject direction, and
- Delays and number of stops of other vehicles were even improved slightly.

Concerning measures for traffic signals, both signal priority and other related measures were proposed for MDCs. While green extension and early green were recommended for signal priority, the improvement of signal programs and control strategies was highly suggested as other important measures for traffic signals.

Essentially, the related aspects for bus prioritisation in MDCs were integrated into an application process. The basic steps of this process were established to provide a clear framework for an application of bus prioritisation. To facilitate an efficient implementation of bus prioritisation in these cities, detailed suggestions on the development of potential strategies were provided.

In the final part, important results were summarised and the effectiveness of bus prioritisation was affirmed. In addition, the significance of this study and recommendations for further studies were provided at last.

This study introduces comprehensive solutions to prioritise buses in the urban road network of MDCs. The results from this study can support the effective application of bus prioritisation in MDCs in the future.

Zusammenfassung

In vielen Städten der Entwicklungsländer sind Busse das Rückgrat des öffentlichen Personennahverkehrs. Aber die meisten dieser Busse fahren in Mischverkehrsbedingungen ohne Priorität und werden an Haltestellen, auf Fahrwegen, und an Lichtsignalanlagen mit einer Reihe von Problemen konfrontiert. Beispiele für Städte, in denen diese Situation existiert, sind von Motorrädern abhängige Städte (MDCs) wie Hanoi und Ho Chi Minh Stadt. Ein Mangel an Priorisierung von Bussen ist seit vielen Jahren eine der wichtigsten Ursachen für die schlechte Qualität des Busverkehrs und das rasante Wachstum des motorisierten Individualverkehrs in diesen Städten. Folglich stehen MDCs vor kritischen Verkehrsproblemen in Bezug auf Verkehrsunfälle, Umweltverschmutzung, Verkehrsüberlastung und wirtschaftliche Verluste.

Um diese problematische Situation zu lösen, stellt diese Arbeit einen integrierten Ansatz zur Priorisierung von Bussen in MDCs vor. Die wichtige Rolle des Busverkehrs und die Notwendigkeit zur Priorisierung von Bussen wurden zunächst begründet. Dann wurden die grundsätzlichen Ansätze der Priorisierung von Bussen basierend auf den Erfahrungen der entwickelten Länder konsolidiert. Als weiterer Teil wurden die vorherrschenden Probleme für Busse an den Haltestellen, auf Fahrwegen, und an Lichtsignalanlagen bestimmt, und das Konzept der Priorisierung von Bussen wurde in MDCs eingeführt. Danach wurden entsprechende Maßnahmen entwickelt und formuliert, um die genannten Probleme zu lösen. Die grundsätzliche Wirkung der meisten potenziellen Maßnahmen wurde auf der Grundlage der Prinzipien der Verkehrstechnik abgeschätzt. Um das Niveau der Auswirkungen von vielversprechenden Maßnahmen zu identifizieren, wurden Sensitivitätsanalysen durchgeführt.

Die Haltestellenlage innerhalb des Fahrstreifens am Fahrbahnrand in Mischverkehrsbedingungen wurde als starker Einflussfaktor identifiziert. Dies beeinflusst die Verkehrsflussqualität von Bussen und anderen Fahrzeugen sowie die Kapazität der Zufahrt zu benachbarten Knotenpunkten. Aus diesem Grund kann eine erhebliche Menge an Verzögerungen für Fahrzeuge vermieden und die Kapazität beträchtlich erweitert werden, wenn die Lage der Bushaltestelle richtig gewählt ist. Diese Studie hat festgestellt, dass die Auswirkungen einer Bushaltestelle auf die Kapazität und Qualität des Verkehrsflusses je nach Position der Haltestelle variiert. Dieser Einfluss ist kritisch innerhalb bestimmter Bereiche nahe Lichtsignalanlagen. Außerhalb dieser Bereiche reduzieren sich die Auswirkungen auf ein bescheidenes oder unbedeutendes Maß. Die Bestimmung dieser Bereiche leistet deshalb einen erheblichen Beitrag, eine ordnungsgemäße Position der Bushaltestelle in Bezug auf die Anforderungen der Kapazität und Qualität des Verkehrsflusses an Lichtsignalanlagen auszuwählen. Basierend auf den Ergebnissen der Sensitivitätsanalyse wird eine Position der Haltestellen mit einem Abstand weiter als 60 Meter von der Haltelinie (für Haltestellen vor Knotenpunkten) oder vom Beginn des abfließenden Stroms eines Knotenpunktes (für Haltestellen nach Knotenpunkten) für allgemeine Verkehrssituationen in MDCs empfohlen.

Bezüglich der prioritären Maßnahmen für Fahrwege wurde der Schluss gezogen, dass die meisten der bestehenden Maßnahmen wie exklusive Busspuren, mit anderen Verkehrsträgern geteilte Busspuren und Vorrang-Fahrspuren kaum in den Verkehrswegen von MDCs

angewendet werden, wenn unterstützende Maßnahmen (z.B. Verkehrsumleitung und Infrastrukturmaßnahmen) nicht gegeben sind. Dabei wird die Bereitstellung zusätzlicher Optionen, welche eine Priorisierung von Bussen ermöglichen, für diese Städte von besonderer Bedeutung sein. Aufbauend auf den praktischen Grundlagen wurden innerhalb dieser Studie zwei neue Maßnahmen einschließlich diskontinuierlicher Busspuren und teilweise dynamischer Busspuren entwickelt. Diese neuen Busspuren werden positive Effekte auf Busse haben, wobei ihre Nebenwirkungen auf den allgemeinen Verkehr auf einem zulässigen Niveau gehalten werden.

Die Sensitivitätsanalyse zeigte, dass diese Spuren bei stark belasteten Verkehrsbedingungen die folgenden Vorteile bieten:

- die Verzögerung der Busse wurde im Bereich des Knotenpunktes um etwa 40% reduziert,
- die Gesamtverzögerung für Personen wurde in Fahrtrichtung um über 20% reduziert und
- die Verzögerungen und Anzahl der Halte anderer Fahrzeuge wurde sogar leicht verbessert.

Bei Maßnahmen im Bereich der Signalsteuerung wurden sowohl Priorisierungen bei der Signalbeeinflussung als auch andere Maßnahmen für MDCs vorgeschlagen. Während die Anpassung der Freigabezeiten für die Signalbeeinflussung vorgeschlagen wurde, wurden Verbesserungen der Signalprogramme und Steuerungsverfahren genau wie andere wichtige Maßnahmen für Lichtsignalanlagen dringend empfohlen.

Im Wesentlichen wurden die Aspekte für die Priorisierung von Bussen in MDCs in einen Anwendungsprozess integriert. Die grundlegenden Schritte dieses Prozesses wurden dargestellt, um einen klaren Rahmen für eine Anwendung einer Bus-Priorisierung zur Verfügung zu stellen. Um eine effiziente Implementierung der Priorisierung von Bussen zu erleichtern, wurden detaillierte Vorschläge zur Entwicklung möglicher Strategien unterbreitet.

Im letzten Teil wurden wichtige Ergebnisse zusammengefasst und die Wirksamkeit der Priorisierung von Bussen wurde bestätigt. Darüber hinaus wurden die Bedeutung dieser Studie aufgezeigt und Empfehlungen für weitere Studien gegeben.

Diese Studie stellt umfassende Lösungen zur Priorisierung von Bussen im städtischen Straßennetz von MDCs zur Verfügung. Die Ergebnisse dieser Studie werden die wirksame Umsetzung der Priorisierung von Bussen in MDCs in Zukunft unterstützen.

Acknowledgement

In order to have a chance to study in Germany, my first thanks are extended to Vietnamese Government and Ministry of Education and Training (MOET) for supporting me the main scholarship. In addition, I would like to express my thanks to the German Foreign Academic Exchange Service (DAAD) for the cooperation scholarship (MOET/DAAD).

To the people who contributed directly to the completion of my dissertation, foremost, I would like to express my deepest gratitude to my supervisor, Prof. Dr.-Ing. Manfred Boltze. The goal of this research is only achieved with his valuable guidance and extensive advice. His dedicated supervision and precious supports gave me an inspiring endeavour to accomplish this dissertation at my best.

The second person who contributed significantly to my research work is my co-supervisor, Prof. Bhargab Maitra. I am extremely grateful for his committed and enthusiastic supervision. A number of improvements in this dissertation were made from his valuable comments and feedback.

My special thanks are for Prof. Dr.-Ing. Dr.-Ing. E.h. Hans-Georg Retzko for his continuous encouragement and valuable advice during my studying time. His extensive knowledge of transport planning and traffic engineering is a perfect example for me to pursue.

I do wish to thank Prof. Tran Dac Su, M.A. Ulla Nothnagel, Dr. Thai Ha Phi, who encouraged and gave me favourable conditions to study at Darmstadt University of Technology.

My sincere thanks are extended to my colleagues at Section Transport Planning and Traffic Engineering. Dr.-Ing. Wolfgang Kittler and Dr.-Ing. Do Quoc Cuong helped me a lot during my first months at Darmstadt University of Technology. A number of useful comments and suggestions for my research were provided by Dr.-Ing. Sven Kohoutek, Dr.-Ing. Nadine Roth, Dr.-Ing. Axel Wolfermann, and Dr.-Ing. Heiko Jentsch at our seminars. The kind and continuous support from Anja T. Zopf, Johanna Nagy-Blohberger, and Nicole v. Stetten was very significant for me.

I wish to acknowledge the helpful and enthusiastic support from Leif Fornauf, the valuable assistance and deep understanding from Philip Krüger, the friendly care and significant proofreading from Frederik Rühl, Stefan Groer, and Moritz von Mörner, and the warm friendship and kind support from Jessica Balluff, Karin Molitor, Oytun Arslan, Ole Ottemöller, Andreas Balster during my staying time in Germany.

My research was also received many valuable comments at the International Doctoral Seminar (IDS) in Transport Planning and Traffic Engineering. For this reason, I would like to express my gratitude to Prof. Hideki Nakamura, Prof. Hanno Friedrich, and Prof. Keping Li.

My thanks are extended to the members of Vietnamese-German Transport Research Centre (VGTRC), particularly Dr.-Ing. Khuat Viet Hung, Dr. Chu Cong Minh, and Mrs. An Minh Ngoc for providing me useful suggestions and necessary data. I also would like to thank Ho Chi Minh

City Department of Transport for supporting transport data, and PTV Planung Transport Verkehr AG for supporting the micro-simulation VISSIM 5.20.

For the people who have a significant influence on my academic career and encourage me to study in Germany, I would like to express my great gratitude to Dr. Vu Duc Sy, Prof. Pham Huy Khang, Prof. Bui Xuan Cay, Prof. Tran Tuan Hiep, Prof. Nguyen Xuan Dao, Prof. Nguyen Sy Ngoc, Prof. Nguyen Quang Toan, M.Sc. Vu Dinh Hien, and Dr. La Van Cham at University of Transport and Communications.

For my beloved family, I owe a debt of gratitude to my parents, Dr. Nguyen Van Viet, Mrs. Bui Thi Quy, and my parents-in-law, Prof. Vu Huu Hai, Mrs. Le Thu Huong. Their continuous and unconditional support for my academic career has inspired me to complete this dissertation. During this time, my wholehearted thanks go to my devoted wife, Vu Phuong Le, who has raised my lovely baby, Nguyen Bao An, during my studying time in Germany. More than ever, I have a strong wish to stay beside my wife and my baby forever.

Table of Contents

1 Introduction

1.1 Research Motivation

Buses are playing an increasingly important role in terms of mobility, safety, efficiency and environmental protection in urban areas. They are considered as an indispensable transport mode in many countries around the world. In fact, they are contributing an essential part to the sustainable transport systems of the most liveable cities.

For this reason, buses are being treated as priority vehicles and provided with a number of priority measures on urban roadways of developed countries. Basically, these measures are classified into three main groups, including signal priority measures, travel way measures, and bus stop measures. These measures aim at eliminating or reducing external disturbances at traffic signals, on travel ways, and at bus stops. The experience from industrialised cities shows that a proper application of bus priority measures will contribute to improve speed, travel time, punctuality, and reliability of buses, and therefore it helps to enhance the quality and attractiveness of bus services [e.g. FGSV (1993); FGSV (1999); FGSV (2003); UITP (2009)].

In motorcycle dependent cities (MDCs) such as Hanoi, Ho Chi Minh City, and Bangkok, however, the operation of bus services is affected adversely by mixed traffic conditions and traffic congestion [e.g. JICA and HPC (2007); JICA, MOT et al (2004); World Bank (2007)]. Therefore, the quality of bus services in these cities remains at low levels. The main reason for this situation is a lack of priority considerations for buses on urban roadways of MDCs for many years. In consequence of a low quality of public transport, MDCs are suffering a rapid increase in usage of individual motorised vehicles in conjunction with a number of problems in terms of traffic accidents, traffic congestion, environmental pollution, and economic loss. Hence, existing problems of urban transport in these cities cannot be solved pertinently and comprehensively if buses are not promoted sufficiently by an application of bus prioritisation.

There could be several factors for a belated application of bus prioritisation to MDCs, but one of the most reliable factors is a lack of rigorous studies on this topic under specific conditions of MDCs. These conditions including roadway conditions, traffic conditions (e.g. traffic flow, traffic loads, bus volumes), control conditions, etc. can be much different compared to those of industrialised cities, where most priority measures for buses have been originally developed and implemented. Therefore, the suitability and effect of each measure can be largely dissimilar under the conditions of MDCs. Besides, other different measures might be developed for satisfying the exclusive condition of these cities. All of these issues are necessary to be examined before an application of bus prioritisation in MDCs.

Thereby, the research on bus prioritisation in MDCs is essentially demanded to fulfil the practical requirements of these cities. These requirements motivate this study to identify proper solutions and to assess their effects for bus services in mixed traffic conditions of MDCs. When the effectiveness of bus prioritisation is revealed, it will help to stimulate an application of bus prioritisation, to promote the development of bus services, and to solve at least partly the rising traffic problems in these cities.

1.2 Research Questions

The aims of this research focus on prioritising buses under mixed traffic conditions of MDCs. To clarify these aims, a number of research questions were posed at the beginning of this work. These questions were fundamentally formulated on the basis of the motivation and essential requirements of this study. They are listed in sequence as follows:

Research question 1:

Why is bus prioritisation essential for MDCs?

Research question 2:

What are the approaches to bus prioritisation in developed countries?

Research question 3:

How is the situation of urban transport in MDCs?

Research question 4:

What are the problems for buses on urban roadways of MDCs?

Research question 5:

What measures are needed to solve the problems for buses in MDCs?

Research question 6:

What is the effect of bus prioritisation measures?

Research question 7:

How can individual aspects of bus prioritisation be integrated into an application process?

Research question 8:

What is the effectiveness of bus prioritisation?

1.3 Aims of the Study

In order to satisfy the research motivation and solve the research questions, the main components of this study aim at

1. Pointing out the role of bus services in urban transport systems of developing countries and clarifying the necessity of bus prioritisation for MDCs.
2. Consolidating the research on bus prioritisation from developed countries.
3. Delineating the existing problems of urban transport in MDCs.
4. Identifying problems for buses at bus stops, on travel ways, and at traffic signals in mixed traffic conditions of MDCs.
5. Developing and formulating measures to prioritise buses at bus stops, on travel ways, and at traffic signals.

6. Examining the effect of bus prioritisation measures and proposing measures for the condition of MDCs.
7. Formulating an application process and strategies of bus prioritisation for MDCs.
8. Clarifying the effectiveness of bus prioritisation.

When all of these aims are reached, the research work will provide useful recommendations on the design of individual measures as well as entire strategies for prioritising buses in urban roadways of MDCs. More significantly, this study can be an important factor for promoting a widespread application of bus prioritisation to these cities in the future.

1.4 Scope and Delimitations

Bus prioritisation is a broad research topic which requires great efforts of traffic engineers from all over the world. Due to the limited time frame, this study focuses primarily on prioritising conventional buses on urban roadways of MDCs such as Hanoi and Ho Chi Minh City. Specific conditions of these cities are highlighted to concentrate on the predefined aims, including roadway conditions (e.g. constrained road space, limited condition for roadway expansion), traffic conditions (incl. mixed traffic flow dominated by motorcycles, high traffic loads in the road network, high bus volumes operating in mixed traffic flow, etc.), control conditions, and other conditions as well.

In addition, measures for prioritising buses are oriented to deal with external disturbances occurring at bus stops, on travel ways, and at traffic signals under mixed traffic conditions. Regarding measures for bus travel ways, the most potential measures will be examined thoroughly. However, unfavourable measures will not be studied in detail. Similarly, related to signal priority measures, an in-depth study on adaptive priority and other more sophisticated measures will not be included because most of the prevailing conditions in MDCs have not facilitated them.

1.5 Methodology and Outline

The methodology of this study is based on German transport planning process (see Figure 1). Thereby, the entire process of this research work is comprised of four major steps as follows:

- Step 1—*Pre-orientation*: To highlight the significance and necessity of bus prioritisation for MDCs.
- Step 2—*Problem Analysis*: To consolidate the experience of bus prioritisation from industrialised cities and figure out the inherent problems for buses in mixed traffic conditions of MDCs.
- Step 3—*Measure Investigation*: To develop measures and assess their effects as well as to formulate a process and strategies for an application of bus prioritisation.
- Step 4—*Conclusions and Recommendations*: To condense the significant result of this study and to make recommendations for further studies.

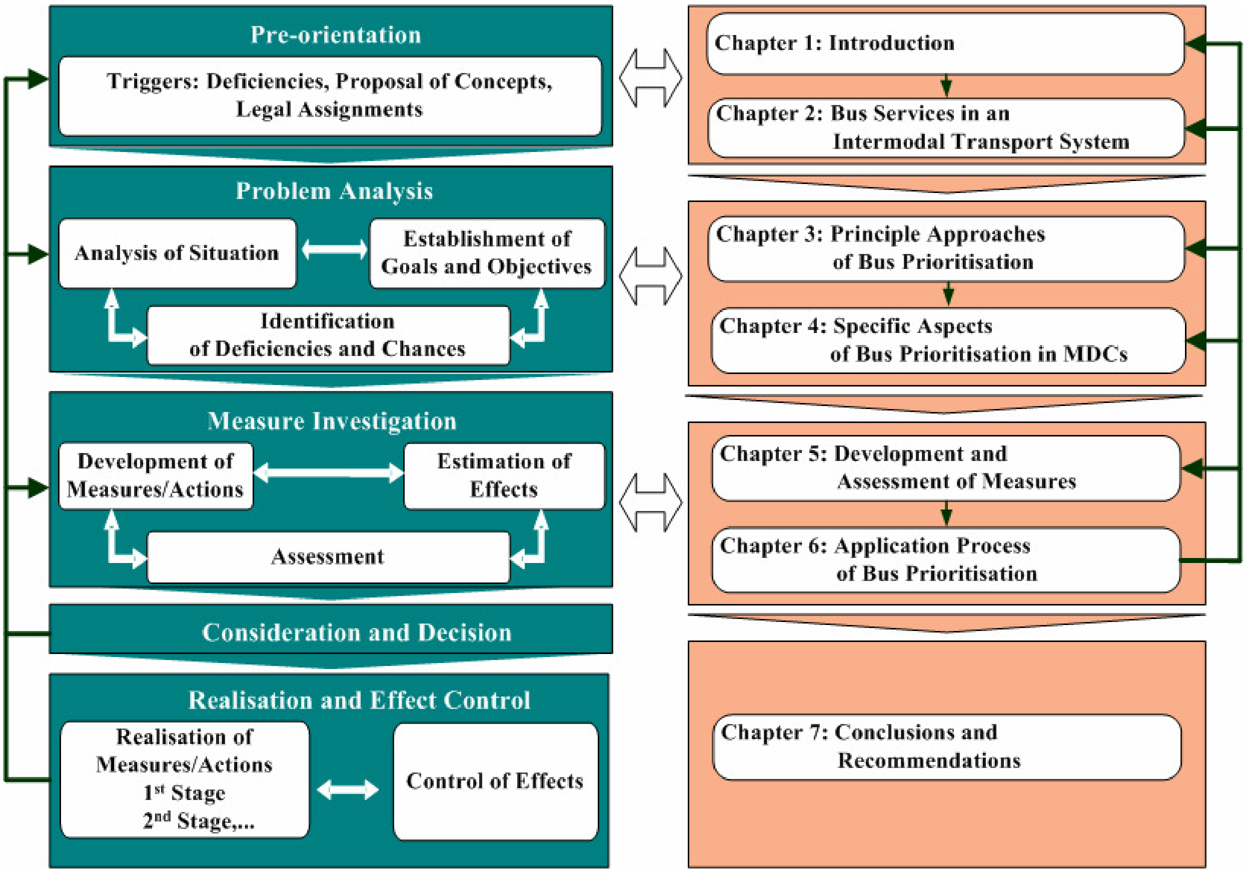

Figure 1: Methodology and structure of the dissertation
[Source of German transport planning process: FGSV (2001b)]

The main text of this dissertation is allocated to seven chapters. This introductory chapter has presented the principal motivation, research questions, and aims of this study. Then the scope and delimitations as well as the methodological approach have been established to direct the research work.

Chapter 2 clarifies the role of bus services in urban areas of developed countries. On the basis of that experience, the role of bus services in MDCs is identified. Subsequently, the low quality of bus services in MDCs is signified in order to show that it is not relevant to the role of bus services in the urban transport system. For this reason, the necessity of bus prioritisation is emphasised for MDCs.

The literature review on bus prioritisation is consolidated in **Chapter 3**. Related measures for prioritising buses in urban roadways are categorised into three principle approaches, including measures for bus stops, travel ways, and traffic signals. The attribute of individual measures is examined in order to acquire their advantageous and disadvantageous aspects. Besides, some discussions about the suitability of measures in the general situation of MDCs are made.

Chapter 4 provides an analysis of urban transport situation and the identification of problems for buses in MDCs. It begins with a clear delineation of the urban transport situation which comprises a number of conflicting problems. Then the problems for buses in mixed traffic conditions are identified by scrutinising their causative factors which are occurring at bus stops, on travel ways, and at traffic signals. To deal with these problems, the concept of bus prioritisation is proposed for MDCs as a key solution to improve the quality of bus services. Then the objective and benefit of bus prioritisation are determined. Afterwards, the level of service for buses and assessment parameters for bus prioritisation are provided.

In order to deal with the arising problems, measures for prioritising buses in mixed traffic conditions are developed and assessed in **Chapter 5**. The basic principle for priority measures is that they must result in positive effects for buses at stops, on travel ways, and at traffic signals, while their side impacts on other vehicles are deliberately kept at permissible levels. For this purpose, the effect and suitability of measures under the condition of MDCs are identified in this chapter.

Chapter 6 unifies individual parts and related issues of this research work in an integrated process. Following this process, detailed suggestions on the development of bus prioritisation strategies are provided.

The conclusion is drawn in **Chapter 7**, in which important results are summarised and significant findings are highlighted. Thereafter, the effectiveness of bus prioritisation is stated. Moreover, some suggestions are made for further studies in connection with an expansion of this topic as well as other potential research directions for dealing with traffic problems in MDCs.

2 Bus Services in an Intermodal Transport System

2.1 History of Bus Services[1]

The operation of horse-drawn traction vehicles for passenger transport in urban areas was considered as an introduction of bus services (see Fig. 2a). This type of vehicles was called "Omnibus". It was a long box on wheels, which could be distinguished from a stagecoach by its higher passenger capacity. Horse-drawn omnibuses operated in some areas around London as early as 1798, but they were considered to appear first in France because of two reasons: (i) they were first used in inner-city areas in France, and (ii) they were generally known by the name "Omnibus" there. For those reasons, bus services were claimed to occur first in Nantes (1826). Soon after that, they appeared in other cities of France, including Bordeaux (1827) and Paris (1828). In Great Britain, bus services were introduced in London in 1829. In the United States, they appeared in New York City in 1827. In Germany, they came up somewhat later than in other parts of Europe, for example, in Berlin (1837), Dresden (1838), Hanover (1852), Leipzig (1860), and Munich (1861).

Thanks to the Industrial Revolution, the successful application of internal combustion engine (ICE) to conventional vehicles provided the technological basis for ICE-powered buses called motorbuses (see Fig. 2b). As a result, motorbuses were introduced in Great Britain (1899), Germany (1903), the United States (1905), and other developed countries.

a. Horse-drawn omnibuses in Paris

b. Motorbus in Hamburg (the early 1950s)

Figure 2: Horse-drawn omnibuses and motorbus
[Retrieved from Vuchic (1981)]

In cities of developing countries, basically, bus services occurred much later due to their stage of development. For instance, they started operating in Hanoi as commuter services across the Red river in the 1920s.[2] In Kuala Lumpur, Jakarta, and Surabaya, the small 7-seater motor buses, called "mosquito buses", were recorded to be used for bus services by the 1930s [Barter (1999)].

1 The data of this section were mainly retrieved from Vuchic (1981).
2 The information was retrieved from the website: http://hanoimoi.com.vn/.

Since then, buses have been improved substantially in many aspects, such as suspension, capacity, body design (e.g. large windows, wide doors, and low floor), emissions, etc. At the present, bus services are playing a crucial role of public transport in many cities around the world.

2.2 Modernisation of Bus Services

2.2.1 Conventional Bus Services

Nowadays, bus services are not only represented by modern vehicles but also by a complex and integrated system. According to the Association of German Transport Companies (VDV), this system includes many components from the complete hardware range (vehicles, routes, stops, control equipment, regulating installations) over the software range (course of operation, timetables, duty rosters, passenger information, fare and tariff frames) to special actions that improve the attractiveness of services (e.g. marketing, public relations).

In order to modernise bus services, telematics[3] and other advanced technologies are widely applied to bus services in developed countries (see Fig. 3).

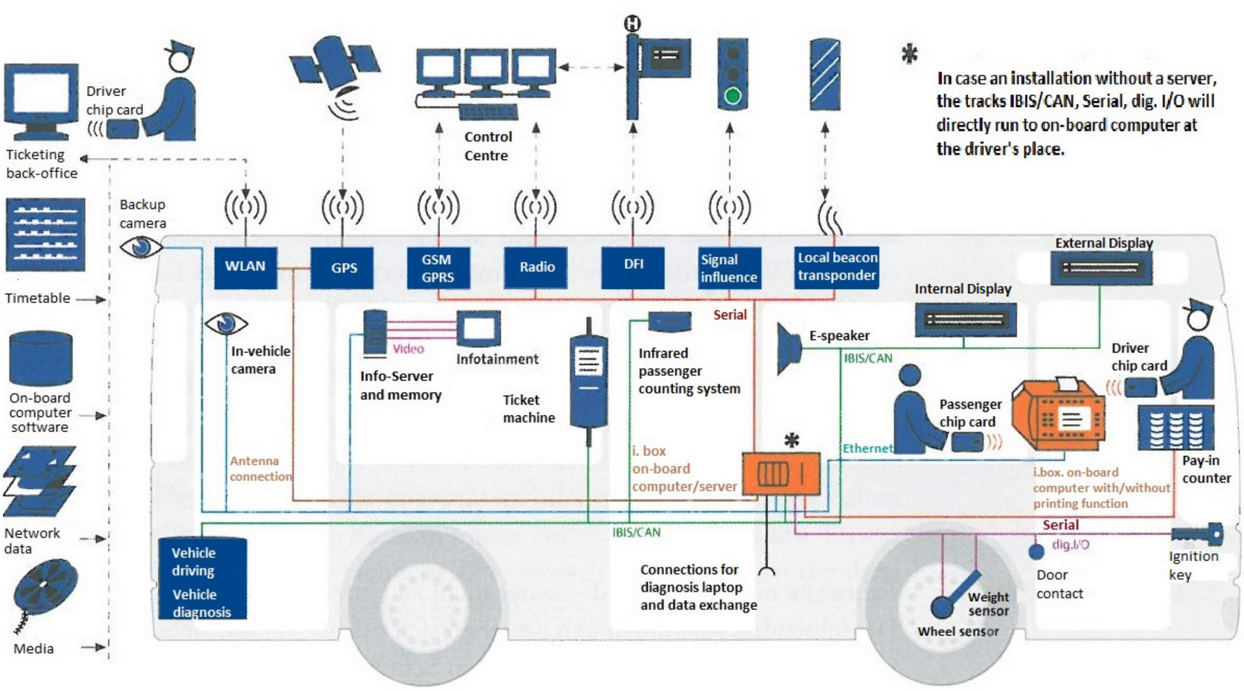

Figure 3: Application of advanced technologies to bus services[4]
[Source: translated from Scholz (2012)]

[3] Telematics is the integrated use of telecommunications and informatics.

[4] WLAN: Wireless local area network; GPS: Global Positioning System; GSM: Global System for Mobile Communications; GPRS: General packet radio service; DFI: Dynamic passenger information; IBIS: Integrated on-board information system; CAN: Controller area network; dig. I/O: Digital input/output

The integration of those technologies is represented by the Intermodal Transport Control System (ITCS). It has been applied successfully to public transport since the early 1970s in Germany [BMVBW & VDV (2001)].

According to Boltze (2007), ITCS is used as a network-wide computerised control system which takes over many important tasks of bus services automatically and regularly. The main components of ITCS consist of

- *Operation and data processing systems in buses*, providing information to drivers and control centre, transferring data to passenger information systems;
- *Passenger information systems*, providing information in vehicles, at bus stops, and via publicly accessible media;
- *Communication systems*, communicating between buses and control centre;
- *Systems to control external devices*, requesting signal priority;
- *Positioning systems*, determining the real-time position of operating buses;
- *Systems for disposition*, comparing between scheduled and actual operations, planning personnel and vehicle use, guaranteeing connections;
- *Systems for data collection*; and
- *Systems for fare collection*.

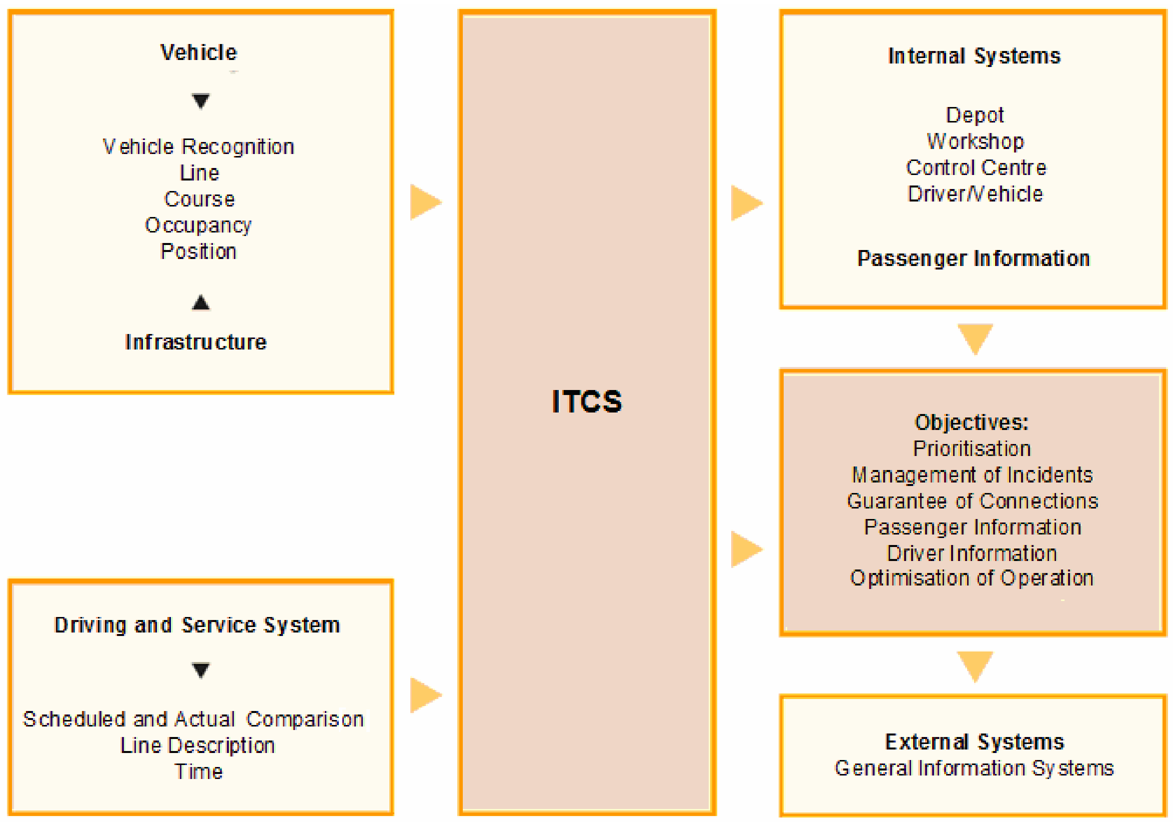

Figure 4: Data flow and objectives of ITCS
[Source: translated from Boltze, Wolfermann, Schäfer (2006)]

Figure 4 presents the data flow and objectives of ITCS. Basically, the main tasks of this control system can be categorised into three stages of the operation as follows:

- Before the operation: planning of resources, development of timetables and passenger information.
- During the operation: operational process, passenger information, and management of incidents.
- After the operation: maintenance, workshop, vehicle supply, data processing, and quality management.

Significantly, an application of ITCS to bus services enables public transport sectors to achieve the following benefits [BMVBW & VDV (2001)]:

- Providing punctual and reliable services,
- Minimising external disruptive influences (e.g. obstructions, congestion, temporary construction sites),
- Reducing the deviation of scheduled operations,
- Connecting in real time with control centre,
- Influencing traffic signals for priority,
- Providing dynamic passenger information,
- Monitoring and guaranteeing connections,
- Reducing both late and early arrivals, ensuring more uniform vehicle sequences,
- Ensuring passenger-friendly services (such as punctuality, real-time information, and reliable ticket machines),
- Supporting drivers the observation of on-time running, and
- Easing pressures for both staffs and drivers.

In addition to those technologies, many strategies have been implemented for promoting buses in urban areas, such as provision of bus lanes, implementation of signal priority, establishment of public transport zones, promulgation of right-of-way rules, etc.

In Germany, for instance, priority measures for public transport have been applied in order to improve its attractiveness since the middle 1960s [VDV (2001)]. According to German Road and Transport Research Association [FGSV (1999)], five groups of measures are provided to prioritise buses, including operational measures, measures for bus stops, measures for travel ways, measures for non-signalised intersections, and measures for signalised intersections. The aims of these measures are to (1) improve bus operating speed, (2) improve service punctuality and regularity, (3) enhance travelling comfort, (4) improve service accessibility, and (5) increase service efficiency. By implementing these measures, the quality and attractiveness of bus services will be improved substantially.

As a result of the modernisation of bus services in cities of developed countries, buses are operating with a high quality of service as shown in Figure 5.

Figure 5: Examples of bus services in Germany (2012)

2.2.2 Bus Rapid Transit

Another modernisation of buses besides the conventional services is Bus Rapid Transit (BRT). BRT is considered as a flexible and rubber-tired mass transit that combines all of the principle components (incl. segregated busways, high quality stations, special vehicles, operations and services, and required amenities) in an integrated system [Transportation Research Board (2003a)]. That system ensures to improve speed, reliability, and identity of mass transit based on buses. (See Fig. 6)

Figure 6: Bus Rapid Transit system, an example of TransMilenio BRT, Bogotá (Colombia)
[Retrieved from the Institute for Transportation & Development Policy (2007)]

According to the Institute for Transportation & Development Policy (2007), BRT systems can be distinguished from the conventional bus services by their superior systems and services, for instance, segregated right-of-way infrastructure, rapid and frequent operations, special marketing and customer services, etc. Compared to other mass transit modes, BRT systems have the advantage of lower investment costs. From the practical experience, a BRT system normally costs about 4 to 20 times less than a tram or light rail transit system, and about 10 to 100 times less than a metro system. Additionally, this system can also provide a high capacity. For example, a capacity of approximately 45,000 passengers per hour per direction was recorded in Bogotá's TransMilenio BRT system. For a standard BRT system without passing lanes, a capacity of 13,000 passengers per hour per direction can be achieved. Therefore, BRT systems have been implemented in many cities around the world, such as Bogotá (Colombia), Pereira (Colombia), Curitiba (Brazil), Guayaquil (Ecuador), Ottawa (Canada), Boston (USA), Jakarta (Indonesia), Taipei (Taiwan), Beijing (China), Seoul (South Korea), Brisbane (Australia), and Rouen (France).

2.3 The Role of Bus Services

2.3.1 Developed Countries

In Germany, according to the Passenger Transport Law (Personenbeförderungsgesetz, PBefG as of 22 November 2011), buses are used for both regional transport (in German: Öffentlicher Personennahverkehr) and long distance transport. The regional bus services are generally accessible for all people in order to satisfy travel demand in urban, suburban, and regional areas. In most cases, these services are distinguished from the long distance ones by their operational range ($\leq$ 50 km), or their route travel time ($\leq$ 1 hour).

According to German Road and Transport Research Association [FGSV (1990)], bus services are used as an indispensable public transport mode in urban areas. They have a series of significant roles consisting of the following:

- *To bring equal opportunities of mobility for all people*. Those include the people who do not have the ability to drive (e.g. too old, too young, or disabled), or who do not have enough financial support for a private vehicle.
- *To improve living conditions, traffic conditions, and citizens' mobility in urban areas* (such as residential areas, shopping centres, and service centres).
- *To improve quality of urban environment.* This role becomes more important in consciousness of citizens.
- *To reduce exhaust emissions.* Since considerable proportion of emissions comes from private motorised vehicles, the use of public transport will contribute to minimise those emissions for urban areas. In Hamburg, estimations indicate that 4,500 tonnes of traffic emissions can be reduced per year if 20% of car drivers shift from the use of their own vehicles to the use of public transport.

- *To reduce noise emissions.* In urban areas, for a same transport capacity of 1000 persons per hour, the noise level emitted by city buses is smaller than that emitted by private cars: 53 dB(A) compared to 55 dB(A) [Bayerisches Landesamt für Umwelt (2007)].
- *To minimise accident risks.* The accident risk regarding fatality and injury can be reduced by using buses instead of individual motorised vehicles. According to German statistics, travelling by buses can be 17 times safer than driving by cars: the average rate of fatality per billion person-km was 0.17 for buses, compared to 2.93 for private cars between the years 2005 and 2009 [Vorndran (2010)].
- *To save energy consumption.* With a same transport distance, the average energy consumption for carrying one person by the bus is about two times less than by the private car [850 kJ/person-km compared to 1800 kJ/person-km][5].
- *To save road space required for passenger transport.*

The following figure shows the designation of regional bus services in the passenger transport system in Germany.

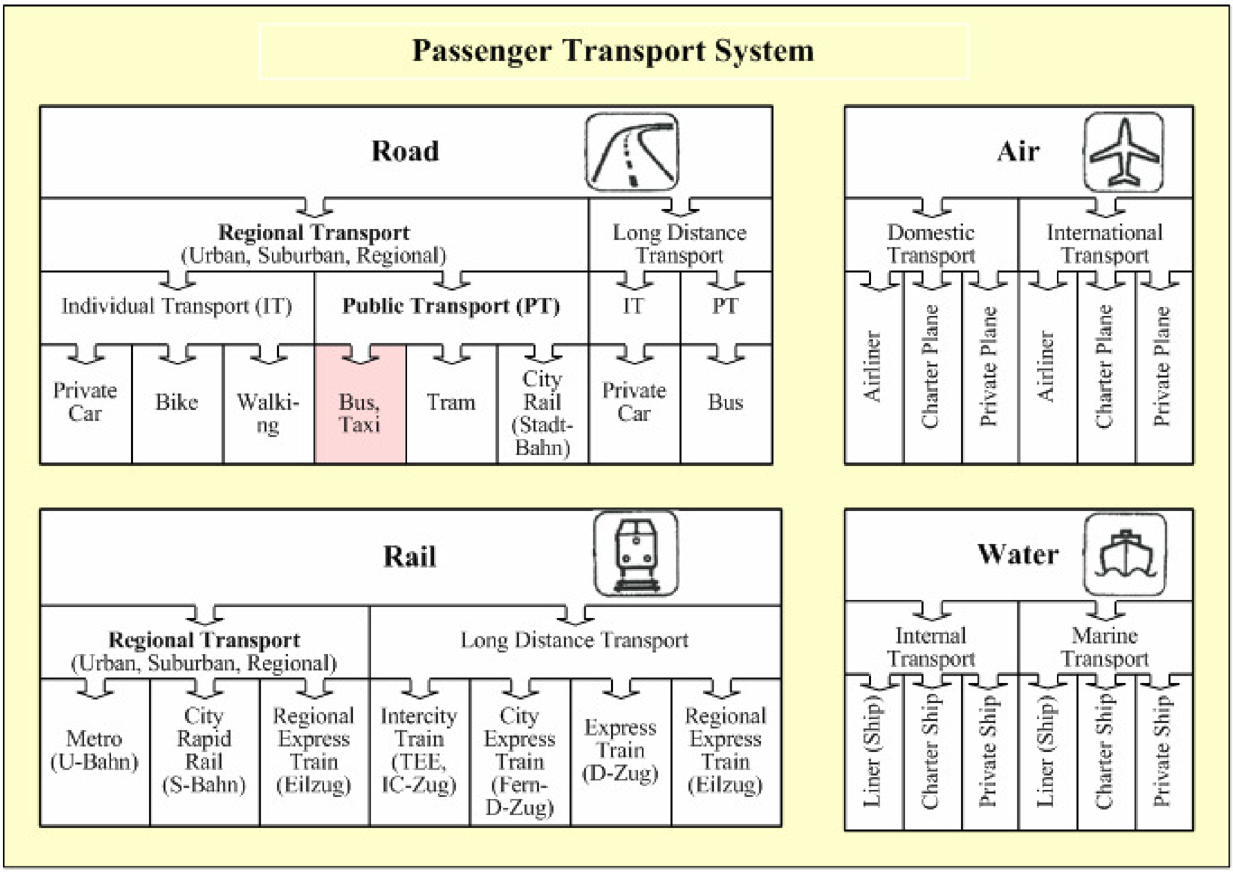

Figure 7: Passenger transport system in Germany
[Source: translated from FGSV (1986a)]

5 The data were retrieved from the website: http://www.thema-energie.de/. (Accessed, March 2013)

Due to the significant roles of buses, according to VDV (1999), the term of "Bus" was replaced by the concept "Bus Transport System" about 40 years ago. The principle idea for this concept is that buses should be upgraded to become as one of the most important modes of urban passenger transport. Therefore, bus transport systems have been modernised and prioritised adequately.

As a result, in the year 2012, bus transport systems with passenger-friendly and environment-friendly services contributed with about 48% of public transport's share. During that year, they served 5.33 billion passengers and transported 35.7 billion passenger-km. [Statistisches Bundesamt (2013)]

In North America, according to Transportation Research Board (2000), bus services play two major roles:

- The first role is to accommodate mode choice of road users whether they use their own automobiles or not. By using bus services, they can avoid confronting traffic congestion during peak periods. Estimations show that transit services help to reduce the growth of more than 4.36 billion person-hours lost due to urban congestion annually in the United States. Therefore, they are essential to ensure mobility, particularly in the central business districts (CBD) of large cities. This role becomes more significant for densely populated areas in conjunction with costly and limited parking provision.
- The second role is to provide basic mobility for the people who are unable to drive (e.g. too young, too old, physically or mentally disabled), and for the people who do not or cannot have either a private car or a driving license.

Nowadays, bus services are the most common form of public transport in the United States. In 2009, for instance, there were totally about 842,000 registered buses, which provided 14.4 billion vehicle-miles of travel. In U.S. urbanised areas, bus services contributed with 53% of the total transit ridership, and served about 10 billion passenger trips during that year. [U.S. Census Bureau (2012)]

2.3.2 Developing Countries

In many motorcycle dependent cities (MDCs) of developing countries, bus services are operating as the backbone of public transport. For instance, they have operated as a major mode of urban public transport in Hanoi and Ho Chi Minh City for several decades. In comparison with industrialised cities, bus services in MDCs have to undertake the heavier tasks because of insufficient transport infrastructure for other public transport modes (such as urban rail, tram, and metro). Therefore, six major roles are identified for bus services in MDCs, as follows:

1. *To provide equal mobility for all people*, including the people who are not able to drive (e.g. too old, too young, or disabled), or who are not able to support a private vehicle.
2. *To save road space for passenger transport*. This role aims to utilise capacity of the road network efficiently in order to reduce investment costs for expanding and constructing new roadways.

3. *To support mode choice of road users*. This role aims to provide other alternatives for road users in order to reduce the growth rate of individual motorised vehicles (incl. motorcycles and private cars), to balance modal share between public transport and individual motorised transport, to improve traffic condition, and to enhance mobility in urban areas.

4. *To minimise traffic accident risks*. The rate of traffic accidents can be reduced significantly by using buses instead of individual motorised vehicles.

5. *To reduce emissions (incl. exhaust emissions and noise emissions)*. An increase in the share of public transport will lead to a decrease in the share of individual motorised transport (the main cause for traffic emissions in urban areas) and result in a decrease in traffic emissions.

6. *To reduce transport costs*. Compared to individual motorised vehicles, buses with higher efficiency in capacity and energy consumption can provide lower costs due to the saving of road space and fuel consumption used for passenger transport.

Although fulfilling the significant roles and being a major mode of urban public transport, buses have not been prioritised and modernised appropriately for a long time (see Fig. 8). In HCMC (2011), for example, bus services carried about 552.1 million passengers, operated on 146 routes with 2,951 vehicles, and contributed with about 10% of the total passenger transport demand [Ho Chi Minh City Department of Transport (2011)]. It should be noted that only about 10% of modal share for public transport is too low even compared with industrialised cities.

Figure 8: Bus services in developing countries, examples from Hanoi and Ho Chi Minh City

The main reason for this unsustainable modal share can be interpreted by a low quality of bus services in MDCs. The following disadvantageous aspects are considered as a main reason for the degraded quality of bus services in these cities:

- Overloaded services during peak periods;

- A considerable disadvantage of speed and travel time, compared to individual motorised vehicles;
- Unpunctual and unreliable services;
- Inconvenient services due to lack of passenger information and passenger services;
- Uncomfortable services due to the scarcity of modern vehicles, equipment, etc.

2.4 Necessity of Bus Prioritisation in MDCs

Currently, motorcycle dependent cities such as Hanoi, Ho Chi Minh City (HCMC), Jakarta, and Bangkok are facing a number of urban transport problems in terms of traffic accidents, traffic congestion, environmental pollution, and economic loss [e.g. JICA and HPC (2007); JICA, MOT et al (2004); WHO (2009); Khuat (2006); Asri et al (2005); Hanaoka (2013)]. They seem to be fallen into a trap of booming individual motorised vehicles (incl. motorcycles and cars). One of the main reasons for this situation in these cities, particularly in Hanoi and HCMC, is that bus services have not been prioritised and modernised adequately for many years, even though they are operating as a major mode of public transport in these cities.

In order to benefit from the significant roles of public transport in urban areas, the quality of bus services must be improved adequately to be accepted by road users. That quality is basically evaluated by speed, travel time, punctuality, reliability, convenience, and comfort of bus services. In MDCs, however, these factors are being impacted adversely by

- *Mixed traffic conditions.* Most of buses are operating on mixed traffic lanes under the condition of high traffic loads. External disturbances from other vehicles reduce the speed, punctuality, and reliability of bus services.
- *Unfavourable signalisation.* Unsuitable signal programs and lack of priority considerations for buses at traffic signals lead to unreasonable delays for them at signalised intersections. These delays induce long and unpredictable travel times, and therefore they impact adversely on speed, punctuality, and reliability of bus services.
- *Inappropriate location of bus stops*. A number of on-line bus stops are situated at unsuitable positions which often lead to problems for the operation of bus services at bus stops, e.g. long delays, improper stopping positions of buses, the overuse of short dwell times, a tendency to skip services, and a risk of accidents for passengers.
- *Other negative impacts caused by urban transport problems*. These problems can include traffic congestion, non-strict traffic discipline, etc.

Therefore, it is essential to prioritise buses in urban areas of motorcycle dependent cities. Bus prioritisation can help to improve the quality of bus services in terms of speed, travel time, punctuality, reliability, convenience, and comfort. Moreover, the attractiveness of bus services can be enhanced substantially by implementing bus prioritisation, which can promote modal shift from individual motorised transport to public transport.

2.5 Conclusions

Since buses first appeared, they have been improved and modernised substantially to become an integrated and modern transport system. At present, they are being used as an indispensable mode of urban public transport in many countries around the world. They play a series of important roles such as providing equal mobility for all people, saving road space, supporting mode choice, minimising accident risks, reducing traffic emissions, and lowering transport costs.

In comparison with individual motorised vehicles (incl. private cars and motorcycles), buses possess a number of advantageous attributes regarding safety, high capacity, environmental sustainability, and economic efficiency. In mixed traffic conditions, however, they are loosing their competitiveness against individual motorised vehicles due to their scheduled operations, limited travel speeds, restricted acceleration/deceleration rates, etc. If no priority measures are given, buses will be an unattractive transport mode. From that point of view, many developed countries have implemented priority measures for buses in order to benefit from their advantages. The successful application of bus prioritisation is proved in many industrialised cities, resulting in a bundle of benefits for community, users, and operators.

In MDCs, however, buses have not been prioritised and modernised appropriately for a long time, even though they are operating as a major mode of public transport. At present, bus services in MDCs are operating with a low quality of service, and not being an attractive transport mode. Certainly, the advantage of bus services cannot be made use with that quality. Consequently, these cities are facing a number of traffic problems involving traffic accidents, traffic congestion, environmental pollution, and economic loss.

In order to take the significant advantages of buses, it is necessary to prioritise them in both planning and operation. *Bus prioritisation is an important solution to improve the quality of bus services, to stimulate modal shift from individual motorised transport to public transport, and to solve in part the rising traffic problems in MDCs.*

3 Principle Approaches of Bus Prioritisation

3.1 Overview

Experience from developed countries shows that bus prioritisation is a key way to improve the quality of bus services. Currently, principle approaches of bus prioritisation aim at eliminating or reducing external disturbances occurring at traffic signals, on travel ways, and at bus stops. For this reason, bus priority measures are basically categorised into three main groups consisting of (1) measures for signal priority, (2) measures for travel ways, and (3) measures for bus stops. The following figure provides an overview on individual measures of each group.

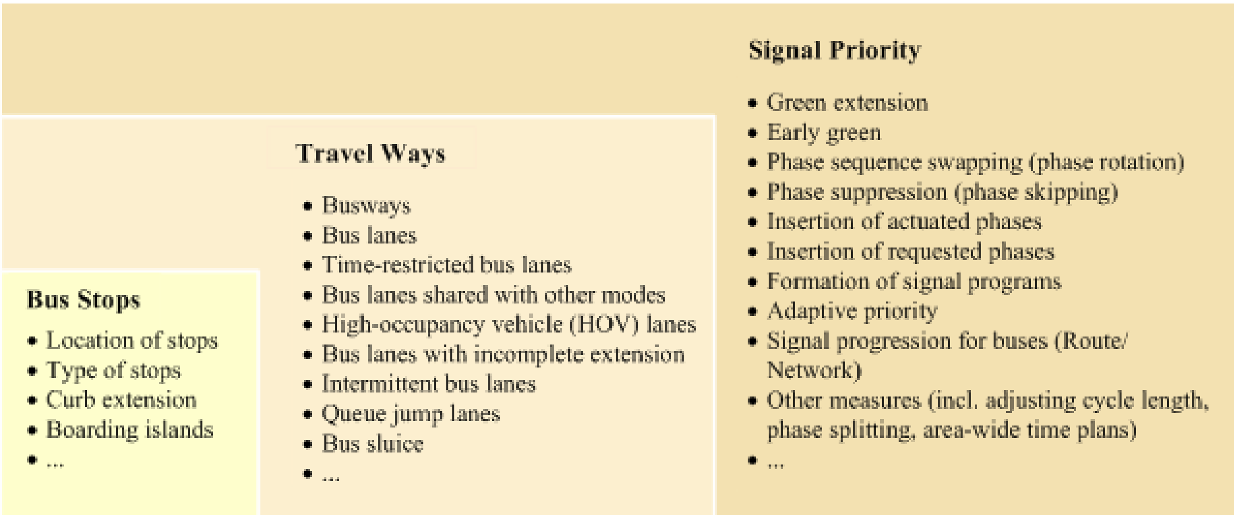

Figure 9: Principle approaches of bus prioritisation

Besides, supportive measures will be further mentioned since they might be needed to support certain principal measures or to provide additional options for prioritising buses on urban roadways. In this chapter, thereby, bus prioritisation is analysed in the sequence of signal priority, travel ways, bus stops, and supportive measures. The detail on these measures is discussed in the following sections.

3.2 Signal Priority

On urban road networks, the operation of buses is basically different from that of other vehicles due to their scheduled stops, restricted acceleration/deceleration rates, and variable dwell times at stops [FGSV (1993)]. Unfavourable traffic signal settings can result in a number of problems regarding delays, variation of travel time, and number of stops for buses. If no priority measures are granted to them, they will suffer a high probability of losing their green times and dropping out the Green Wave[6].

[6] Green Wave: "A Green Wave is created by coordinating the signal programs of neighbouring intersections, so that the majority of the vehicles travelling at a certain speed can pass several intersections without stopping", FGSV (1992).

For this reason, buses should be prioritised at traffic signals because of their fundamental roles and their high capacity of passenger transport in urban transport systems. The aims of signal priority are to improve the attractiveness of bus services, to increase travel speed, and to enhance punctuality of bus services [FGSV (1999)]. Signal priority is a cost-effective method to improve quality of bus services and to enhance regional mobility. As a result, it has been applied in many cities in Europe, North America, and other regions. [Intelligent Transportation Society of America (2005)]

Since signal priority for buses is activated at the microscopic level of signal control strategies, an overview of these control strategies will be provided firstly in the follow-up section.

3.2.1 Signal Control Strategies

According to the German "Guidelines for Traffic Signals" [RiLSA—FGSV (2010)], signal programs operate at two levels of control strategies (see Table 1), including macroscopic level (group A) and microscopic level (group B). These control strategies are summarised in the following.

The macroscopic control strategies are mainly used for the long-term change of traffic loads in the network or over certain areas. Traffic signals are adapted to different traffic situations macroscopically by specific signal programs selected from a given set of signal programs. There are three types of macroscopic control strategies, including time-dependent selection (A1), traffic-dependent selection (A2), and traffic-dependent formation of signal programs (A3).

The microscopic control strategies are activated from the macroscopic level, serving short-term changes of traffic loads. These control strategies can be divided into three different sub-categories, depending on which elements of the signal program are variable. They embody (i) fixed-time signal program, (ii) signal program adaptation, including green time adjustment, phase swapping, demand phase, and time-offset adjustment, and (iii) signal program formation.

Fixed-time signal programs do not provide a modification of signal program elements. Thereby, they should be used only when traffic loads remain unchanged for a certain period of time.

In control strategies of signal program adaptation, the elements of signal program can be modified and actuated to the prevailing traffic situation. It means that the change of traffic situation within some seconds or within the cycle time at individual intersections is taken into account instantly.

Signal program formation enables to modify variably the elements of signal program in a traffic-actuated way. This control strategy provides the highest flexibility to adapt signal programs to the change of traffic situation.

Signal control strategies can be activated at the local or network level. In addition, these strategies can be activated under time-dependent control, or traffic-dependent control in forms of either rule-based or model-based control. However, model-based control systems have not been widely applied up to now. The main obstacles for a widespread propagation of these systems are interface problems and high investment costs as well as insufficient knowledge regarding their benefit for overall traffic flow and their impacts on environment. In Germany, for this reason, the research project AMONES[7] funded by the Federal Ministry of Transport, Building and Urban Development has been conducted in order to clarify these related issues. [Boltze et al. (2011a)]

Table 1: Overview of the control strategies

	Control strategies: General term	Control strategies: Main feature of signal program modification	Number	Activation – Local level: Time-dependent	Activation – Local level: Traffic-dependent, Rule-based	Activation – Local level: Traffic-dependent, Model-based	Activation – Network level: Time-dependent	Activation – Network level: Traffic-dependent, Rule-based	Activation – Network level: Traffic-dependent, Model-based	Traffic-dependent variable elements of the signal program: Cycle time	Phase sequence	Number of phases	Green time	Time offset
A: Macroscopic control level	Signal program selection	Time-dependent signal program selection	A1	X			X			Variable elements of the signal program according to control strategies of group B				
		Traffic-dependent signal program selection	A2		X	X		X	X					
	Signal program formation	Traffic-dependent signal program formation	A3		X	X		X	X					
B: Microscopic control level	Fixed-time signal program		B1	Activation according to control strategies of group A										
	Signal program adaptation	Green time adjustment	B2										X	
		Phase swapping	B3								X			
		Demand phase	B4									X	X	
		Time-offset adjustment	B5											X
	Signal program formation	Free modification possible	B6							X	X	X	X	X

Legend: potential control strategies for MDCs are marked by the shaded areas.

[Source: RiLSA—FGSV (2010), with an improvement based on Boltze et al. (2011a)]

In accordance with the previous study conducted by Do (2009), the signal control strategies including signal program selection (at the macroscopic level), fixed-time signal program and signal program adaptation (at the microscopic level) are recommended as potential control strategies for MDCs.

[7] AMONES: Application and analysis of model-based traffic signal control in urban road networks

3.2.2 Control Strategies for Signal Priority

As mentioned previously, signal priority for buses is implemented at the microscopic control level. According to FGSV (1993), control strategies for signal priority are classified into two categories, including strategies for isolated intersections, denoted from *E 1* to *E 5*, and strategies for routes/networks, denoted from *S/N 1* to *S/N 6*. The summary of these control strategies and the recommendation on potential measures are given in Table 2.

Table 2: Signal priority measures

<table>
<tr><th colspan="9">Intersection Level</th></tr>
<tr><th rowspan="3">Strategies</th><th colspan="8">Measures</th></tr>
<tr><th rowspan="2">Green extension</th><th rowspan="2">Early green</th><th rowspan="2">Phase swapping</th><th rowspan="2">Phase suppression</th><th rowspan="2">Actuated phases</th><th rowspan="2">Requested phases</th><th colspan="2">Priority with optimisation process</th></tr>
<tr><th>No</th><th>Yes</th></tr>
<tr><td>Strategy E 1</td><td>X</td><td>X</td><td></td><td></td><td></td><td></td><td>X</td><td></td></tr>
<tr><td>Strategy E 2</td><td>X</td><td>X</td><td>X</td><td></td><td></td><td></td><td>X</td><td></td></tr>
<tr><td>Strategy E 3</td><td>X</td><td>X</td><td></td><td>X</td><td>X</td><td></td><td>X</td><td></td></tr>
<tr><td>Strategy E 4</td><td>X</td><td>X</td><td></td><td>X</td><td></td><td>X</td><td>X</td><td></td></tr>
<tr><td>Strategy E 5</td><td colspan="6">Formation of signal programs</td><td></td><td>X</td></tr>
</table>

<table>
<tr><th colspan="2">Route/Network Level</th></tr>
<tr><th>Strategies</th><th>Measures</th></tr>
<tr><td>Strategy S/N 1</td><td>Formation of signal progression for buses
by coordinating fixed-time programs of neighbouring traffic signals</td></tr>
<tr><td>Strategy S/N 2</td><td>Adaptation of signal progression for buses
by adjustment of green time</td></tr>
<tr><td>Strategy S/N 3</td><td>Adaptation of signal progression for buses
by adjustment and insertion of green time</td></tr>
<tr><td>Strategy S/N 4</td><td>Responsive formation of signal progression for buses
by the modified green time, phase number, phase sequence and cycle length</td></tr>
<tr><td>Strategy S/N 5</td><td>Responsive formation of signal progression for buses
by adjustment and insertion of green time, and the traffic-actuated cycle time</td></tr>
<tr><td>Strategy S/N 6</td><td>Responsive formation of signal progression for buses
by traffic-actuated signal programs</td></tr>
</table>

Legend: potential signal priority measures for MDCs are marked by the shaded areas.

[Adapted from FGSV (1993)]

It should be noted that the terminology of signal priority might be worldwide different. In North America, for instance, according to the Intelligent Transportation Society of America (2005), signal priority is categorised into three types of strategies, including passive priority (such as cycle length adjustment, phase splitting, and area-wide timing plans), active priority (incl. green extension, early green, actuated bus phases, phase insertion, and phase rotation), and adaptive priority (incl. signal priority with adaptive signal control systems, and adaptive signal priority).

The measures for active priority in North America are almost similar to these in Germany. Besides, the *adaptive priority* is likely analogous to the strategy *formation of signal programs*. For passive priority, the strategy involving *area-wide timing plans* is similar to the control strategy *S/N 1*. However, the usage of *cycle length adjustment* and *phase splitting* is not mentioned in Germany, mainly because of its modest effectiveness in general traffic conditions. Additionally, under heavily loaded conditions, those measures can lead to critical impacts on other traffic, particularly in terms of intersection capacity and signal coordination. Therefore, they are not recommended for MDCs.

Based on FGSV (1993), the most important aspects of these control strategies will be addressed to consider their applicability to MDCs in the following parts.

Control Strategies for Isolated Intersections

Strategy E 1: Green Extension and Early Green

This strategy is the simplest control strategy of signal priority, which is comprised of green extension and early green measures. It allows signal programs to shorten the green time of non-priority phases and prolong the green time of priority phases. While an early green time is effective for buses approaching traffic signals during red intervals, a green extension could be useful for those arriving during the last seconds of their phases. These measures do not modify the cycle length and phase setting (such as number of phases and phase sequence). Besides, they do not require additional clearance intervals so there is no negative impact on capacity of the intersection. Therefore, this strategy and its measures are highly recommended for MDCs.

Strategy E 2: Green Extension, Early Green, and Phase Sequence Swapping

Apart from green extension and early green measures, this strategy allows signal programs to change the phase order which can be swapped from non-priority phases to priority phases in order to favour the movement of buses. Because the cycle length and number of phases have to be kept unchanged in this control strategy, the degree of saturation, capacity, and queue length of interfered phases can be impacted negatively, particularly during peak periods. Thereby, the measure of phase swapping will be further examined for an application to MDCs in another chapter.

Strategy E 3: Green Extension, Early Green, Phase Suppression, and Actuated Phases

Compared to the previous ones, this strategy provides another function of inserting actuated phases for buses at certain time points within the cycle length. Besides, it also allows suppressing or shortening the green time of non-priority phases in order to serve the actuated phases for buses.

The primary conditions for an implementation of this strategy include sufficient queuing space and low to medium traffic loads at signalised intersections. Thereby, this control strategy along with its individual measures will be further studied under the condition of MDCs.

Strategy E 4: Green Extension, Early Green, Phase Suppression, and Requested Phases

This control strategy allows an insertion of requested phases for buses in response to their requests. Depending on traffic situation, one or more phases of individual traffic can be shortened or suppressed; and the requested phases can be inserted during the cycle length as long as the degree of saturation, queue length, and waiting time of non-priority traffic remain at permissible levels. When bus volumes are high, the request of buses should be limited conditionally in order to reduce side impacts of signal priority on other traffic.

This strategy benefits buses significantly at traffic signals; however, its negative impacts on other traffic can be critical in general conditions of MDCs. For this reason, its individual measures need a further discussion in another chapter.

Strategy E 5: Formation of Signal Programs

This control strategy grants signal priority by real-time calculations of signal program elements including the number of phases, phase sequence, cycle time, and green time. These elements are optimised by certain targeted parameters (e.g. total delay, capacity, number of stops). However, it often requires adequate application conditions and sophisticated control equipment. Besides, extensive costs for planning, extra equipment, operation, and maintenance must be needed. Therefore, this control strategy is not recommended for current conditions of MDCs.

Control Strategies for Routes/Networks

Strategy S/N 1

In this strategy, signal progression for buses is formed by adapting green bands in the time-distance diagram based on their trajectory characteristics, e.g. their speed and dwell times. Normally, signal coordination of individual motorised traffic as well as pedestrians and cyclists can be remained partially.

Under general conditions of MDCs, it should be noted that Green Waves for traffic flow in main directions cannot be disregarded if they are available. Thereby, signal progression for buses should be created by an alternative arrangement of bus stop location.

Strategy S/N 2

In this strategy, Green Waves for individual motorised traffic along the close sequence of neighbouring intersections are basically maintained while signal progression for buses is taken into account. By adjusting green bands of individual mortised traffic at their ends, signal progression can be granted to buses if their requests are verified. To implement this control strategy, boundary conditions involving traffic loads, queuing space, permissible waiting time, and Green Waves for other traffic must be examined.

Strategy S/N 3

Compared to strategy *S/N 2*, this control strategy enables to insert green times for buses during the cycle length. Green bands of individual motorised traffic are only maintained during limited duration. When this control strategy is applied, sufficient capacity reserve and queuing space of intersections must be available.

In MDCs, as mentioned previously, Green Waves for traffic flow in main directions cannot be disregarded if application conditions for them are met. However, this control strategy can impact critically on signal coordination of other traffic because of the variable insertion of green times for buses. Therefore, it is not recommended for MDCs.

Strategy S/N 4

Basically, this strategy enables to remain signal coordination for individual motorised traffic if buses are not present. Otherwise, if they request for signal priority, this coordination will be abolished to prioritise buses. This control strategy should be applied to intersections with low traffic loads or low bus volumes. Normally, a number of detection systems must be provided in order to monitor traffic situation of non-priority streams (e.g. to monitor queue lengths). In addition, a recovery strategy of signal programs after giving priority to buses will be needed to restore Green Waves for individual traffic.

Due to the considerable impact on general traffic flow and restricted conditions for an application, this strategy is not encouraged for MDCs.

Strategy S/N 5

This control strategy can be applied for small groups of neighbouring traffic signals (from 5 to 7 traffic signals). Within these groups, the flexible design of signal programs is feasible. It allows buses to influence signal programs by extending cycle time, adjusting or inserting green times in order to generate signal progression for buses. Depending on specific traffic situation and priority requests, the cycle length can vary from cycle to cycle, and the flexible signal progression for buses can be formulated. To implement this control strategy effectively, the delimitations of applied areas, involving network features (intersection spacing and queuing space), location of bus stops, directional traffic loads, must be examined carefully.

The prerequisite conditions for this strategy basically include intensive communications between control devices, extensive control equipment (such as detection systems, communication systems, control systems, etc.) as well as high system costs for planning, installation, maintenance, and operation. Therefore, this strategy is not highly proposed for MDCs due to lack of basic conditions for its application.

Strategy S/N 6

This strategy enables to form signal programs more flexibly in order to grant signal progression to buses. However, it often requires some restricted conditions (e.g. reasonable traffic loads, availability of modern control equipment, etc.) for an application. In MDCs, these conditions are generally not met. Additionally, the requirement of high investment costs for its application can be another difficulty. Hence, this strategy is not highly recommended for MDCs.

3.2.3 Levels of Signal Priority

According to FGSV (1993), there are two levels of signal priority: absolute priority and conditional priority. The absolute priority is the strongest form of signal priority for buses in order to serve them with nearly free movements at signalised intersections. On the other hand, the conditional priority must guarantee some certain conditions, and it serves buses conditionally at traffic signals. The summary on these levels as well as their applications are given in the following based on the guidance of FGSV (1993).

Absolute Priority

Absolute priority enables buses to pass through intersections nearly without stops and waiting times, or with inconsiderable waiting times. However, the negative impact of absolute priority on other traffic (incl. individual motorised traffic, pedestrians, and bicycles) must be examined carefully. Besides, the capacity of the road network when signal priority is implemented must be considered in advance.

Generally, absolute priority can be applied if the following conditions at intersections are satisfied, including:

- Sufficient queuing space,
- Low to medium degrees of saturation on intersection approaches,
- Non-requirement of signal coordination for other traffic, and
- Availability of dedicated lanes for public transport vehicles.

Conditional Priority

If the conditions for absolute priority are not met, conditional priority is an alternative. The following conditions might be considered for conditional priority:

- Signal coordination for other traffic,
- Minimum green times for other traffic,
- Maximum waiting time for non-motorised traffic,
- Queue length,
- Degrees of saturation of other traffic streams,
- Bus volume,
- Conflicting priority requests between bus lines, etc.

Application of Priority Levels

The guidance on the selection of priority levels is given in Table 3. This selection is explained as follows:

- If absolute priority (A) is marked only, A is recommended for an application.

- If conditional priority (B) is marked only, A is not appropriate. Therefore, B is relevant to an application.
- If both of A and B are marked, both of them can be applicable. An application of whether A or B can be decided depending on specific situation.

Since the prevailing conditions of MDCs are normally restricted for an application of the absolute priority level, the conditional one is recommended for these cities. In this manner, the side impact of signal priority on other traffic can be kept at permissible levels.

Table 3: Selection of signal priority levels

No.	Conditions	Details	Levels of signal priority	
			Absolute (A)	Conditional (B)
1	Queuing space	sufficient	X	
		insufficient		X
2	Degree of saturation of private motorised traffic	low to medium	X	
		high	X	X
		oversaturated		X
3	Travel ways	mixed lane	X	X
		dedicated lane	X	
4	Signal coordination for private motorised traffic	yes		X
		no	X	
5	Signal coordination for pedestrian/cyclist traffic	yes		X
		no	X	
6	Conflicting requests between public transport lines	yes	X	X
		no	X	
7	Public transport frequency	low to medium	X	
		high	X	X
8	Type of public transport	bus	X	X
		tram	X	X
		city train	X	

[Source: translated from FGSV (1993)]

3.2.4 Supporting Technologies for Signal Priority

Detection Systems

According to BMVBW & VDV (2001), detection systems for signal priority must fulfil the following requirements:

- Possible to transmit requests over long distances (up to 500 m),
- High reliability of system operation,
- Ability to perform rapid control,
- Appropriate for checking buses at any arrival speeds,
- Short time frame for registering (not exceed one second),
- No requirements of drivers' intervention, and
- High accuracy of location detection for requesting and terminating signal priority.

In Germany, the most common detection systems used for signal priority consist of inductive systems, beacon systems, and satellite-based detection systems. Based on BMVBW & VDV (2001), the summary of these systems is given in the following parts.

Inductive Systems

An inductive loop detector consists of a wire loop installed under road pavements, power supplies, and evaluation circuits. By measuring and evaluating the change in the magnetic alternating field, inductive systems can be used as detection systems for signal priority.

In practice, depending on specific situation, the requirements of inductive systems can be different as follows:

- If buses operate on their separate lanes, the presence and location of requesting buses can be determined by normal inductive systems.
- If buses operate on mixed traffic lanes, inductive loop detectors with the special evaluation must be used to distinguish different types of vehicles in mixed traffic flow.
- If data transmission from buses to controllers is required, additional on-board transducers must be needed. The integrated on-board information system (IBIS) can be used to provide necessary information.

However, inductive loops are generally not adequate when buses operate in mixed traffic conditions. The main reason is that they possibly detect the incorrect requests disturbed by private traffic and they can only provide minor information content for some comprehensive measures of signal priority. [RiLSA—FGSV (1992)]

Beacon Systems

Beacon systems are being commonly used for detection systems of signal priority in Germany. The operation of these systems is based on transceiver principles, using infrared radiation (IR) as the transmission medium (see Fig. 10).

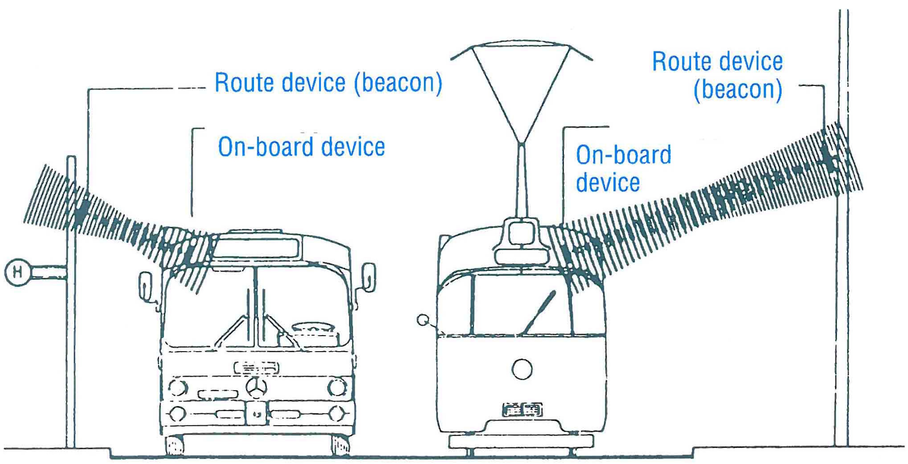

Figure 10: Beacon systems for signal priority
[Source: BMVBW & VDV (2001)]

Infrared beacon systems consist of receivers and transmitters equipped both on vehicles (on-board devices) and on roads (route devices or local beacons). Basically, a direct light-of-sight connection between on-board devices and local beacons must be required. On-board devices transmit their signals continuously, while local beacons are activated only by passing buses. When a bus enters the detection areas of a local beacon, signals from on-board device are sent to the local beacon. Depending on the type of beacon systems, bus requests can be sent directly from the bus to the signal controller via radio, or indirectly through the local beacon linked to the controller by cable.

Compared to inductive systems, beacon systems enable to exchange more types and volumes of information (e.g. vehicle presence, direction, line recognition, degree of occupancy, etc.) between vehicles and roadside installation. [RiLSA—FGSV (1992)]

Satellite-Based Detection Systems

Satellite-based detection systems consist of the on-board unit (the GPS receiver in conjunction with the on-board computer) and the receiver at the signal controller. These systems can be integrated into Intermodal Transport Control System (ITCS). Based on Global Positioning System (GPS) signals, the real-time location of buses is detected for the use of signal priority (see Fig. 11).

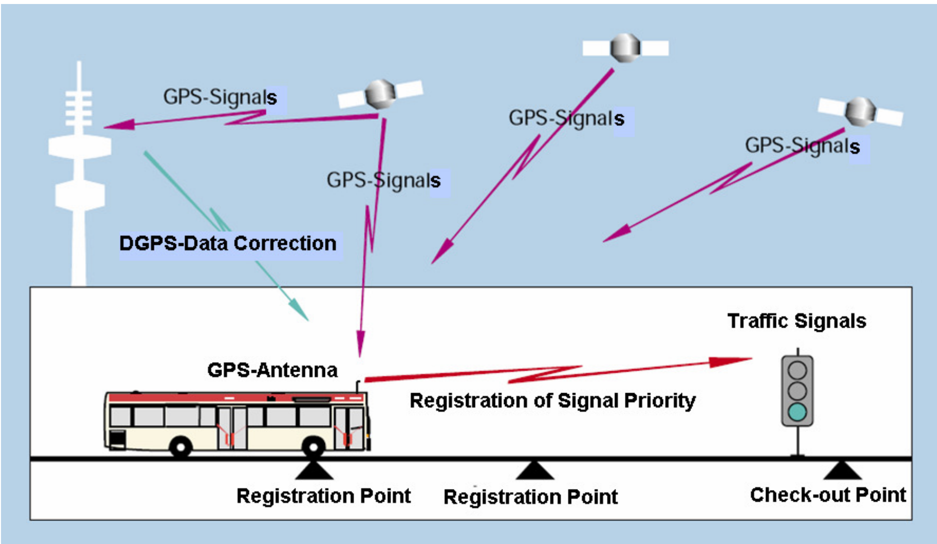

Figure 11: Example of satellite-based detection systems for signal priority
[Source: Freie und Hansestadt Hamburg Baubehörde (2000)]

When a bus approaches a predefined detection zone (or virtual detection zone) before traffic signals, the on-board unit will generate bus requests automatically. Then the requests are sent from the bus to the signal controller via radio transmission. In order to implement signal priority efficiently, the location of the bus must be determined as precise as possible. However, the error of GPS location detection normally ranges between 50 and 60 m, thereby this detection is not sufficient in accuracy for registering signal priority. To deal with this problem, Differential

Global Positioning System (DGPS) with the error ranging between 5 and 10 m is currently used as satellite-based detection systems for signal priority.

In the United States, according to Intelligent Transportation Society of America (2005), the most common detection technologies used for signal priority consist of (1) hard-wired loop detection, (2) light-based detection, (3) sound-based detection, (4) radio-based detection, and (5) satellite-based detection. The major attributes of these technologies are summarised as follows:

- *Hard-wired loop detection* consists of a transponder attached to underside of a bus, and a detection receiver that integrates with the signal controller. The advantage of loop detection systems includes the utilisation of existing loop detectors, reliable detection, stability with weather conditions, and non-requirements of line-of-sight or visibility. Moreover, the priority cancellation is easily implemented by inserting another loop after the stop line. However, the limitation of these systems is that they need to be placed and maintained appropriately.
- *Light-based detection* is one of the most widely used detection systems for signal priority, and it has been well tested for many years. This system contains an infrared strobe emitter located on a bus, and an infrared detector placed at the local intersection. However, this detection type requires line-of-sight between emitters and detectors. Thereby, its main disadvantage involves the obstruction (e.g. obstructions caused by trees, traffic signs), weather conditions, and potential false detection with nearby intersections.
- *Sound-based detection* includes audible and non-audible detection. Audible detection is mainly used for emergency vehicles, and it is not practical for transit signal priority. Otherwise, non-audible detection (digital sound wave recognition system) can be used for this purpose. The advantage of this detection system is that it does not depend on light-of-sight and visibility issues between the emitter and the detector. However, this system has some problems with the possibility of false detection, lack of vehicle identification, and logging capabilities.
- *Radio-based detection system* includes two types. The first type consists of radio frequency (RF) transponders mounted on buses and RF tag readers installed at upstream of signalised intersections. The second type embodies antennas and receivers mounted at intersections to receive radio signals from radio transmitters located on buses. The data (incl. identification number, travel direction, time, date, and duration) can be transmitted by radio signals to receivers. The advantage of this detection system is that it does not depend on light-of-sight and visibility issues. However, the costs for equipment are relatively high, and this system often requires suitable curb-side locations for mounting necessary equipment.
- *Satellite (GPS)-based detection* basically has two major types. The first type of GPS-based detection consists of the in-vehicle unit and the field unit located at the signal controller. The real-time location of buses is updated constantly by using a GPS-based AVL (automatic vehicle location) system. Based on vehicle schedule deviation,

passenger load, and other factors, data information is sent from the in-vehicle unit to the field unit. Then the priority message with regard to vehicle or route number, vehicle approach, priority level, etc. is evaluated at the field unit. Subsequently, the decision whether to grant or reject signal priority is made by the signal controller or the traffic control centre, depending on the system architecture. The second type of GPS-based detection allows for the determination of vehicle location, speed, and heading. This system requires the installation of radio transceivers on transit vehicles and radio receivers at intersections. The decision to grant signal priority to a transit vehicle is made based on the information (incl. location, speed, and heading information) which is sent from the transceiver to the receiver as the vehicle enters the intersection's radio range.

Communication Systems

Communication systems are needed for interconnecting between components of signal priority systems. Depending on the system architecture (centralised or decentralised), requirements for communication systems can be different.

According to Intelligent Transportation Society of America (2005), basically, there are two types of communications as follows:

- The first type involves local communications between buses and signal controllers. Typically, these communications are integrated with detection systems.
- The second type is communications between local controllers and control centre. These communications can be deployed by means of physical connections (fibre optic or copper cable), or wireless technology. It should be noted that if physical connections have not been implemented yet, wireless communications would be more preferable in order to reduce infrastructure costs for communication systems.

Nowadays, mobile radio communications are important for numerous applications in public transport, particularly in Germany. These communications consist of analogue professional mobile radio (radiotelephony and radio data transmission), digital professional mobile radio, and Global System for Mobile Communications (GSM). Due to worthwhile cost-effective solutions, GSM technologies are emerging in the public transport sector with a number of applications to personnel management, Intermodal Transport Control System (ITCS), information systems, and security technologies. [BMVBW & VDV (2001)]

3.2.5 Benefits and Costs of Signal Priority

Signal priority is being deployed successfully in many industrialised cities around the world. Based on the practical experience of these cities, an application of signal priority can result in the following benefits:

- Reduction in travel time for prioritised buses,
- Reduction in average delay at traffic signals for prioritised buses,
- Reduction in variability of travel time for bus services,

- Reduction in average total person delay at traffic signals,
- Reduction in number of stops for prioritised buses,
- Improvement of average speed for prioritised buses,
- Improvement of punctuality for bus services,
- Improvement of attractiveness for bus services,
- Increase in ridership for public transport,
- Encouragement of modal shift from private transport to public transport,
- Savings of vehicles and drivers for public transport operators, etc.

The costs for signal priority mainly include implementation costs and maintenance costs. These costs might vary from region to region, depending on a number of factors such as existing technologies of signal control devices, detection and communication systems, number of equipped intersections, number of equipped buses, system architecture of signal priority (centralised or decentralised), etc. The following table summarises the benefits and costs of signal priority in selected cities around the world.

Table 4: Examples of benefits and costs of signal priority in selected cities[8]

Cities	**Number of equipped intersections**	**Number of equipped buses**	**Benefits**			**Costs**	
			Decrease in travel time	Increase in speed	Other benefits	Implement-ation costs	Maintenance costs annually
Munich	-	-	7 minutes	24%	Saving of 1 bus	€2.209 million	-
	-	-	6 minutes	18%	Saving of 12 buses	€1.063 million	-
Stuttgart	34	-	-	12%	Saving of 1 bus per line; 10% increase in ridership	$4 million	-
Oakland	62	21	9%	-	-	$0.325 million	-
Seattle	28	1400	5.5-8%	-	14-24% decrease in number of stops; 35-40% decrease in travel time variability	$2.655 million	$0.028 million
Los Angeles	654	283	19-25%	-	Increase in ridership	$10 million	inconsiderable
Portland	250	650	-	-	Improved reliability; Saving of vehicles	$5.8 million	inconsiderable
Vancouver	63	28	16 minutes	-	23% of modal shift from auto to transit; 40-50% decrease in travel time variability	$0.86 million	$0.024 million
Auckland	174	734	8 minutes	-	11s delay saving per intersection	$6.9 million	-

Notes: "-" unknown

[Summarised from BMVBW & VDV (2001), Intelligent Transportation Society of America (2005), UITP (2009)]

8 The costs given in the table may not be comparable since exact time points of signal priority implementation are not known.

3.3 Travel Ways

3.3.1 Busways

The concept of busways was first taken shape in 1969, and the principle for this concept is to provide “a high speed, express-type bus rapid transit commuter service” [Hebert (1979)]. According to Transportation Research Board (2003b), busways are the highest degree of space separation for buses. Typically, two-direction roadways are allocated for the exclusive use of buses. These roadways allow buses to operate at relative high speeds (the maximum speed ranging from 70 to 80 km/h) and with their high frequency (see Fig. 12).

Figure 12: Grade-separated busway in Ottawa, Ontario
[Source: Transportation Research Board (2003b)]

Since most of busways are arranged within freeways, only few of them have their independent roadway alignments. They often have few stations along their entire lengths. As a result, bus services on corridors are mostly unavailable although there is a high frequency of buses running through. In North America, busways are mainly used for large cities in conjunction with densely populated downtowns, heavy peak-hour bus ridership, and high bus volumes. [Transportation Research Board (2000); Vuchic (1981)]

3.3.2 Exclusive Bus Lanes

Exclusive bus lanes are traffic lanes which are reserved and designated only for the operation of buses. They are separated from other traffic lanes by fixed physical strips or pavement markings. These lanes can be arranged on curb side of streets, called curb-side bus lanes; or they can be designated in the middle position of streets, called median-side bus lanes. Besides, they can be assigned as concurrent-flow or contra-flow bus lanes. Compared to concurrent-flow bus lanes, contra-flow bus lanes suffer less interference from other traffic because traffic enforcement for these lanes is easier than for the other ones. However, the safety concern of contra-flow bus lanes seems more critical than that of concurrent-flow ones [Vuchic (1981)].

Experience from Germany and other developed countries illustrates that a provision of bus lanes is the most effective priority measure compared to other measures such as traffic control measures or vehicle based measures. An application of bus lanes in urban areas has significantly positive effects on the travel speed, punctuality, driving comfort, attractiveness, flexibility and reliability of bus services. In Wiesbaden (Germany), for instance, the average travel time of buses reduced by 27%, and their average speed increased by 13.6% during peak periods after implementing bus lanes. In Paris, when bus lanes were introduced in 1974, there was a 7.7% increase in passenger's number for the first time after 15 years. In Washington, the implementation of bus lanes resulted in a considerable reduction in bus travel time and a significant increase in modal share of buses between 1970 and 1973. [VÖV/VDA (1979)]

An arrangement of bus lanes depends largely on bus frequency, roadway conditions, traffic conditions, and other conditions as well. In European cities, for instance, those conditions basically include bus frequency, the volume to capacity ratio of roadways, occupancy of buses, and number of available traffic lanes [VÖV/VDA (1979)]. In North America, an application of bus lanes relies mainly on peak-hour directional volumes of bus flow and passenger flow, and available traffic lanes on roadways [Transportation Research Board (2003b)].

Curb-Side Bus Lanes

Curb-side bus lanes can be used in the form of concurrent-flow or contra-flow bus lanes on streets where loading and unloading activities of local traffic and delivery traffic are absent at least on one side. If not, unlawful parking and stopping activities of that traffic can block the bus lane. Curb-side bus lanes are often integrated with curb-side stops which provide the better accessibility compared to that of median-side ones. [RASt 06—FGSV (2006a)]

These lanes can be arranged on one side or on both sides of streets, depending on roadway conditions, traffic control measures, parking requirements, operation of local and delivery traffic, and directional volumes of bus services. Figure 13 presents possible arrangements of curb-side bus lanes in urban streets having from there to six lanes.

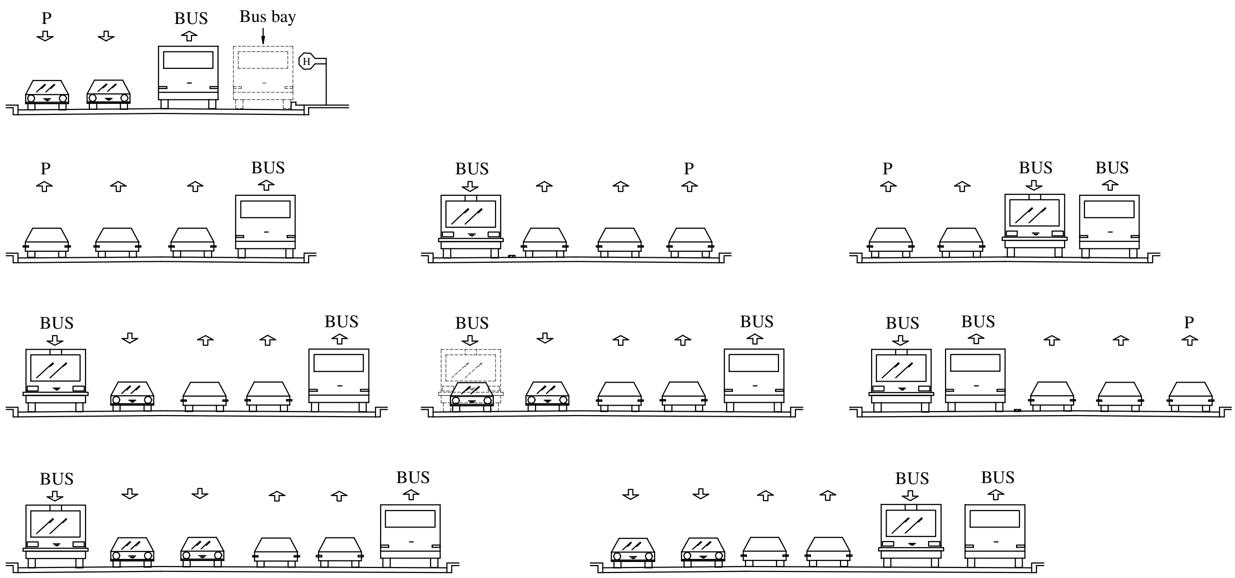

Figure 13: Possible arrangements of curb-side bus lanes in urban streets
[Source: VÖV/VDA (1979)]

Curb-side bus lanes are the most common form of priority measures for bus travel ways. They are convenient for scheduled stops as well as passenger boarding and alighting. However, they often suffer interference from other traffic, for instance, from right-turning vehicles, loading and unloading vehicles, park-seeking vehicles, accessing and exiting traffic from local streets, and marginal friction (i.e. close to curbs, trees, poles, and pedestrians) [Vuchic (1981)]. The effectiveness of these lanes is influenced by traffic guidance (traffic signs, pavement markings, and traffic education) as well as traffic enforcement [Transportation Research Board (2010)].

Median-Side Bus Lanes

Generally, these lanes have some advantages compared to curb-side ones because they are not affected by unlawful stopping and parking vehicles as well as other interference. Therefore, the travel speed of buses on median-side bus lanes is often higher than on curb-side ones [VÖV/VDA (1979)]. However, they must require islands for the passenger boarding and alighting at median-side bus stops so that they may cause unfavourable accessibility for passengers (see Fig. 14).

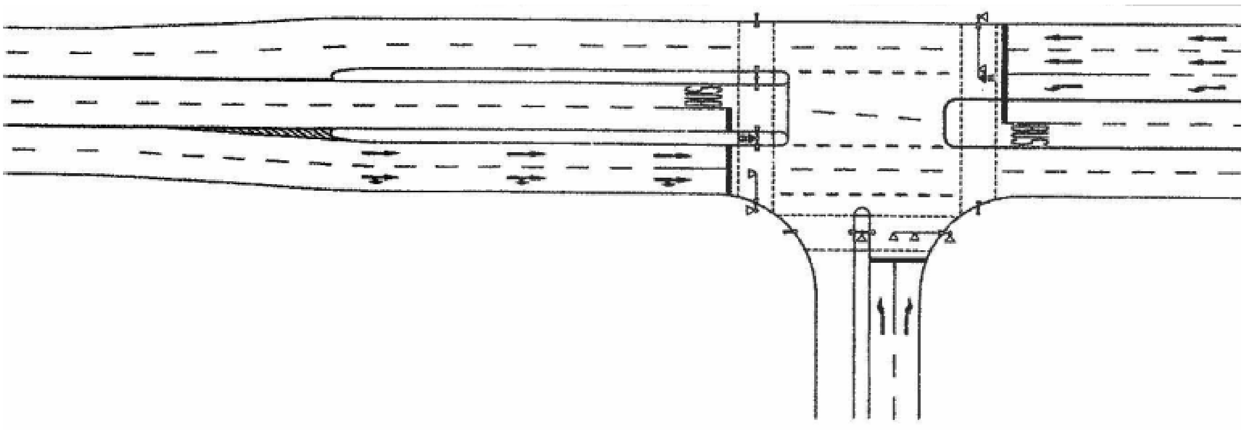

Figure 14: Median-side bus lane
[Source: RASt 06—FGSV (2006a)]

If tram lines are present, these lanes can be combined with tram tracks for the operation of buses and trams in both directions. This combination is popular in European cities. These lanes are considered as bus lanes shared with tram lines. Otherwise, if they are used for buses only, they can be arranged for either one or both directions, depending on service requirements and roadway conditions; basically, one bus lane is allocated to each direction of roadways. [RASt 06—FGSV (2006a)]

3.3.3 Reversible Bus Lanes

If only one bus lane is allocated to the operation of buses in both directions, it has to be shared for each direction during specified time periods. This lane is called a reversible bus lane (see Fig. 15). Reversible bus lanes could be appropriate when road space is not sufficient to arrange two lanes for buses in both directions, e.g. in case of three-lane streets. [EAÖ—FGSV (2003)]

In order to operate these lanes, traffic control, traffic enforcement, and technical efforts must be required sufficiently. However, an arrangement of bus stops in the range of these lanes as well as safety and accessibility concerns of those stops can be a considerable disadvantage of reversible bus lanes.

Figure 15: Reversible bus lane
[Source: EAÖ—FGSV (2003)]

3.3.4 Time-Restricted Bus Lanes

Another form of bus lanes is time-restricted bus lanes, i.e. these lanes are used for buses only during certain periods of the day (see Fig. 16). In other periods, they can be opened for general traffic. Time-restricted bus lanes can be appropriate in certain circumstances, e.g. local traffic needs to load and unload on curb-side lanes, or the operation of delivery traffic is required at least for a certain time of the day. For this type of bus lanes, restricted periods of time as well as misusing concerns must be considered in advance. [EAÖ—FGSV (2003)]

Figure 16: Example of time-restricted bus lane in Germany
[Source: EAÖ—FGSV (2003)]

3.3.5 Bus Lanes Shared with Other Modes

Bus lanes shared with other specified modes can be considered as a priority measure for bus travel ways, compared to mixed traffic lanes. This measure helps to utilise capacity of these lanes more efficiently, particularly if bus volumes are not high enough for an arrangement of exclusive bus lanes.

If these lanes are used, it is necessary to consider permissible accessibility for other specified vehicles such as bicycles, taxis, and emergency vehicles. This measure would be suitable for central areas to encourage the use of public transport and non-motorised transport. Experience from Germany shows that buses can operate harmoniously with taxis on curb-side lanes if traffic volumes of buses and taxis do not exceed correspondingly 60 buses/hour and 100 taxis/hour. Buses may also share their lanes with bicycles on curb-side lanes if safety and traffic flow quality of both buses and bicycles are proved. Generally, overtaking activities between buses and bicycles can be performed safely if these lanes fulfil the width of 4.75 m. In core urban areas where applying environmental protection measures, cyclists may be allowed to travel on these lanes if conditions regarding the speed of buses, bus stop spacing, and signal priority are examined in advance. [EAÖ—FGSV (2003)]

3.3.6 High-Occupancy Vehicle Lanes (HOV Lanes)

HOV lanes are preferential lanes reserved for the use of high-occupancy vehicles (number of occupants > 1) in order to increase the person capacity of roadways. The definition of high-occupancy vehicles may vary depending on local policies. These vehicles often consist of buses, taxis, carpools, and emergency vehicles. HOV lanes are allocated either on freeways or on urban streets which have relatively high bus volumes. [Transportation Research Board (2000)]

Figure 17: HOV lane
[Retrieved from the website http://www.fhwa.dot.gov/]

These lanes benefit buses and other high-occupancy vehicles with time-savings compared to those of regular traffic lanes. When roadways are being congested, these vehicles may still travel freely. In order to encourage the use of high-occupancy vehicles, these lanes should not be operated at or near their capacities. In addition, level of service provided for HOV lanes should be better than for regular traffic lanes. [Transportation Research Board (2003b)]

3.3.7 Bus Lanes with Incomplete Extension

Webster (1972) introduced the bus lane with incomplete extension to the stop line (see Fig. 18). By theoretical considerations and experience, he realised that most benefits of bus lanes occur in the range of signalised intersections. The design of a full bus lane that ends at the stop line will help to reduce considerably travel time of buses at traffic signals, but it can cause a reduction in capacity of the intersection approach and an increase in delays for other traffic. Therefore, a bus lane with incomplete extension to the stop line can be a compromise between the conflict goals.

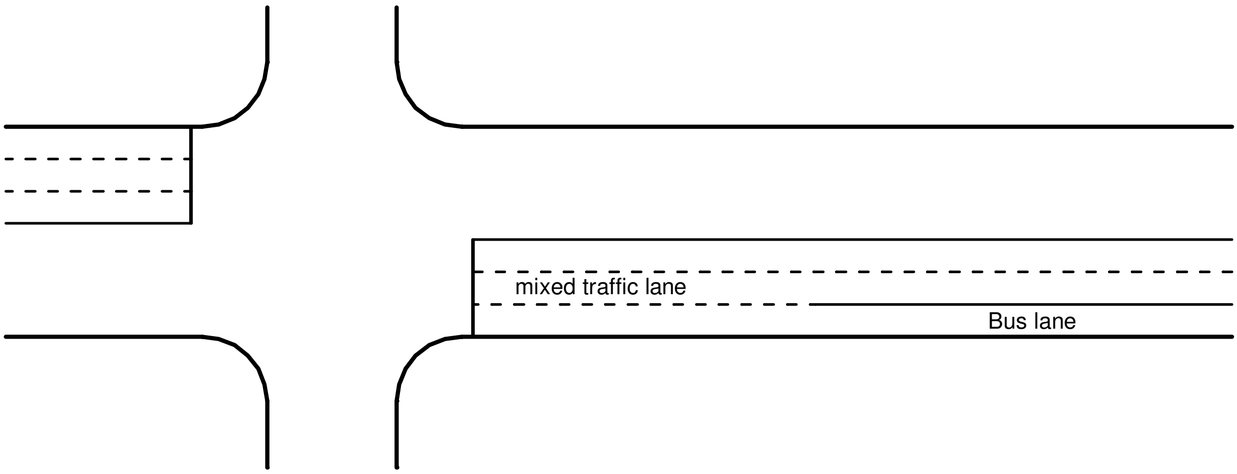

Figure 18: Bus lane with incomplete extension
[Source: Webster (1972)]

Experiments were conducted to evaluate the effect of this bus lane. In his study, the end of the bus lane was gradually moved back from the stop line, resulting in different distances between them. When these distances were ascending, there was an increase in capacity of the intersection approach but a rise in bus delay. An appropriate ending position of this lane can be estimated by a compromise between bus delay, person delay, delay of other vehicles, and capacity of the intersection approach.

3.3.8 Intermittent Bus Lanes

The concept of Intermittent Bus Lane (IBL) was introduced by Viegas in 1996. IBLs are considered as an approach of giving priority to bus travel ways. "IBL consists of a road lane in which the status of each section changes according to the presence or not of a bus in its spatial domain: when a bus is approaching an IBL, the status of that lane is changed to BUS lane, and after the bus moves out, it becomes open to general traffic again". [Viegas et al. (2007)]

a. Vertical signalisation–Variable Message Sign

b. Horizontal signalisation–LEDs on the pavement

Figure 19: Vertical and horizontal signalisation of IBL
[Source: Viegas et al. (2007)]

According to Viegas et al. (2007), in order to separate IBL from the adjacent lane, a set of horizontal LEDs[9] is installed on the pavement and placed on the line separating the lanes, and it will be flashing when the IBL is "on". Besides, Variable Message Signs are used as vertical signalisation at the beginning of IBL section. When the system estimates the arriving bus, the longitudinal signals will be flashing on, and IBL is activated and changed to the special lane which only allows the bus to move in. Other vehicles already travelling on this lane can keep flowing or change to adjacent lanes, but vehicles from other lanes cannot use the IBL.

3.3.9 Queue Jump Lanes

At signalised intersections, vehicular queues may impede buses to approach stop lines and receive their green times. If those queues are critical, buses may have to wait for more than one cycle length to pass through the stop lines even though they approach the intersections during suitable intervals to receive their green times.

A queue jump lane is constituted by a partial curb-side lane or a long bus bay ending at the stop line, which allows buses to avoid long queues of other vehicles at traffic signals. This measure benefits buses significantly, particularly at signalised intersections operating with heavy traffic loads.

Because only a partial lane is used for the queue jump lane, the number of lanes at the downstream intersection is often less than that at the upstream intersection. If no leaving aids of signalisation are given, other vehicles on adjacent lanes may not allow buses to go ahead immediately when the signals turn green. Consequently, the collision between buses and other vehicles may occur, and buses might have to wait for a time to re-enter normal traffic lanes from

[9] LEDs: Light-emitting diodes

their queue jump lane. Therefore, leaving signal aids should be provided to enable buses to depart safely and easily before the release of other vehicles at traffic signals.

According to RiLSA (1992), there are two types of leaving signal aids, consisting of protected leading green and advance permissive signals (see Fig. 20). Protected leading green requires all necessary intergreen times between buses and other traffic to be kept. It allows buses to leave queue jump lanes or bus bays during short periods of time. In some cases, road users may suffer unnecessary waiting time if signal requests of buses are not utilised. Otherwise, advance permissive signals do not require additional intergreen times since they are activated during regular green times of the bus phase.

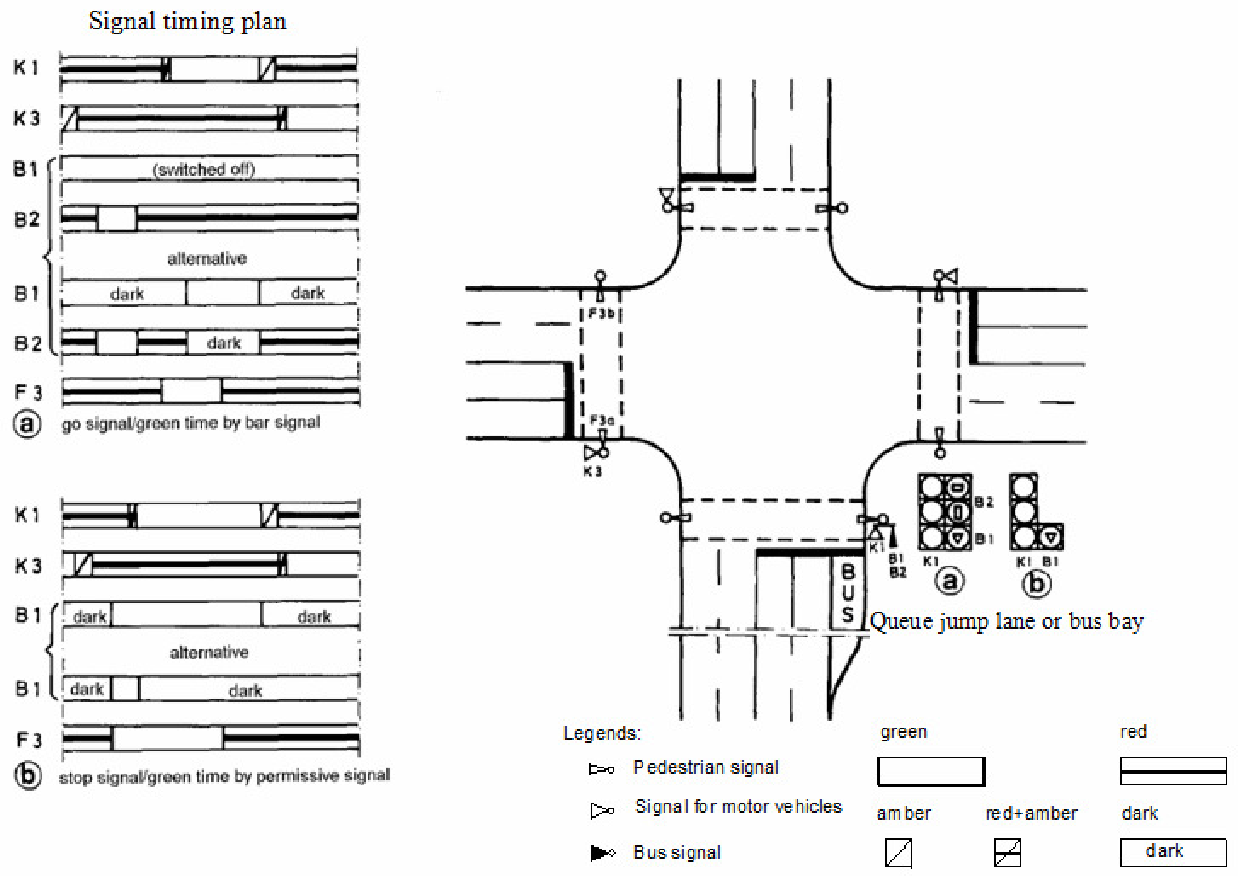

Figure 20: Queue jump lane or bus bay with bar signal (a) and permissive signal (b)
[Source: RiLSA—FGSV (1992)]

3.3.10 Bus Sluice

Bus sluice is a special design at the end of an intersection approach (see Fig. 21). This design allows buses easily to change their direction from a bus lane on the right-hand edge of the carriageway. Additional signals are required to keep private traffic at a distance about 30 m before the main signal heads. Leaving time for buses is indicated by the bus signal located at that distance. This measure permits buses easily to leave their lane and get into appropriate lanes for their continuing trips. [RiLSA—FGSV (1992)]

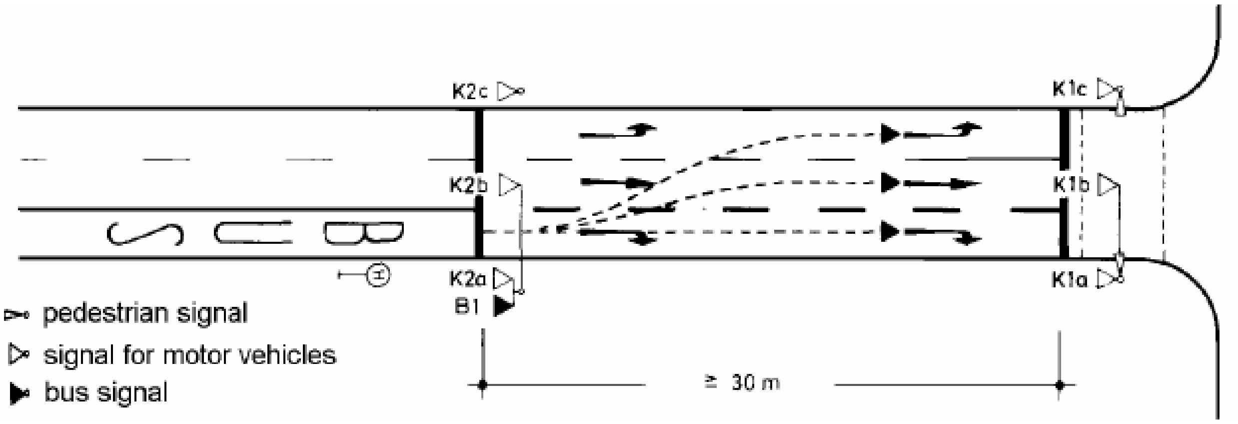

Figure 21: Bus sluice
[Source: RiLSA—FGSV (1992)]

3.4 Bus Stops

3.4.1 Measures for the Location of Bus Stops

According to EAÖ—FGSV (2003), the determination of bus stop location is generally influenced by the requirements of passengers, the interest of public operators and other road users, and local conditions. These factors are given as follows:

- The requirements of passengers: short distances from origin or to destination; safe and comfortable accessibility for all passengers.
- The interest of operators: undisturbed movements to bus stops; short passenger exchange time; desired overlapping transfer time; acceptable waiting time at traffic signals; adaptation to signal coordination; signal aids for leaving stops; and reasonable stop distances.
- The interest of other road users: capacity of intersection approaches; queue length after stopping buses; pulling out/into general traffic flow; positions of pedestrian crossing (regarding visibility between motorists and pedestrians near stopping buses); turning conflicts between buses and other vehicles; the guidance of bicycle traffic; visibility between motorists and cyclists within the intersection area; and requirements of pedestrian traffic for sufficient walking paths and waiting areas.
- Local conditions: existing roadway conditions; intensity of land use; and requirements for bus stop design.

Longitudinal Location

Basically, the location of bus stops along the roadway is classified into three types: stops before intersections (near-side stops), stops behind intersections (far-side stops), and stops away from intersections (mid-block stops).

Generally, bus stops are located in the range of intersections or near pedestrian crossings. The location of bus stops must be examined in order to provide passengers with safe, easy and comfortable accessibility. Besides, the clarity of bus stops should be taken into account in order to permit road users to adjust their movements early in agreement with the prevailing traffic situation at the stops. For this reason, the visibility of all road users must be checked carefully. [EAÖ—FGSV (2003)]

Stops before the intersection might cause additional delays for buses since they can miss their green intervals due to their variable dwell times. If these stops are used in combination with bus bays, special signals for leaving aids should be implemented to provide buses with leading green times. Otherwise, stops behind the intersection have some advantages, for instance, signal priority in response to bus requests can be switched more reliably, variable dwell times at stops will not have considerable impacts on bus delays. Furthermore, these stops can provide the better visibility for passengers, pedestrians, and approaching vehicles. [RiLSA—FGSV (1992); EAÖ—FGSV (2003)]

According to the German Guidelines for Traffic Signals [RiLSA—FGSV (1992)], if neighbouring signal programs are coordinated, stopping time of buses at their stops should be coincided with red periods between the end and the beginning of two successive green bands. By arranging bus stops alternatively before and after signalised intersections, it enables buses to join Green Waves of private traffic from a near-side stop at a given intersection until a far-side one of the following intersection.

Vuchic (1981) indicated that there are several factors influencing the choice of bus stop location. Among these factors, signal coordination should be taken into account since it can have a notable effect on the speed of buses. Besides, the accessibility of passengers must be carefully considered, i.e. stops should be located where waiting passengers are protected safely from other traffic, space for circulation must be sufficient, the pedestrian flow on sidewalks must not be impeded, and walking distances between stops should be examined for transferring between different bus lines. It is desirable to select the positions which minimise interference (e.g. interference caused by turning, merging, and re-entering movements) and safety hazards.

Demetsky et al. (1982) conducted the evaluation on the location of bus stops, which was based on the judgements provided by city traffic engineers and transit operators. Several factors were used in this evaluation, including bus stop spacing, bus stops in market areas, transfer points, the safety of passengers, the interaction between bus and other traffic, impacts on traffic operation, impacts on general traffic, and effects on adjacent land use/development. The result of their study indicated that far-side stops are more preferable than near-side and mid-block ones.

Transportation Research Board (1996) recommended that the determination of bus stop location involves the selection between near-side, far-side, and mid-block stops. This selection is often influenced by a number of factors such as passenger origins and destinations, pedestrian access, potential patronage, bus route, intersecting transit routes, signal priority, traffic control devices, intersection geometry, impact on the intersection operations, parking requirements, presence of queue jump lanes, physical road side constraints, and adjacent land use and activities.

It is apparent that the selection of bus stop location is influenced by a number of factors. At heavily loaded signalised intersections, the factors with respect to capacities and traffic flow quality of intersection approaches involved cannot be disregarded, particularly under the condition in MDCs. However, the available calculation of the impact of bus stops seems to contain some simplifications which might be not appropriate for MDCs. This issue is clarified more in the following discussions.

In the United States, according to Transportation Research Board (2000), the impact of an on-line bus stop on capacity at traffic signals is formulated by an intended reduction in the saturation flow rate of the subject lane group. This reduction is represented by an *adjustment factor for blocking effect* (denoted by f_{bb}). The calculation of this factor is based on the assumption of an average blockage time of 14.4 seconds during the green interval. The value of this factor depends primarily on number of lanes in the lane group and number of buses stopping per hour at bus stops. However, a simplification was made for that impact since this factor is set equally within the ranges of 250 ft (approx. 76 m) from the upstream or downstream intersection. That means both near-side and far-side bus stops within those ranges have the same impact on the subject lane group; further than those ranges, however, that impact is not considered.

In Germany, with reference to the "Handbuch für die Bemessung von Straßenverkehrsanlagen" [*Manual for the Design of Road Infrastructure*, HBS—FGSV (2001/2009)], the impact of on-line bus stops is not taken into account at traffic signals. The reason for this simplification might be derived from reasonable traffic loads at signalised intersections in German cities. Besides, when bus volumes are high, they are normally separated from other vehicles due to their right-of-way policies in the planning phase.

It should be remarked that the mentioned simplifications can be reasonably acceptable in industrialised cities because of their prevalent conditions. However, under the condition of mixed traffic flow (dominated by motorcycles) and heavy traffic loads in MDCs, the impact of bus stops might be largely different, corresponding to different positions of bus stops near traffic signals. Thereby, an in-depth study on this issue will be conducted in another chapter.

Latitudinal Location

The latitudinal location of bus stops in cross sections of roadways can be classified into two major types: curb-side stops (stops in the edge of streets) and median-side stops (stops in the middle position of streets).

Curb-side stops are commonly used when buses operate on curb-side bus lanes or mixed traffic lanes. Differently, median-side stops are basically used for median-side bus lanes, and they generally require combined islands for the passenger boarding and alighting. Compared to curb-side stops, median-side ones need more considerations regarding the safety and accessibility for passengers.

In MDCs, most of bus stops are curb-side stops which are located on mixed traffic lanes. Therefore, this research will focus mainly on this type of bus stops.

3.4.2 Other Measures for Bus Stops

Type of Bus Stops

Bus stops can be situated directly on normal traffic lanes (on-line stops) or outside those lanes with bus bays (off-line stops).

An on-line bus stop, which is situated directly on a travel lane, is the portion of a roadway marked or signed for the use of buses when loading or unloading passengers. Generally, there might be several loading areas at a bus stop, depending on the rate of bus arrivals and passenger service time at that stop. [Transportation Research Board (1996)]

Differently, a bus bay is a specially designed area which is separated from travel lanes and off the normal section of a roadway. It allows other vehicles on those lanes to flow freely regardless of stopping buses at their bay. Therefore, bus bays are highly recommended on roadways operating with high volumes or high speeds, such as suburban or arterial roads. Generally, the selection of this measure is influenced by the following factors: traffic volumes on the curb lanes, travel speed, bus volumes, passenger volumes, dwell times at bus stops, potential accidents for passengers at stop location, potential conflicts between buses and cars, sight distance, etc. Depending on the location of bus bays relative to intersections, there are far-side, near-side, and mid-block bus bays, in which a far-side placement is desirably suggested. There can be different types of bus bay design, including typical bus bay, open bus bay, partial open bus bay, and queue jumper bus bay. [Transportation Research Board (1996)]

In MDCs, the most common type of bus stops is on-line stops which are located directly on mixed traffic lanes. These bus stops often cause a number of problems for both buses and other vehicles at traffic signals. For this reason, problems of these stops and measures for them in the condition of MDCs will be studied in the following chapters.

Stops with Curb Extension

This measure can be applied to streets having curb-side parking lanes and operating with high lateral traffic volumes. In this case, a provision of curb extension will benefit buses by time savings when they enter their stops and re-enter travel lanes, especially during peak periods. Besides, illegal parking or stopping activities in the range of stop areas can be also prevented by an installed curb extension. Another advantage is that a bus stop with curb extension needs smaller space than a bus bay. Besides, this measure contributes to enhance safety, comfort, and accessibility for passengers. [EAÖ—FGSV (2003)]

Boarding Islands

Boarding islands assist buses in reducing unnecessary delays in multiple lane streets where parking activities, slow traffic, and delivery traffic on curb-side lanes are permissible, and right-turning traffic on the bus approach is heavy. These islands allow buses to dwell between travel lanes so that they can use a faster lane for entering stops and merging into travel lanes from their stops (see Fig. 22). However, if this measure is applied, the safety and accessibility for passengers must be considered carefully. [Transportation Research Board (2003b)]

a. Before the implementation

b. After the implementation

Figure 22: Example of boarding island
[Source: Transportation Research Board (2003b)]

3.5 Supportive Measures

Apart from the principal measures as mentioned previously, the following supportive measures are mainly proposed for prioritising buses in MDCs:

- Parking restrictions or prohibitions where parking activities impact adversely on the operation of buses.
- Extra traffic regulations and enforcement.
- Improvement of lane separation and intersection layout at traffic signals by pavement markings if necessary.
- Traffic rerouting: permanent or periodic rerouting for heavily loaded directions in which buses are operating.
- Infrastructure measures: e.g. an expansion of roadways, improvement of intersection layout, etc.

These measures are highly recommended for certain situation of MDCs since these cities often suffer more disadvantageous conditions than those of industrialised ones. If local conditions are met, the application of supportive measures will help to enhance the effectiveness of principal measures or to provide more alternatives for prioritising buses. Thereby, supportive measures will be addressed along with principal measures when necessary.

3.6 Conclusions

Bus prioritisation has been applied widely and successfully in many cities around the world, particularly in industrialised cities. A number of measures for prioritising buses are implemented in urban areas. The principle approaches of these measures aim at minimising external disturbances for buses at traffic signals, on travel ways, and at stops. As a result, the speed, travel time, punctuality, reliability, and quality of bus services will be improved substantially.

Signal priority is commonly deployed in Europe, North America, and other developed regions. There are two levels of control strategies for signal priority: intersection and route/network levels. At the intersection level, green extension, early green, phase swapping, phase suppression, actuated phases, and requested phases are recommended as potential measures for MDCs. However, the measure involving formation of signal programs or adaptive priority is not recommended for these cities due to its high investment costs and other restricted conditions. At the route/network level, signal coordination of fixed-time programs and adjustment of green times in order to grant signal progression to buses are proposed for MDCs, due to their modest impacts on Green Waves of other vehicles. Moreover, conditional signal priority is suggested since it is suitable for the prevailing conditions of MDCs. The suitability of each measure might depend largely on local conditions, such as roadway, traffic, control, and other related conditions. These aspects will be further examined in Chapter 5.

Experience from developed countries illustrates that a provision of fully separate travel ways such as busways or exclusive bus lanes has significant positive effects on the quality of bus services. Under the general condition of MDCs, however, those measures can be unfavourable due to constrained roadways and traffic conditions in these cities. Therefore, a partial priority for bus travel ways, such as time-restricted bus lanes, incomplete bus lanes, queue jump lanes, or other similar measures, might be more appropriate to such conditions. These measures will be further scrutinised under the condition of MDCs in Chapter 5.

Bus stops are considered as an important component of bus services, which provide the accessibility for passengers to use public transport. The measures for bus stops basically include a determination of their location relative to traffic signals, an application of bus bays, curb extension, or boarding islands. Under the condition of MDCs, the measure involving the determination of on-line bus stop location will be focused since it might have consider impacts on capacity and traffic flow quality of intersection approaches involved. For this reason, the location of bus stops will be studied in detail in Chapter 5.

In addition, supportive measures such as parking restrictions or prohibitions, extra traffic regulations and enforcement, improvement of lane separation, traffic rerouting, infrastructure measures, etc. were recommended for MDCs. In the following chapters, these measures will be addressed in combination with principal measures when necessary.

It should be noted that most of the experience of bus prioritisation is acquired from industrialised cities. In addition, among those cities, the effectiveness of each priority measure can vary because of dissimilarities in traffic situation and local conditions. More importantly, the situation is much different in motorcycle dependent cities where traffic flow is dominated by a large number of motorcycles. Therefore, it is necessary to examine existing problems and specific conditions of MDCs before a further study on these measures. The related issues will be discussed in the next chapter.

4 Specific Aspects of Bus Prioritisation in MDCs

4.1 Situation of Urban Transport

4.1.1 General Situation

The general situation of urban transport in MDCs is briefly delineated in Figure 23. In this figure, the major prevailing problems of urban transport are classified into two different groups including the causes and consequences of the problems. Then they are discussed one after the other in the follow-up sections.

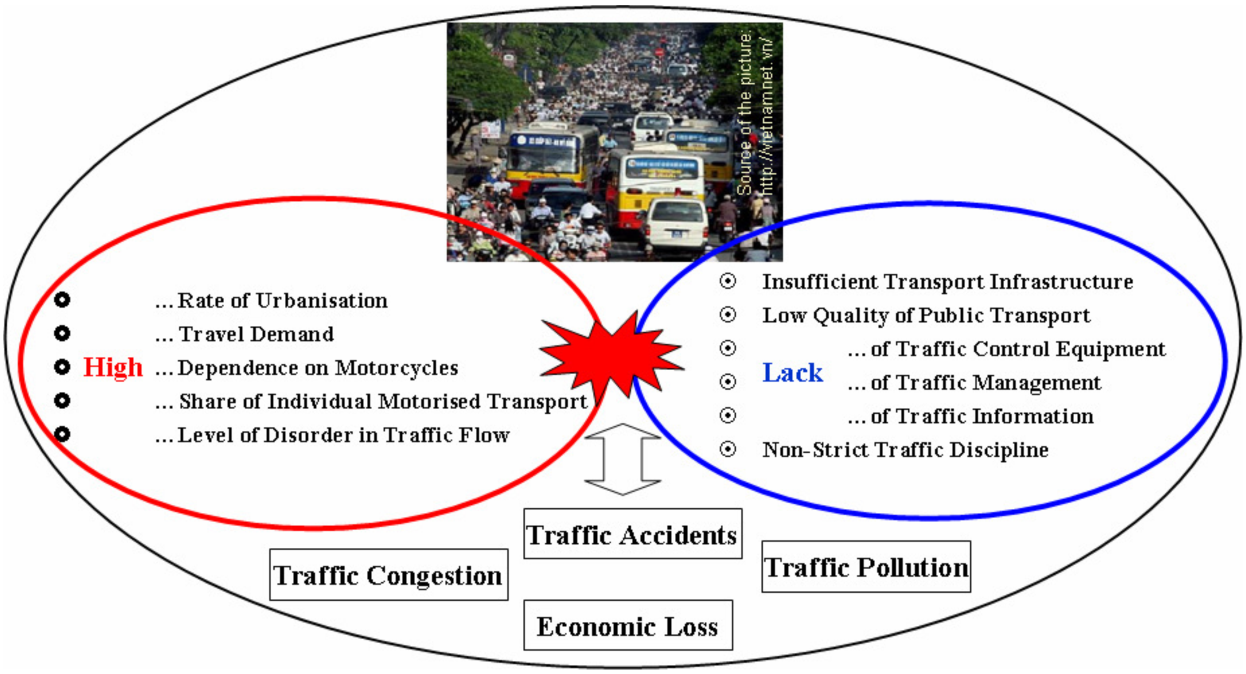

Figure 23: General situation of urban transport in MDCs

4.1.2 Causes

High Rate of Urbanisation

According to the World Bank (2000), urbanisation is defined as "*a process of relative growth in a country's urban population accompanied by an even faster increase in the economic, political, and cultural importance of cities relative to rural areas*". It is a worldwide trend, being a natural consequence and stimulus of economic development in most countries. The progress of urbanisation in developing countries is taking place much faster than in developed ones.

Obviously, a faster process of urbanisation in developing countries generally accompanies by a rapid growth of population in their cities. However, the expansion of urban transport systems, particularly transport infrastructure cannot follow the rapid increment of transport demand. Consequently, that process has brought a number of transport problems involving motorisation, traffic congestion, traffic pollution, and traffic accidents to these cities.

For example, urban population of Vietnam was recorded about 30% of total population in 2010. Estimations show that the rate of urbanisation in Vietnam is around 3% annually between 2010 and 2015, compared to that of 0% in Germany, 1.2% in the United States, 1.7% in Indonesia, and 1.8% in Thailand. [10] The two largest cities of Vietnam, namely Hanoi and Ho Chi Minh City (HCMC), are ranked among the most populated cities in Asia, with their population (2010) of 6.56 million and 7.39 million respectively [General Statistics Office (2011)]. Besides, in these cities, the population concentration of urban core areas is often very high (e.g. greater than 20,000 inhabitants/km^2) compared to other cities. The following figure shows the expansion of urban areas in Hanoi from 1983 to 2003.

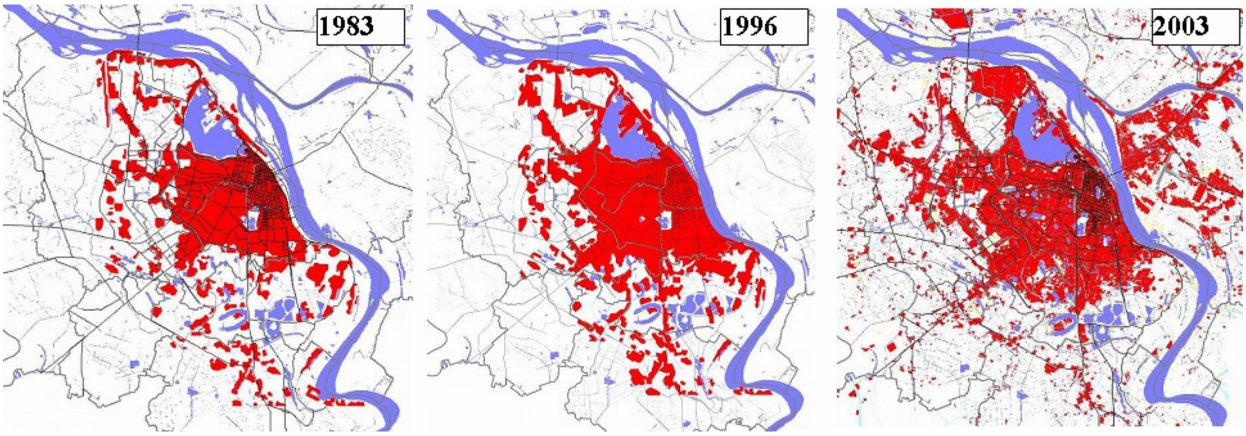

Figure 24: Expansion of urban areas in MDCs, an example of Hanoi from 1983 to 2003
[Unknown scale maps, source: JICA & HPC (2007)]

High Travel Demand

Due to dense population and relatively high daily trip rates in urban areas, travel demand in MDCs is considerably high. For instance, the average daily trip rates of Hanoi (2005) and HCMC (2002) were about 2.7 and 3.0 trips/person/day respectively, compared to 1.7 trips/person/day in Jakarta (2002) and 2.3 trips/person/day in Bangkok (1995) [JICA & HPC (2007)]. These rates are also relatively comparable to those in developed countries. For example, the average daily trip rate in Germany (2008) was 3.41 trips/person/day [Deutsches Institut für Wirtschaftsforschung (2011)].

In HCMC, it was estimated that there were 15.9 million trips (including walking trips) per day accounted for the year 2002. During the observation time between 1996 and 2002, the growth rate of both daily trip rate and total trips increased annually by around 8%. It is forecasted that the total demand will increase by 2.4 times from 2002 to 2020. In the case of Hanoi, the total travel demand (including walking trips) was 11 million trips per day in 2005, and it is estimated to increase to 18 million trips per day by 2020. [JICA, MOT, HCMC-PC. (2004); JICA & HPC (2007)]

[10] The data were retrieved from Central Intelligence Agency (2011)

Besides, the variability of travel demand is another problem (see Fig. 25). Since large proportions of total travel demand are concentrated during certain periods of the day (called peak periods), they potentially result in overloaded situation for the road network in these cities.

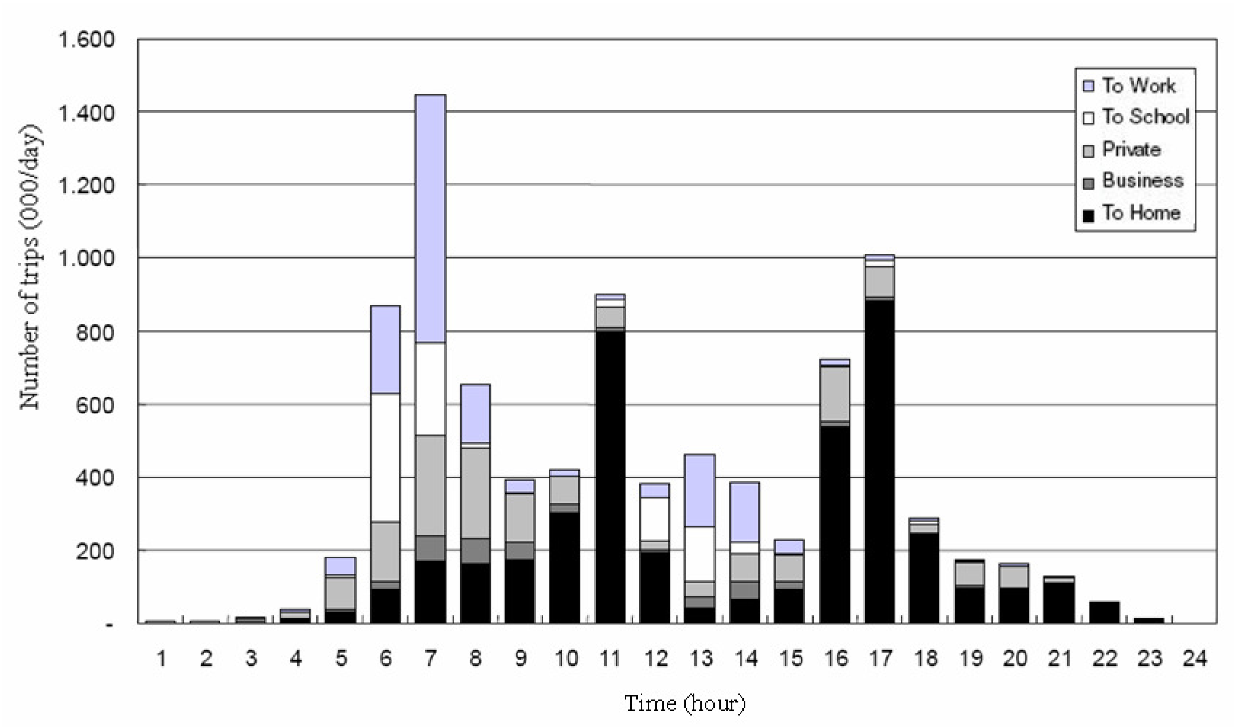

Figure 25: Hourly distribution of travel demand in MDCs, an example of Hanoi (2005)
[Source: JICA & HPC (2007)]

High Dependence on Motorcycles

The term "Motorcycle Dependence" was introduced by Khuat (2006) in his dissertation "Traffic Management in Motorcycle Dependent Cities". To define the level of motorcycle dependence, he used three groups of indicators, including the vehicle ownership, the availability of alternatives to individual motorised vehicles, and the use of motorcycles. Based on these indicators, Hanoi, Ho Chi Minh City, Delhi, Jakarta, Bangkok, and Taipei are considered as Motorcycle Dependent Cities (MDCs). These cities have different levels of motorcycle dependence, ranging from low to high levels. Among them, Hanoi and Ho Chi Minh City were determined as the typical motorcycle dependent cities. The dependence of urban transport on motorcycles is very high in both Hanoi and HCMC. The motorcycle ownership in Hanoi and HCMC was about 400 motorcycles per 1000 inhabitants, being much higher than other MDCs (266 motorcycles/1000 inhabitants in Bangkok, 174 motorcycles/1000 inhabitants in Delhi, and 165 motorcycles/1000 inhabitants in Jakarta). [Khuat (2006)]

Already in HCMC (2002), it was estimated that 90% of households possessed their own motorcycles, in which 53% of them had two or more than two motorcycles. During the period from 1996 to 2002, the number of motorcycles was doubled to more than 2 million. For the case of Hanoi, the annual growth rate of motorcycle was 14% during the period between 1990 and 2003. [JICA, MOT, HCMC-PC. (2004); JICA & HPC (2007)]

By 2012, the number of motorcycles in Hanoi and HCMC had been already over 3.5 and 4.5 million, respectively.

To some extent, motorcycles are contributing their role to passenger transport of these cities due to their mobility and their relative efficiency in utilising road space. However, high level of motorcycle dependence is also posing many problems for urban transport in these cities.

High Share of Individual Motorised Transport

The rapid increase in ownership and usage of private vehicles has led to a high proportion of individual motorised transport and unbalanced modal share of urban passenger transport in these cities. More critically, the modal share of non-motorised transport (cycling and walking) and public transport remains at inadequate levels.

In HCMC, for instance, there was a considerable decrease in the share of bicycles between 1996 and 2002, dropping from 32% to 14%. In 2002, the share of public transport was only about 1.4% while the share of individual motorised transport (motorcycles and cars) was around 65%. [JICA, MOT, HCMC-PC. (2004)]

As shown in Figure 26, the share of public transport in Hanoi and HCMC was much smaller than that in other Asian cities. This unbalanced modal share constituted by a low proportion of public transport and a high proportion of individual motorised transport reveals the unsustainable urban transport systems in both of these cities.

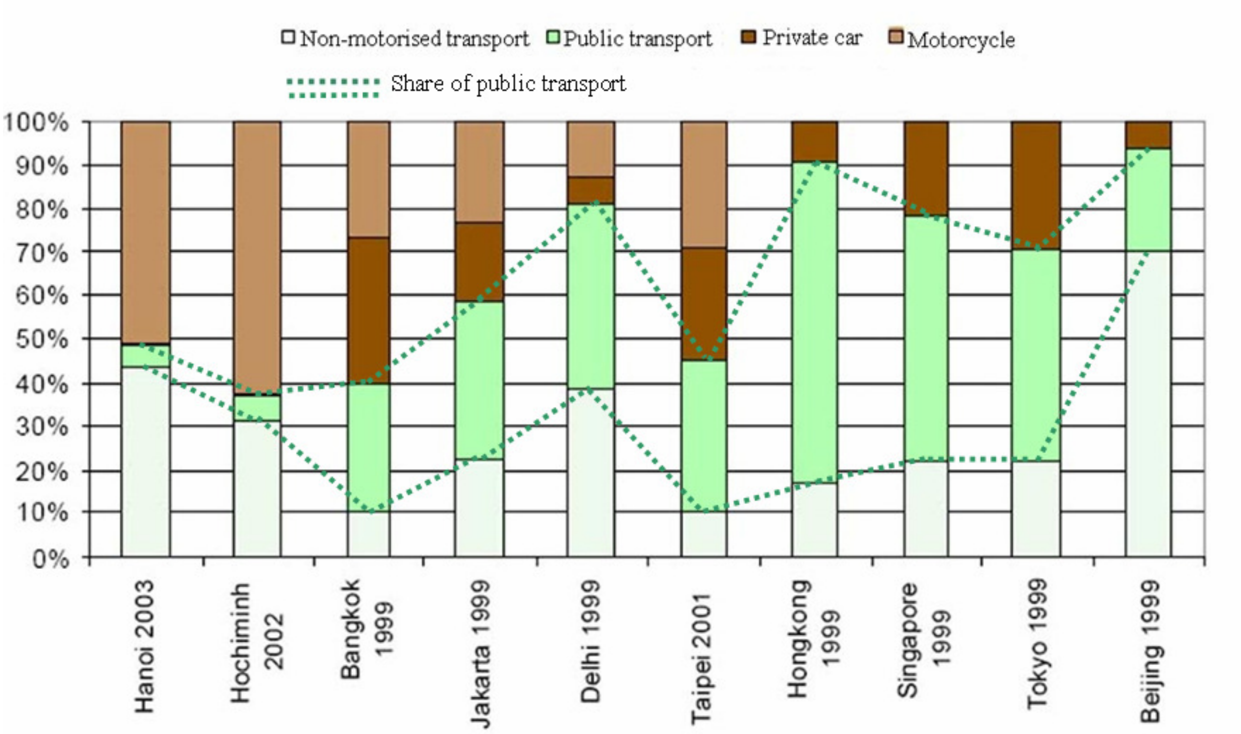

Figure 26: Modal split of passenger transport in some Asian cities
[Retrieved from Khuat (2006)]

High Level of Disorder in Traffic Flow

Mixed traffic conditions dominated by motorcycles in conjunction with lack of orderly traffic movements lead to a distinguishable picture of traffic flow in MDCs, compared to that in industrialised cities. Apart from the common vehicles such as cars, buses, trucks, and bikes as in industrialised cities, there are a large number of motorcycles being used in MDCs. Furthermore, in some places, tricycles, and other types of vehicles are still being used. Consequently, different types of vehicles along with spontaneous driving behaviour of road users (particularly motorcyclists) and lack of complying with right-of-way rules are making traffic flow in MDCs highly disordered, particularly during peak hours (see Fig. 27).

Figure 27: Examples of mixed and disordered traffic flow in MDCs
[Retrieved from websites (http://baodatviet.vn/, http://tamnhin.net/, http://laodong.com.vn/)]

Insufficient Transport Infrastructure

Basically, passenger transport of large cities must be based on both road and rail transport, but one of them is being absent in both Hanoi and HCMC at this time. In the past, tramway systems occurred quite early (from 1880s to 1900s) in these cities. However, due to some reasons, they were removed several decades ago.

Figure 28: Early existence of tramways in Hanoi and HCMC
[Retrieved from websites (http://vov.vn, http://phapluattp.vn)]

At present, thereby, passenger transport in these cities is being dependent on road transport (see Fig. 29). However, the quality of road transport is degrading because of its insufficient infrastructure and facilities against an increasing number of private vehicles. For instance, many streets have inadequate widths and different cross sections. There are very few bus lanes and bicycle lanes in these cities. Currently, most of buses are operating on mixed traffic lanes without priority considerations. Pedestrian environment is generally insufficient in both quantity and quality even though it is one of the most important factors to encourage the use of public transport. Parking facilities are also a critical concern in these cities.

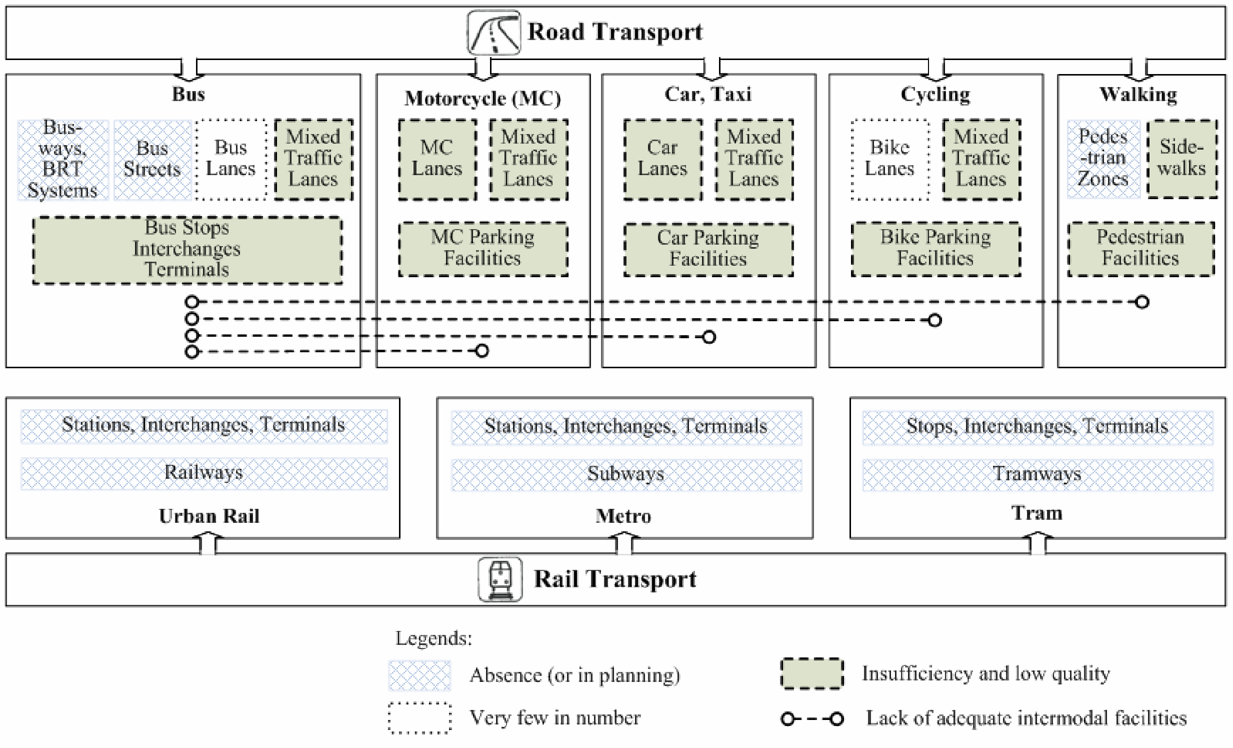

Figure 29: General situation of infrastructure[11] for passenger transport in Hanoi and HCMC (2011)

Low Quality of Public Transport

As mentioned previously, public transport in Hanoi and HCMC is relying mainly on bus services. However, their quality remains at low levels. Normally, buses are overloaded and they suffer high and unpredictable delays in congested mixed traffic during peak hours (see Fig. 30).

Figure 30: Examples of poor quality of bus services in Hanoi and HCMC

[11] Water transport and air transport were not mentioned due to their inconsiderable modal share of urban passenger transport.

In addition, lack of adequate facilities (incl. vehicles, bus stops, control equipment, etc.) for bus services impacts adversely on their quality. Furthermore, improper passenger information (incl. incomprehensible, unclear, and inflexible information as well as unavailable information at the beginning, during, and after the journey) is another causative factor to reduce the attractiveness of bus services in MDCs [Kittler (2004)].

Consequently the speed, travel time, punctuality, reliability, convenience, and comfort of bus services are being affected seriously. At present, buses are not a favourable transport mode in the perception of most citizens.

Lack of Adequate Traffic Control Equipment

In MDCs, traffic control devices such as traffic signs, pavement markings, signal control devices, etc. have been insufficient. They are not appropriate for the requirements of urban transport systems, particularly for mixed traffic conditions with high traffic loads. Most of them are old or backward, not being modernised for many years. In addition, nearly all traffic devices are operating statically, i.e. they cannot adapt to the change of traffic situation (see Fig. 31).

Figure 31: Examples of traffic control devices in MDCs (Vietnam)

For instance, there are currently about 1,400 intersections in HCMC; however, only about 590 of them are equipped with signal control.[12] Most of traffic signals are operating with fixed-time programs, mainly having two-phase control (i.e. left-turning movements are mostly not protected by signalisation). Beside, most of traffic signals are old and different in types (see Fig.32). At some signalised intersections, pedestrian signals are not provided or provided for only one side. Due to lack of proper connections between local controllers and control centres, most of traffic signals are operating independently. [JICA, MOT, HCMC-PC. (2004)]

A lack of official guidelines is posing many problems for improving traffic signal control in MDCs. This issue was deeply studied by Do (2009) in his research "Traffic Signals in Motorcycle Dependent Cities". He concluded that most of signal programs have not been designed appropriately due to lack of knowledge and technology. For example, current signal programs are operating with inadequate signal phasing, unreasonable green times and intergreen times, inadaptable program elements, lack of consideration for pedestrians, etc. From these deficiencies, the guidelines for traffic signals in MDCs are in progress of being issued.

[12] The data were supported by Ho Chi Minh City Department of Transport in 2011.

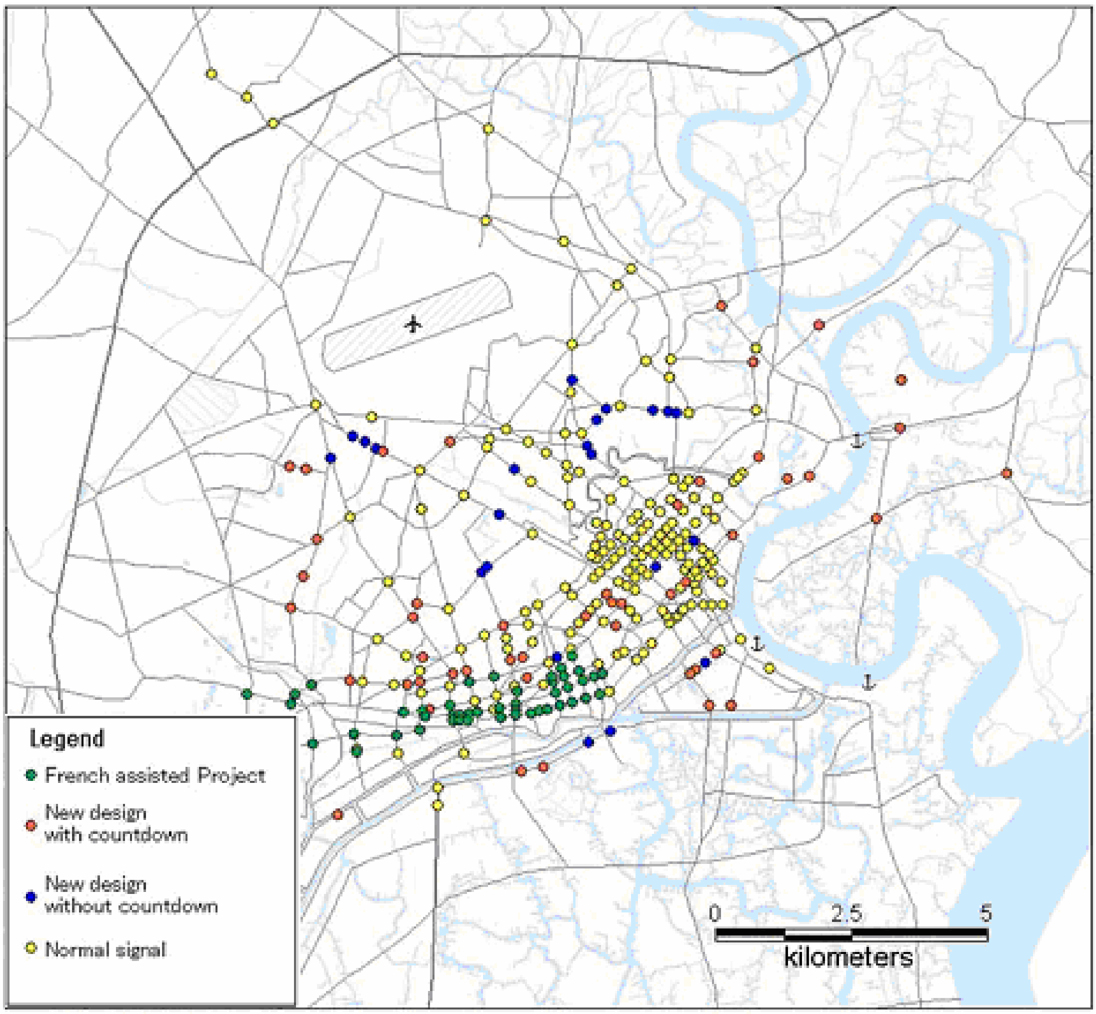

Figure 32: Arrangement of traffic signals in MDCs, an example of HCMC
[Retrieved from JICA, MOT and HCMC-PC (2004)]

Lack of Implementing Traffic Management Measures

According to Boltze (2003), the aim of traffic management is "to influence traffic and transport with a bundle of measures to bring travel demand and supply of transport systems in an optimised balance". Traffic management involves a number of measures which aim to avoid, to shift, and to control traffic (see Fig. 33).

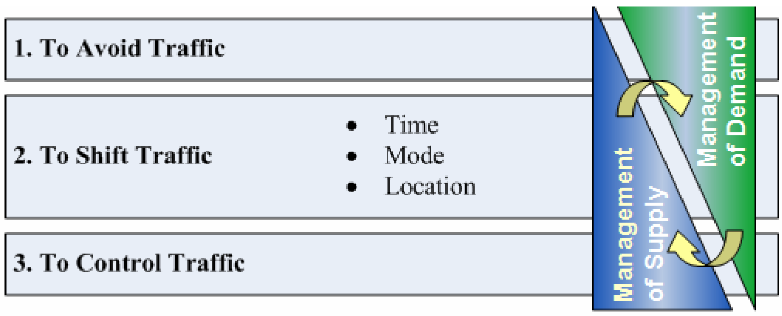

Figure 33: General principles of traffic management
[Source: Boltze (2003)]

Regarding traffic management measures in MDCs, Khuat (2006) proposed five groups of measures, including (i) public transport measures, (ii) non-motorised transport measures, (iii) individual motorised measures, (iv) multimodal and intermodal transport measures, and (v) freight transport measures. These measures were classified into different priority levels depending on their effectiveness (involving mobility, safety, environment and resources, and economy) as well as their applicability (involving cost of measure, technical systems, institution, and public acceptance).

In comparison with constructional measures which often require high investment costs (for planning, implementation, operation, and maintenance) and long periods, traffic management measures basically do not require such requirements. When the development of infrastructure is not able to satisfy the increment of traffic demand, traffic management measures can be a suitable solution. However, they have not been applied sufficiently and effectively in MDCs, especially the measure groups which prioritise public transport and non-motorised transport.

Lack of Traffic Information

The provision of traffic information, especially real-time information will help both road users and operators optimise their purposes and minimise the impact of traffic problems. That information basically includes three basic groups of information: (i) passenger information; (ii) general information involving road conditions (traffic congestion, detours, warnings of incidents, etc.), and (iii) individual information (routing, parking, etc.). Furthermore, the proper integration and distribution of traffic information between operators, users, agencies, enterprises, and other related parties will enhance mobility, safety, efficiency, and sustainability of urban transport systems.

However, traffic information has not been considered appropriately in MDCs, e.g. road users nearly do not receive any real-time information when they travel on roadways.

Non-Strict Traffic Discipline

Analysing traffic situation in Hanoi, Fornauf (2009) concluded that traffic rules and regulations are ignored by a number of road users. Among those rules, he found that right-of-way rules, signalisation's rules, and other rules regulated by traffic signs are the most common rules to be violated. Besides, lack of sufficient traffic education and traffic enforcement is also the consequence of non-strict traffic discipline in MDCs.

In general, non-strict traffic discipline in MDCs is mainly derived from the following activities:

- Violation of traffic regulations given by traffic signs,
- Violation of traffic rules regulated by signalisation and pavement markings,
- Disregard for right-of-way rules,
- Violation of pedestrian environment,
- Spontaneous driving behaviour in the range of intersections, and
- Illegal parking and stopping activities on roadways.

4.1.3 Consequences

Traffic Accidents

According to WHO (2009), globally, more than 1.2 million people lost their lives each year because of traffic accidents on the road. In general, traffic accidents in low-income and middle-income countries are much more critical than those in high-income countries. For instance, the mortality rate caused by traffic accidents per 100,000 inhabitants is 21.5 in low-income countries and 19.5 middle-income countries, compared to 10.3 in high-income countries. Furthermore, although having only 48% of the world's vehicles, low-income and middle-income countries make up about 90% of the world's fatalities on roadways.

In Vietnam (2012), there were 10,081 incidents recorded, leading to 9,838 deaths and 7,624 injuries. In one day, on average, there were about 28 accidents which killed 27 persons and injured 21 persons in this country.[13] According to statistics, most of traffic accidents in Vietnam were involved motorcycles, making up about 60 to 70% of the total number of incidents, injuries, and fatalities.

In MDCs, traffic accidents are now becoming a serious concern for both citizens and local authorities. In HCMC (2011), for example, there were 994 incidents recorded, leading to 842 fatalities and 461 injuries [Ho Chi Minh City Fatherland Front Committee (2012)]. The number of accidents was observed to reduce gradually in recent years. However, the mortality rate caused by traffic accidents in both Hanoi and HCMC is still much higher than that in industrialised cities.

Traffic Congestion

In industrialised cities, generally, traffic congestion occurs because of special incidents (e.g. constructional sites, accidents, weather conditions, etc.), or a sudden increase in traffic demand due to special events (e.g. exhibition, sport, or music events).

In MDCs, however, apart from those factors, the high to overloaded traffic demand, lack of control equipment, and non-strict traffic discipline can be additional factors for traffic congestion in these cities. It occurs quite often during peak periods, mostly at intersections (the most critical points in the urban road network) because of their insufficient capacities and potential obstructions.

In Ho Chi Minh City, for instance, there were 54 congestion incidents which lasted for over 30 minutes in 2010 [Ho Chi Minh City Department of Transport (2010)]. In 2012, traffic congestion was observed at 67 and 76 congestion points in Hanoi and Ho Chi Minh City, respectively [Ministry of Transport of Vietnam (2013)]. At present, traffic congestion is one of the most serious traffic problems for these cities.

Traffic congestion has negative impacts on many aspects such as the increased travel time, reduced mobility, waste of fuel consumption, air pollution, health problem, economic loss, etc.

[13] The data were retrieved from the website of Ministry of Transport [http://giaothongvantai.com.vn/. (2013)]

Pollution Caused by Traffic

Exhaust Emissions

Since motorised transport normally requires the combustion of fossil fuels to produce energy translated to propulsion, air pollution is a result of that process. It produces various pollutants such as carbon monoxide, carbon dioxide, soot, various gaseous and liquid vapour hydrocarbons, oxides of sulphur and nitrogen, sulphate and nitrate particulates, ash, and lead. Among these pollutants, the most principal ones which impact adversely and critically on human health include lead, various types of particulate matter, ozone, various toxic VOCs[14], nitrogen dioxide, ammonia, and sulphur dioxide. [Gorham (2002)]

According to WHO (2004b), particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2) have adverse effects on both the respiratory system and cardiovascular system. These effects are also related to the short-term and long-term exposure as follows:

- Short-term exposure: lung inflammatory reactions, respiratory symptoms, adverse effects on the cardiovascular system and respiratory symptoms, effects on pulmonary function, increase in medication usage, increase in hospital admissions, and increase in mortality.
- Long-term exposure: increase in lower respiratory symptoms, reduction in lung function especially in infants and children, reduction in lung function development, and reduction in life expectancy.

Although traffic pollutants cause many serious problems for human health, they have not been considered adequately in MDCs, particularly in Hanoi and HCMC.

The report from Vietnamese Ministry of Natural Resources and Environment (2007) indicates that air quality in most areas of Hanoi and HCMC is being at critical levels. For instance, the annual mean value of PM_{10} concentration in HCMC (the years 2003–2006) was around 80 $\mu g/m^3$, compared to Vietnamese limit value of 50 $\mu g/m^3$, and the suggested value of 20 $\mu g/m^3$ from the guidance of WHO (2006). Considerably, a value of over 200 $\mu g/m^3$ was recorded at one measurement station in Hanoi in the years 2003 and 2004. Besides, the one-hour mean value of total suspended particulates (TSP) concentration on roadways was very high, ranging from 310 to 2690 $\mu g/m^3$ in HCMC (January 2002–June 2007), and about 500 $\mu g/m^3$ in Hanoi (January 2006–June 2007), compared to Vietnamese limit value of 300 $\mu g/m^3$. Apart from particulate pollutants, NO_2, SO_2, and CO concentrations in core areas of these cities were also at high levels.

Noise Emissions

Noise emissions are also remaining at critical levels in MDCs. For example, noise levels of 90–100 dB(A) were measured in some streets in Hanoi. In HCMC (2005), noise levels ranging from 66 to 87 dB(A) were recorded in some residential areas, which notably exceeded the limit level of 60 dB(A). [Vietnamese Ministry of Natural Resources and Environment (2007)]

[14] Volatile organic compounds

The main factors influencing noise emissions mainly include the distance to the place of exposition, road surface type, traffic demand, vehicular conditions, share of heavy vehicles, driving speed, quality of traffic flow, and weather condition [Boltze & Kohoutek (2009)]. In MDCs, the place of exposition, traffic demand, vehicular conditions, quality of traffic flow, and weather conditions can be considered as the most disadvantageous factors causing high levels of noise emissions, compared to those in industrialised cities.

Economic Loss

The economic loss caused by traffic problems in MDCs basically involves the loss of persons and properties due to traffic accidents, increased travel time due to traffic congestion, reduced mobility and economic efficiency, environmental pollution, human health problems caused by environmental degradation, waste of energy for transport, vehicular worn-out problems, etc.

In fact, a full-scale estimation of total economic loss due to traffic problems is likely impossible. However, the loss caused by some aspects can be estimated roughly. For example, the loss of road crash injuries is estimated at roughly 1% of gross national product (GNP) for low-income countries [WHO (2004a)], and the loss of traffic congestion is considered from 2 to 3% of gross domestic product (GDP) for mega cities of developing countries [JICA, MOT, HCMC-PC. (2004)].

4.2 Traffic Problems for Buses

4.2.1 Problems at Traffic Signals

Traffic Signal Control

On urban roadways, the operation of buses is often affected by traffic signals. In MDCs, the main problems for buses caused by traffic signal control often involve the following aspects:

- *Inadequate design of signal programs*: A number of signal programs with their elements such as intergreen times, number of phases, green times, cycle length, and time offset have not been designed properly.
- *Lack of considerations for buses in signal program design*: For instance, insufficient green times for bus-operating directions, absence of signal priority, and lack of signal progression for buses are the main causes for their unreasonable delays at traffic signals (see Fig. 34).
- *Insufficient control strategies at both macroscopic and microscopic levels*: The limitation of signal control strategies impacts adversely on the operation of buses at traffic signals. Regarding macroscopic control strategies, for example, only time-dependent control strategy is being activated manually. For microscopic control strategies, more inappropriately, fixed-time programs are almost being used. Currently, traffic signals cannot be adapted properly to the change of traffic situation.

Figure 34: Examples of unfavourable signals for buses in HCMC (2011) and Hanoi (2009)

Due to the problems of traffic signal control, buses often suffer unreasonable and unpredictable delays at traffic signals, which impact adversely on the operation of bus services.

Intersection Layout

In most cases, approaching lanes for buses at signalised intersections, such as bus lanes or queue jump lanes, are not provided. As a result, buses are potentially impeded critically by extensive queues of vehicles at traffic signals, in particular during peak periods.

Furthermore, pavement markings and lane separation at a number of signalised intersections have not been provided appropriately.

Traffic Behaviour

At traffic signals, the following behaviour of road users can have negative impacts on the operation of buses:

- Priority rules for buses in diverting and merging have not been complied.
- Right-of-way rules are ignored by most road users. For example, buses can be impeded by other vehicles from unprivileged streams, even though they belong to the privileged ones. This situation typically occurs at signalised intersections without protected phases for left-turning movements.

4.2.2 Problems on Travel Ways

Main Impediments

On Non-Signal Affected Segments

Due to high traffic volumes and constrained road space, most of buses are operating on mixed traffic lanes shared with other vehicles (see Fig. 35). The difference in both shape and motion characteristics between buses and other vehicles often leads to their mutual impediments in mixed traffic flow. Due to the limitation in speed, acceleration/deceleration rates, and manoeuvrability, buses normally suffer more disadvantage than other vehicles on non-signal affected segments.

Figure 35: Examples of buses operating on mixed traffic lanes in HCMC (2011)

On Signal Affected Segments

Since space separation between buses and other vehicles is generally not provided in the range of signalised intersections, most of buses are suffering impediments caused by extensive queues during peak hours. Those queues often have serious impacts on the operation of buses and make their travel times unpredictable on signal affected segments.

In addition, the operation of buses is potentially impeded by skewing movements of vehicular traffic in the range of signalised intersections. From field observations, these movements were recognised to have considerable impacts on both buses and other vehicles, particularly when the volume of turning traffic is high but it is not separated appropriately on these segments.

Other Potential Impediments

Apart from the main impediments as mentioned previously, buses might suffer other potential impediments which can be derived from

- Parking or stopping activities on curb-side lanes,
- Local accessing traffic from side streets or alleys,
- Commercial activities on side walks or curb-side lanes, etc.

4.2.3 Problems at Bus Stops

The most common type of bus stops in MDCs is on-line stops which are located directly on the rightmost traffic lanes. These stops are the simplest form of bus stop design, and they are normally placed near traffic signals. However, problems for both buses and other vehicles can be observed at a number of these bus stops.

The first problem is related to inadequate near-side bus stops which are located inside regular queues caused by signalisation. In this situation, buses often have to wait for green times to release the queue before they can reach freely their stops (see Fig.36). For this reason, they most likely miss their first green times at traffic signals because during those times they have to wait for the dissipation of the queue as well as load and upload passengers at their stops. In addition, the approach of buses to the stops is often impeded by densely surrounding two-wheel vehicles. As a result, the risk of collisions between buses and other vehicles might arise. Besides, the performance of buses at their stops is affected adversely, which can lead to improper stopping positions, overused short dwell times, and tendency of skipping services at bus stops. Consequently, passengers who have to board or alight at these stops are confronting with unsafe and inconvenient bus services.

a. The bus stop was blocked by queuing vehicles. b. The bus had to wait for dissipating the queues.

Figure 36: Example of an improper bus stop position before traffic signals (2011)

The second problem is a result of improper far-side stops located right behind signalised intersections. At these stops, stopping buses will narrow down the outflow cross section at the downstream intersection. Under heavy traffic conditions, temporary queues behind the stopping buses might extend, which can impede the regular release of other traffic streams involved, reduce capacity of intersection approaches, and lead to congestion as well.

The third problem involves the skewing movement of buses in the range of bus stops. Under mixed traffic conditions, as mentioned previously, buses often avoid travelling on curb-side lanes if other traffic lanes are available for them. However, they need to enter their stops located on curb-side lanes. In order to get into their stops, they must change their movements between those lanes, resulting in their first skewing movements before the bus stops. After stopping at the stops for the passenger boarding and alighting, they tend to change to a faster lane or make a directional movement, leading to their second skewing movements behind the stops. In heavy traffic conditions, such movements are difficult to perform because of numerous vehicles surrounding them. This situation is much worse when bus stops are close to traffic signals since buses must either wait for a sufficient gap or cut across adjacent traffic streams to perform their movements. Consequently, the skewing movement causes additional delays for buses as well as reduces capacity and traffic flow quality at signalised intersections.

In addition to the mentioned problems, buses might be impeded in the range of their stops by illegal parking or stopping vehicles, other activities, or overloaded bus stops.

4.2.4 Other Problems

Apart from the problems at traffic signals, on travel ways, and at bus stops, the operation of buses can be impacted by other problems of urban transport, such as:

- Overloaded traffic demand in the urban road network,
- High probability of traffic congestion,
- Non-strict traffic discipline, and
- Lack of infrastructure, traffic control equipment, etc.

4.2.5 Problem Sequence of Bus Services

The problems for buses at traffic signals, on travel ways, and at bus stops in conjunction with other problems are causing uncontrollable delays for buses and leading to a reduction in capacity of roadways (see Fig. 37).

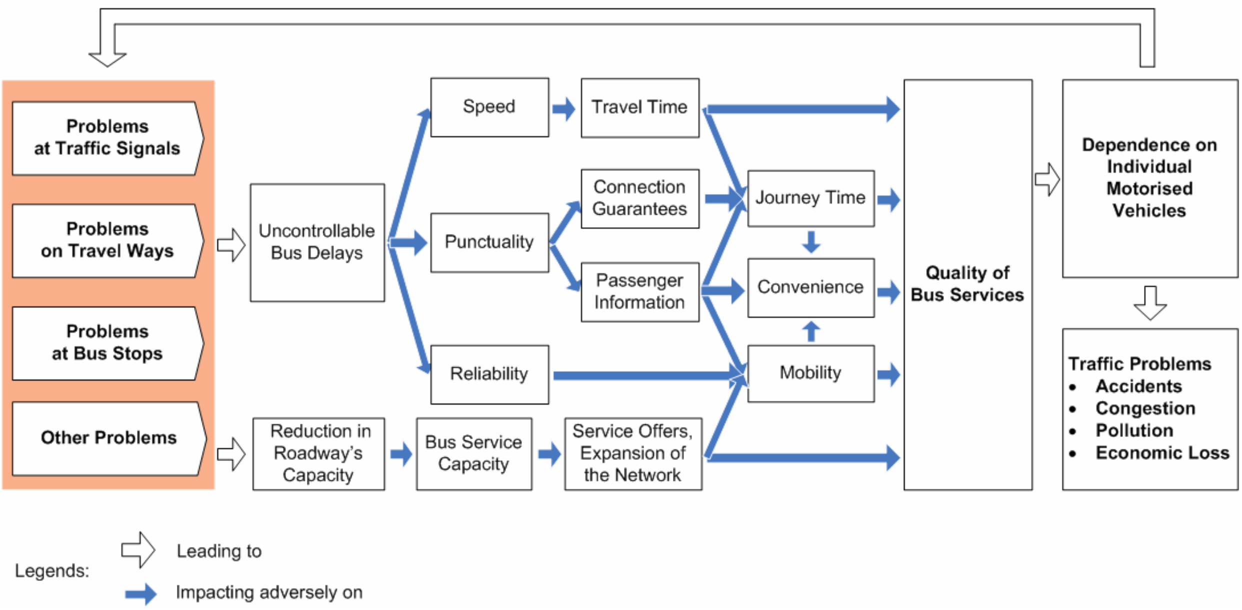

Figure 37: Problem sequence of bus services in MDCs

On the one hand, uncontrollable delays of buses on urban roadways are impacting adversely on the speed, punctuality, and reliability of bus services. On the other hand, the decreased roadway's capacity is influencing negatively the provision (e.g. frequency) and network development (such as spatial expansion, accessibility, and connections) of bus services

Consequently, the travel time, journey time, guarantee of connection, passenger information, mobility, and convenience of buses services cannot be provided properly, which degrade the quality of bus services in MDCs. In fact, the poor quality of bus services in many years is one of the main causes for the dependence of urban transport on individual motorised traffic in these cities.

If corresponding solutions to these problems are not implemented, the problem sequence of bus services will continue acting and causing more serious problems for both bus services and urban transport of these cities in the future. To solve this situation, the concept of bus prioritisation is introduced to MDCs in the following section.

4.3 Bus Prioritisation for MDCs

4.3.1 Definition and Objectives

Bus Prioritisation is defined as an important component of *Bus Service Acceleration*[15]. It is comprised of four groups of measures: bus stops, travel ways, traffic signals, and supportive measures (see Fig. 38).

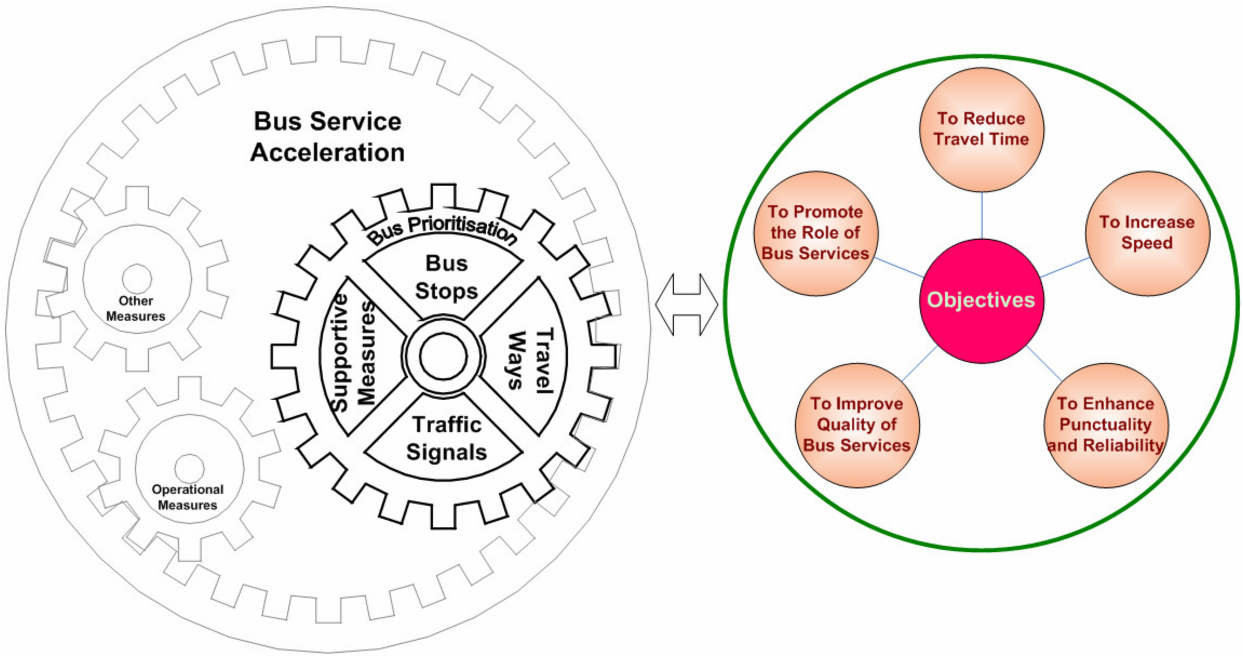

Figure 38: Definition and objectives of bus prioritisation for MDCs

The main objectives of bus prioritisation are to reduce bus travel time, to increase bus speed, to enhance punctuality and reliability, to improve the quality of bus services, and to promote the role of bus services in MDCs. In addition, bus prioritisation also aims to maximise and integrate benefits of the community, users, and operators in the short, medium, and long term.

The benefits of bus prioritisation to the relevant participants are given as follows:

- Community: improvement of safety, roadway capacity, environmental sustainability, and economic efficiency.
- Users: acquisition of a better quality of public transport services regarding punctuality, reliability, time savings, convenience, and comfort.

[15] The term "Bus Service Acceleration" is based on „Merkblatt für Maßnahmen zur Beschleunigung des ÖPNV mit Straßenbahnen und Bussen", FGSV (1999).

- Operators: improvement of service efficiency by savings of drivers, vehicles, and fuel consumption; enhancement of service quality; opportunities of improving service attractiveness, expanding service offers, and increasing public transport ridership.

4.3.2 Quality Measures for Bus Services

Level of service (QSV[16]) is used to evaluate the quality (quality of service) of bus services. In Germany, it is classified into six levels denoted by the capital letters from A (the best level) to F (the worst level). Generally, six criteria are used to determine the quality of bus services [HBS—FGSV (2001a); FGSV (2010a)], consisting of

- Travel time ratio between buses and individual motorised vehicles,
- Average travel speed of buses,
- Transport quality inside transit vehicles,
- Punctuality and guarantee of connections,
- Average waiting time of buses at traffic signals, and
- Probability of operating disturbances at bus stops (this criterion is used for buses operating on exclusive bus lanes only).

In MDCs, due to a lack of quantitative measures to characterise operational conditions of bus services in mixed traffic conditions, the quality of bus services has not been evaluated in most cases. For this reason, it is necessary to propose a set of quality measures based on the experience from a developed country such as Germany.

Therefore, three major criteria are proposed to determine the level of service for buses operating in mixed traffic conditions in MDCs. These criteria include average waiting time at traffic signals (w_{Bus}), average travel speed (V_{Bus}), and travel time ratio between buses and individual vehicles (t_{Bus}/t_{IV})[17]. They are provided in the following table.

Table 5: Proposal of criteria for the quality assessment of bus services in MDCs

Level of Service	Average waiting time at traffic signals, w_{Bus} [s]	Average travel speed V_{Bus} [km/h]	Travel time ratio t_{Bus}/t_{IV} [-]
A	≤ 5	≥ 24	< 1.0
B	≤ 15	≥ 22	1.0 to <1.5
C	≤ 25	≥ 19	1.5 to < 2.1
D	≤ 40	≥ 15	2.1 to < 2.8
E	≤ 60	≥ 10	2.8 to < 3.8
F	> 60	< 10	≥ 3.8

[Adapted from HBS—FGSV (2001a), FGSV (2010a)]

16 QSV stands for “Qualitätsstufen des Verkehrsablaufs” in German language. [LOS is equivalent in English.]

17 IV: individual vehicles

4.3.3 Specific Conditions and Assessment Parameters

Specific Conditions for Bus Prioritisation

Compared to general conditions of industrialised cities, the condition of MDCs can be considerably different. Thereby, the most distinguishable conditions of these cities should be taken into account thoroughly for an application of bus prioritisation. These conditions are depicted as follows:

- Traffic flow: mixed traffic conditions dominated by motorcycles.
- Traffic volumes: high traffic volumes on urban roadways during peak periods.
- Road space: restricted space for infrastructure measures.
- Prevailing traffic signal control: fixed-time programs with improper signal coordination.
- Traffic loads at signalised intersections: normally ranging from high to oversaturated levels during peak periods.
- Travel ways for buses: almost consisting of mixed traffic lanes.
- Bus stops: mostly including on-line bus stops located near traffic signals.

Assessment Parameters

Based on the assessment of traffic flow quality at traffic signals [RiLSA—FGSV (1992); HBS—FGSV (2001)] and the guidance on bus priority [FGSV (1993); FGSV (1999)], a set of parameters is proposed for the assessment of prioritisation measures in MDCs as follows:

- Delay of buses,
- Delay of other vehicles,
- Total person delay,
- Number of stops of buses,
- Number of stops of other vehicles,
- Queue length,
- Capacity of intersection approaches,
- Travel time ratio between buses and other vehicles, and
- Average travel speed of buses.

4.3.4 Factors of Success and Hindrances

Factors of Success

Public Acceptance

One of the most important factors to ensure a success in bus prioritisation is a clear endorsement of the community and local authorities in these cities. An increasing awareness of traffic accidents, traffic congestion, environmental pollution, and economic loss due to the unsustainable urban transport is transparent to both citizens and local authorities. For instance, the development of bus services and the improvement of their quality are determined as an important task of Hanoi and HCMC in order to reduce serious impacts from traffic problems in these cities [Ministry of Transport of Vietnam (2013)]. Therefore, an application of bus prioritisation will be highly encouraged in MDCs.

Technical and Functional Aspects

Technical and functional aspects regarding signal control systems (hardware and software), detection systems, and communication systems for certain prioritisation measures have been currently feasible and well tested in developed countries since they have been applied there for many years. By utilising that experience, an application of these systems to MDCs will be promisingly successful.

Effectiveness

Bus prioritisation provides benefits not only for passengers but also for the community and public transport operators. Its effectiveness mainly consists of an improvement of the speed, travel time, punctuality, reliability, and quality of bus services. More significantly, a higher quality of bus services will lead to a larger share of public transport in MDCs, which contributes to the safety, mobility, capacity efficiency, environmental sustainability, and economic efficiency of passenger transport. Thereby, this fundamental effectiveness of bus prioritisation can be a key point for a decision on its application.

Hindrances

Traffic Discipline

Lack of strict compliance with traffic rules and regulations of road users can be considered as one of the most challenging hindrances. In the condition of non-strict traffic discipline, the effectiveness of bus prioritisation measures can be affected adversely. To solve this hindrance, traffic control, surveillance, education, and enforcement should be considered carefully at the same time.

Organisational and Institutional Aspects

The main issue regarding organisational and institutional aspects consists of (i) lack of cooperation and coordination between related institutions, (ii) overlaps in functions between these institutions [Khuat (2006); Fornauf (2009)]. For instance, the governmental structure of bus services in Hanoi and HCMC is based on the three-level model, including political level represented by City People's Committee, directorate level (e.g. Hanoi transport and urban works and services, Hanoi urban transport management and operation centre), and enterprise level (e.g. Hanoi transport and services corporation). Insufficient cooperation between related institutions as well as their unclear responsibilities can cause delays for the application and effect control of bus prioritisation in these cities. Thereby, this issue should be considered and improved in advance.

Costs

Investment costs for implementing bus prioritisation, particularly for the measures involving signal priority can be another hindrance. However, the effectiveness achieved from bus prioritisation can much surpass its investment.

4.4 Conclusions

At the present time, the situation of urban transport in MDCs comprises a bundle of existing problems which are conflicting and impacting on each other in a sophisticated way.

Bus services are not an exception of that overall situation. They are operating with a low quality of service due to their uncontrollable delays, unpunctuality, unreliability, overloaded situation, insufficient passenger information, and so forth. One of the main reasons for a degradation of their quality is that buses are suffering a number of problems at traffic signals, on travel ways, at bus stops, and other problems as well. These problems were analysed comprehensively in respect of their individual elements and their entire sequence. This analysis will be subsequently utilised for the development of bus prioritisation measures.

To deal with the problems for buses and improve the quality of bus services, the concept of bus prioritisation has been proposed for MDCs, consisting of four main groups of measures, namely measures for bus stops, measures for travel ways, measures for traffic signals, and supportive measures. The main objectives of bus prioritisation are to reduce bus travel time, to increase bus speed, to enhance punctuality and reliability, to improve the quality of bus services, and to promote the role of bus services in MDCs. Moreover, bus prioritisation also aims at maximising and integrating benefits of the community, users, and operators.

In order to support the development and assessment of measures, the specific conditions of MDCs and assessment parameters for bus prioritisation were formulated. Besides, the factors of success and hindrances were discussed to clarify the advantageous and disadvantageous aspects for its application. All of these issues are necessary for the development and assessment of prioritisation measures which will be studied in the next chapter.

5 Development and Assessment of Measures

5.1 Measures for Bus Stops

5.1.1 Development of Measures

When determining the location and type of bus stops, certain factors must be taken into account. Generally, these factors can be categorised into six groups, including safety, locality, facilities, acceptability, capacity, and traffic flow quality (see Fig. 39). In reality, these factors are often conflicting and therefore the determination of bus stop location is a challenging task for traffic engineering. In order to balance potential conflicts, a comprehensive insight of the bus stop design into each factor should be gained. This insight will help to generate better solutions to the design of bus stops.

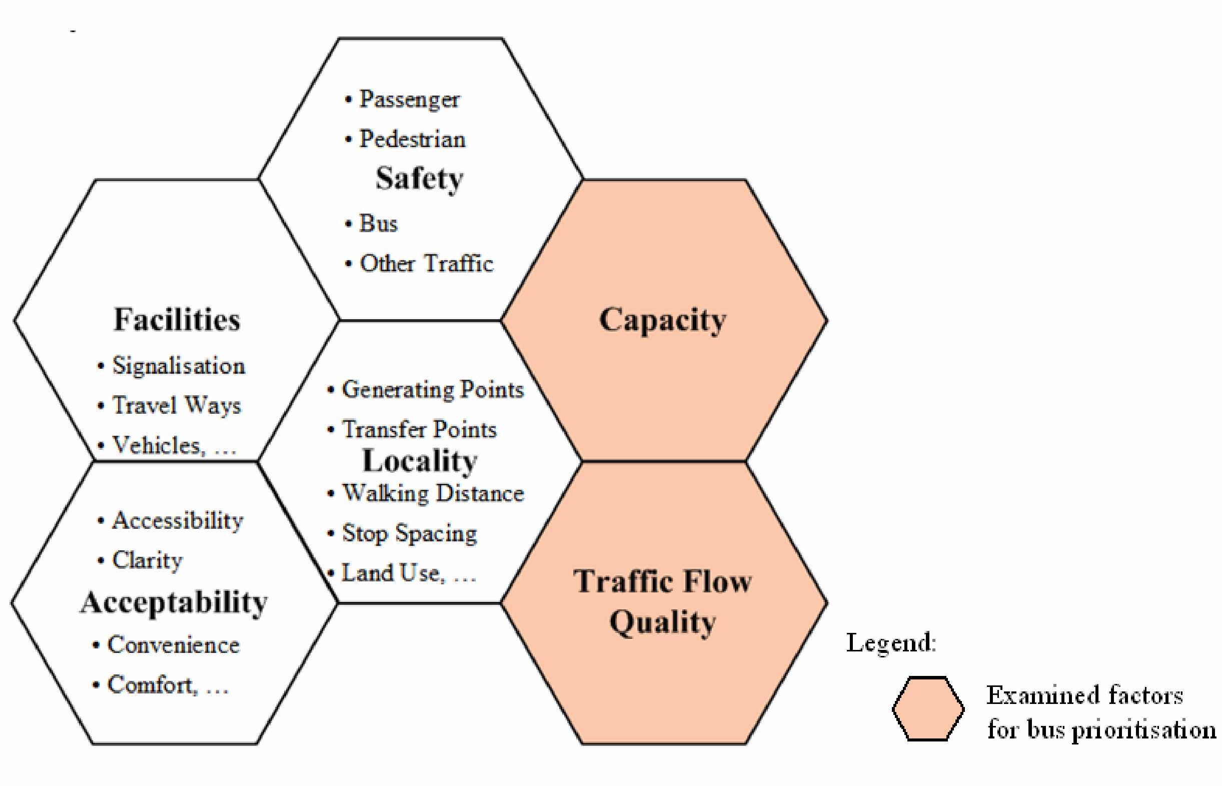

Figure 39: General factors for determining the location and type of bus stops in MDCs

In developed countries, a numbers of rigorous recommendations regarding the factors of safety, locality, facilities, and acceptability for bus stops have been provided [e.g. EAÖ—FGSV (2003), Transportation Research Board (1996), Vuchic (1981), Demetsky et al. (1982), etc.]. These recommendations can be utilised for motorcycle dependent traffic without or with minor modifications. However, recommendations on the impact of bus stops on capacity and traffic flow quality at signalised intersections (as mentioned in Chapter 3, Section 3.4.1) have been still limited in number, and they might not be relevant to the mixed traffic condition dominated by motorcycles in MDCs.

From the analysis (as presented in Chapter 4, Section 4.2.3), it is estimated that both capacity and traffic flow quality of intersection approaches can be reduced considerably if an on-line bus stop is located on them. The impact seems to become more serious when bus stops are situated closely to traffic signals and traffic loads on intersection approaches are high. Therefore, it is necessary to develop measures which enable to reduce side impacts of bus stops on capacity and traffic flow quality at signalised intersections.

In MDCs, as mentioned in chapter 4 (Section 4.2), buses are operating conventionally on mixed traffic lanes with on-line bus stops. This combination often induces a number of problems for both buses and other vehicles, in particular when bus stops are placed near traffic signals. Table 6 summarises the main causes and consequences of problems.

Table 6: Problems of on-line bus stops concerning capacity and traffic flow quality

No.	Problems	Possible Causes	Possible Consequences
1	Obstructions of buses at bus stops	• Vehicular queues during red intervals • Stops being overloaded by other buses • Illegal stopping/parking activities in the range of bus stops	- To impede a free entrance of buses to their stops - To increase delays for buses at their stops - To increase delays for buses at traffic signals - To increase number of stops for buses
2	Obstructions of other vehicles at bus stops	• Stopping buses at their on-line stops	- To impede vehicular traffic on travel lanes involved - To reduce effective green times at traffic signals - To reduce capacity of travel lanes involved - To increase degrees of saturation for lanes involved - To increase delays for other vehicles - To increase number of stops for other vehicles
3	Obstructions due to temporary queues behind bus stops	• Stopping buses at their on-line stops located at inadequate positions (e.g. right behind the intersection)	- To inhibit the regular release of other traffic streams - To reduce capacity of other approaches - To decrease traffic flow quality of other approaches - To increase probability of traffic congestion
4	Impediments due to skewing movements	• Skewing movements of buses in the range of their stops • Skewing movements of other vehicles influenced by stopping buses	- To lead to unsmooth streams at traffic signals - To reduce capacity of approaches involved - To increase delays for buses - To increase delays for other vehicles - To increase number of stops for buses - To increase number of stops for other vehicles
5	Perturbations in the range of bus stops	• Rough alterations in acceleration/deceleration rates	- To lead to jerkily vehicular movements - To increase delays for buses - To increase delays for other vehicles - To increase number of stops for buses - To increase number of stops for other vehicles

From the causes and consequences of the problems, necessary measures are developed in order to solve the problems at bus stops. The following parts provide more details about the development of measures corresponding to given problems.

Obstructions of Buses at Their Stops

The obstruction caused by queuing vehicles during red intervals can be avoided by adjusting the location of bus stops to a proper position at which the stops are not affected by back-queuing vehicles, i.e. bus stops should be placed outside regular queuing areas. Besides, a stop behind the intersection can help to reduce this type of obstruction since the downstream section normally operates under free-flowing traffic conditions.

In addition, the obstruction caused by other sources such as overloaded bus stops and illegal parking/stopping activities can be eliminated or relieved by supportive measures. These measures basically consist of increasing the number of loading areas at bus stops, prohibiting vehicles from parking and stopping illegally in the range of bus stops, and enforcing strictly these rules.

Obstructions of Other Vehicles at Bus Stops

At an on-line bus stop, stopping buses on a mixed traffic lane can interrupt the continual movement of other vehicles on that lane and reduce capacity of the intersection approach involved. Unlike driving behaviour in industrialised cities, road users in MDCs tend to overtake the stopping buses by utilising adjacent lanes. That situation often results in disturbances around the bus stop. The level of disturbances becomes more serious when the stop gets closer to the intersection.

To alleviate this problem, an arrangement of a bus bay is an adequate measure in case space conditions facilitate it. Otherwise, the location of the stop should be adjusted to a proper position at which traffic density is not critical permanently or periodically. In this manner, less constrained overtaking activities can be performed and less interfering encroachment on adjacent lanes can be expected. As a result, this adjustment helps to reduce side impacts of stopping buses on capacity and traffic flow quality of the intersection approach.

Obstructions due to Temporary Queues behind Bus Stops

If an on-line stop is located right after the intersection, the obstruction due to temporary queues potentially occurs, especially under the condition of high traffic loads. These queues can block the regular release of other approaches. Consequently, both capacity and traffic flow quality at the intersection can be decreased noticeably. Besides, these queues can increase the risk of collisions when conflicting streams are released, and they might lead to congestion for the intersection as well.

To avoid this situation, on-line bus stops should not be located right behind signalised intersections. Otherwise, bus bays should be installed.

Impediments due to Skewing Movements

In industrialised cities, basically, individual travel lanes are normally allocated to individual rows of vehicles running on those lanes. In MDCs, however, multiple rows of vehicles are able to operate on one travel lane because of the mixed traffic condition dominated by motorcycles.

Therefore, skewing movements can be commonly observed in mixed traffic flow, particularly at traffic signals and around stopping vehicles. These movements generally contain skewing movements of buses in the rage of bus stops and skewing movements of other vehicles around stopping buses. These movements often induce considerable impediments for both buses and other vehicles. They become serious as they are close to traffic signals at which traffic density is often high. They can impact adversely on capacity and traffic flow quality of intersection approaches.

To reduce impediments caused by skewing movements, bus stops should not be situated closely to traffic signals. Moreover, an arrangement of bus bays will help to reduce skewing movements of other vehicles caused by stopping buses.

Perturbations in the Range of Bus Stops

Rough alterations in acceleration or deceleration rates of both buses and other vehicles are the main cause leading to perturbations in the range of bus stops. These alternations can pose adverse impacts on delays, number of stops, and collision risks for vehicular traffic. In addition, they also induce jerkily movements for vehicles surrounding bus stops, particularly when the stops are close to traffic signals.

A suitable position of on-line bus stops can help to solve this problem. If spatial conditions are not restricted, the replacement of on-line stops by bus bays is recommended.

Summary of Measures for Bus Stops

The measures for dealing with the mentioned problems of on-line bus stops in mixed traffic conditions are summarised in Table 7.

Table 7: Measures for bus stops in mixed traffic conditions

Measures / Problems	Adjustment of bus stop location	Arrangement of bus bays	Implementation of supportive measures
1. Obstructions of buses at their stops, caused by			
- Vehicular queues during red intervals	x		
- Overloaded bus stops			x
- Illegal stopping/parking activities			x
2. Obstructions of other vehicles, caused by			
- Stopping buses at their stops	x	x	
3. Obstructions due to temporary queues, caused by			
- Stopping buses at bus stops located at inadequate positions	x	x	
4. Impediments caused by			
- Skewing movements of buses in the range of bus stops	x		
- Skewing movements of other vehicles	x	x	
5. Perturbations in the range of bus stops, caused by			
- Rough alterations in acceleration/deceleration rates	x	x	

5.1.2 Estimation of Measure Effects

Implementation of Supportive Measures

Supportive measures for bus stops should be implemented in advance to minimise foreseeable problems. These measures basically consist of increasing number of loading areas for overloaded bus stops, prohibiting illegal parking/stopping activities in the range of bus stops, and promulgating priority rules for transit vehicles. These measures will contribute to an increased traffic flow quality of buses.

Arrangement of Bus Bays

An arrangement of bus bays can relieve obstructions of other vehicles and skewing movements caused by stopping buses. In addition, perturbations in the range of bus stops will be reduced significantly. Thereby, capacity and traffic flow quality of intersection approaches will be improved. This measure is highly recommended for streets having a limited number of lanes or for directions operating with signal coordination.

However, it should be noted that typical bus bays with improper positions might not prevent buses from being affected by vehicular queues at traffic signals during red intervals, especially when degrees of saturation on intersection approaches involved are at critical levels. Those queues might still block a free entrance of buses to their stops and result in additional delays for them at their stops as well as at traffic signals. Besides, impediments caused by skewing movements of buses cannot be eliminated by a bus bay.

Adjustment of Bus Stop Location

This measure can be suitable where an expansion of road space for an installation of bus bays is not feasible. Locating bus stops outside regular queuing areas at traffic signals will help buses to avoid waiting for the dissipation of queues at their stops and to minimise the probability to miss the green time. Hence, delays and number of stops can be reduced noticeably for them.

Adjusting the location of bus stops to positions with low to medium traffic density will allow overtaking activities of other vehicles to be performed more easily and smoothly. Besides, temporary queues building up behind bus stops can be reduced significantly. This measure also contributes to reduce skewing movements and perturbations in the range of bus stops. As a result, an increase in capacity of intersection approaches and an improvement of traffic flow quality for both buses and other vehicles can be achieved.

As mentioned in Chapter 4 (Section 4.2.3), on-line bus stops are the most common type of bus stops in MDCs. From the analyses, the location of bus stops is estimated to have noticeable influence on capacity and traffic flow quality of intersection approaches involved. The reason is that the impact of bus stops on those intersection approaches can vary largely, corresponding to different bus stop positions and different traffic loads. An examination of the impact of bus stops at traffic signals will help to clarify the effect of this measure. For this reason, a sensitivity analysis will be conducted in the following section.

5.1.3 Sensitivity Analysis

Study Intersection

To quantify the impact of bus stops on capacity and traffic flow quality of intersection approaches under mixed traffic conditions of MDCs, a hypothetical signalised intersection with a nearby bus stop is examined by utilising traffic simulation tool. In this analysis, traffic conditions were simplified in order to minimise turbulence of some factors (particularly the factors are not related to the bus stop or traffic loads) on the result. Therefore, a one-way approach signalised intersection, just consisting of straight-ahead movements, was formulated in this experiment (see Fig. 40).

At the intersection, buses were allocated to operate in the direction from west to east with a volume of 60 buses/hour. They were assigned to travel on the mixed traffic lanes in combination with the on-line stop located in the range of the intersection. The dwell times at the bus stop were assumed following the normal distribution with the mean of 15 seconds and the standard deviation of 2 seconds—$N(15, 4)$.

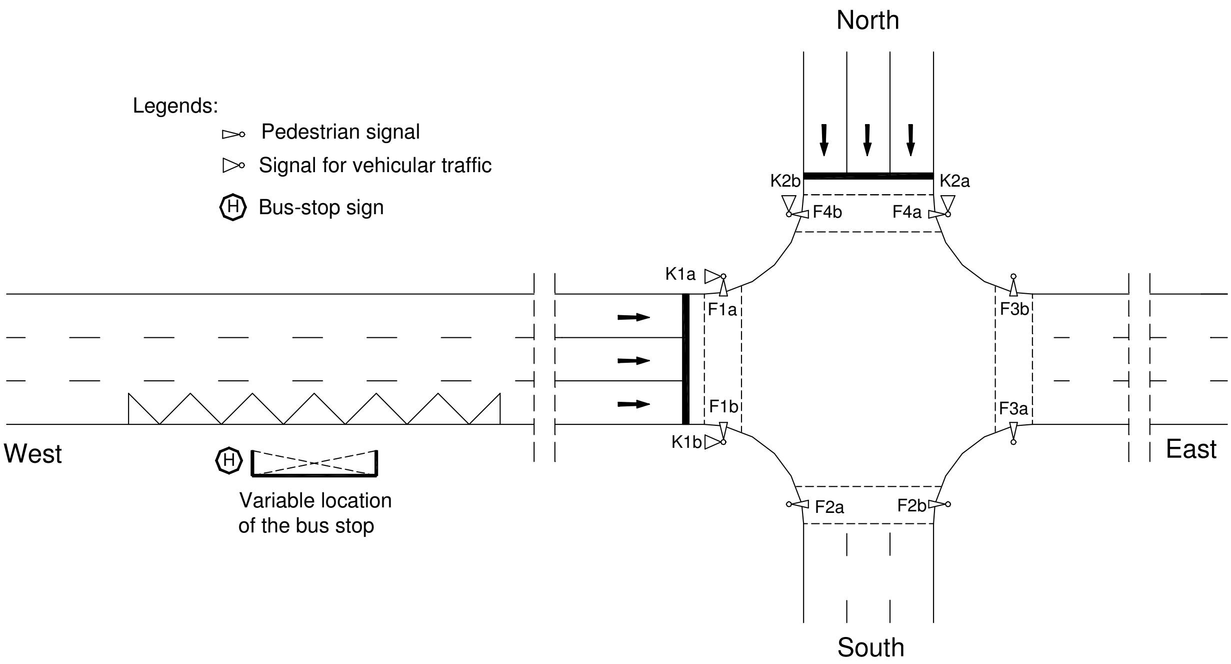

Figure 40: Study intersection for the sensitivity analysis

A fixed-time signal program with two-phase signal control was applied to the study intersection. The cycle length was 80 seconds, in which 10 seconds were assigned to the total intergreen time, and the remaining 70 seconds were allocated for green times of vehicular traffic. Intergreen times between traffic streams were determined carefully and given in the form of intergreen time matrix. This intergreen time matrix and the signal timing plan are provided in Figure 41.

Since the two intersection approaches were intentionally loaded with equal traffic loads at traffic signals, the green times were allocated equally for them with the value of 35 seconds. Green times for pedestrian traffic were determined by required intergreen times between pedestrian and vehicular traffic. These green times (t_F) must be greater than the regulated minimum values.

Ending signal groups	Starting signal groups: K1	K2	F1	F2	F3	F4
K1		5	5		8	
K2	5			8		5
F1	9					
F2		7				
F3	7					
F4		9				

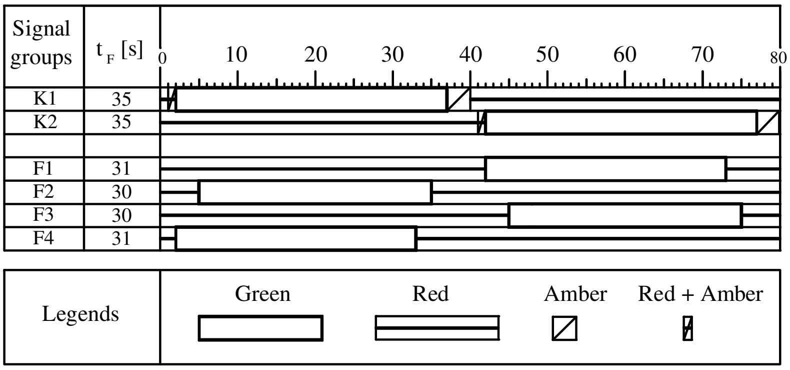

Figure 41: Intergreen time[18] matrix and signal timing plan of the study intersection

The related factors for this analysis are given in Table 8.

Table 8: General factors for the analysis of the bus stop

Factors	Descriptions
1. Geometric Factors of the Intersection	
Number of lanes on the bus-operating approach	3
Number of lanes on the crossing approach	3
Lane width	3.5 m
Gradient of the intersection approaches	0%
2. Signalisation Factors	
Signal control strategy	fixed-time program
Signal coordination with neighbouring intersections	uncoordinated and isolated intersection
Number of phases	2
Cycle length	80 s
Total intergreen time	10 s
Green time for the bus-operating approach	35 s
Green time for the crossing approach	35 s
3. Traffic Factors	
Traffic composition of the bus-operating approach	85% motorcycles, 10% (cars + buses), 5% bikes
Traffic composition of the crossing approach	85% motorcycles, 10% cars, 5% bikes
Proportion of the straight-ahead movements	100%
Proportion of the turning movements	0%
Traffic loads of the bus-operating approach	different degrees of saturation at traffic signals
Traffic loads of the crossing approach	different degrees of saturation at traffic signals
Pedestrian volume of each pedestrian crossing	200 pedestrians/h
4. Factors Related to Bus Services	
Directional operation of the bus services	from west to east
Bus volume	60 buses/h
Distribution of the dwell times at the bus stop	$N(15, 4)$
Number of loading areas at the bus stop	2
Type of the bus stop	on-line stop
Location of the bus stop	different positions
Type of bus vehicles	standard bus

[18] The unit for the intergreen time is second.

To conduct the sensitivity analysis, the location of the bus stop was gradually moved to different predefined positions in succession at the upstream and downstream intersection. Each position of the bus stop was examined at different degrees of saturation (denoted by g) on the intersection approaches, including g = 0.65, 0.8, and 0.9.

Assessment Parameters

To assess the impact of the bus stop on capacity and traffic flow quality of the intersection approaches, the following parameters were used in the analysis:

- Discharge rate (veh/h),
- Delay of buses[19] (s/bus),
- Delay of other vehicles (s/veh),
- Number of stops of buses[20] (-/bus), and
- Number of stops of other vehicles (-/veh).

Simulation

The micro-simulation VISSIM 5.20 was utilised in this analysis. In order to simulate mixed traffic conditions in MDCs, firstly, necessary input parameters were collected in Hanoi and Ho Chi Minh City, including speed distribution, acceleration distribution, deceleration distribution, standstill distance, vehicle types, etc. Then the simulation was calibrated by saturation time-headways of homogeneous flows of motorcycles and cars at traffic signals. Besides, the relationship of speed and flow rate was used for verifying the simulation under mixed traffic conditions. More details about the simulation tool and the calibration process are given in Appendix B.

In the next stage, the study intersection and its related factors except for the bus stop were modelled similarly in the simulation. The arrival of buses at the intersection was generated randomly. Then a scenario without a bus stop at the intersection was created, called the base scenario. In this scenario, the intersection approaches were firstly loaded with oversaturated traffic demands in order to determine their capacities. By using data collection points located at the outflow cross sections behind the stop lines, those capacities were collected.

In the following stage, the bus stop was created at different predefined positions. For each position of the bus stop, intended traffic demands, in turn, were allocated to both intersection approaches in order to achieve their equal degrees of saturation (g = 0.65, 0.8, and 0.9). Other factors were kept independent of bus stop positions. One bus stop scenario of the analysis was defined as a scenario with a certain position of the bus stop, and it was divided into sub-scenarios due to different degrees of saturation on the intersection approaches. Furthermore, the base scenario was also taken into account for making comparison with bus stop scenarios.

[19] Delay caused by dwell times at the bus stop is not included.

[20] Stops of buses due to boarding and alighting activities at the bus stop are not included.

In order to collect the value of assessment parameters, measurement points were determined. For measuring traffic flow quality of the bus-operating direction, the measurement segment was selected to cover the range of the bus stop and potential queues behind it. As seen in Figure 42, traffic flow quality was measured on the segment between cross sections 1 and 3, and the discharge rate of the bus-operating approach was counted at cross section 2 behind the stop line.

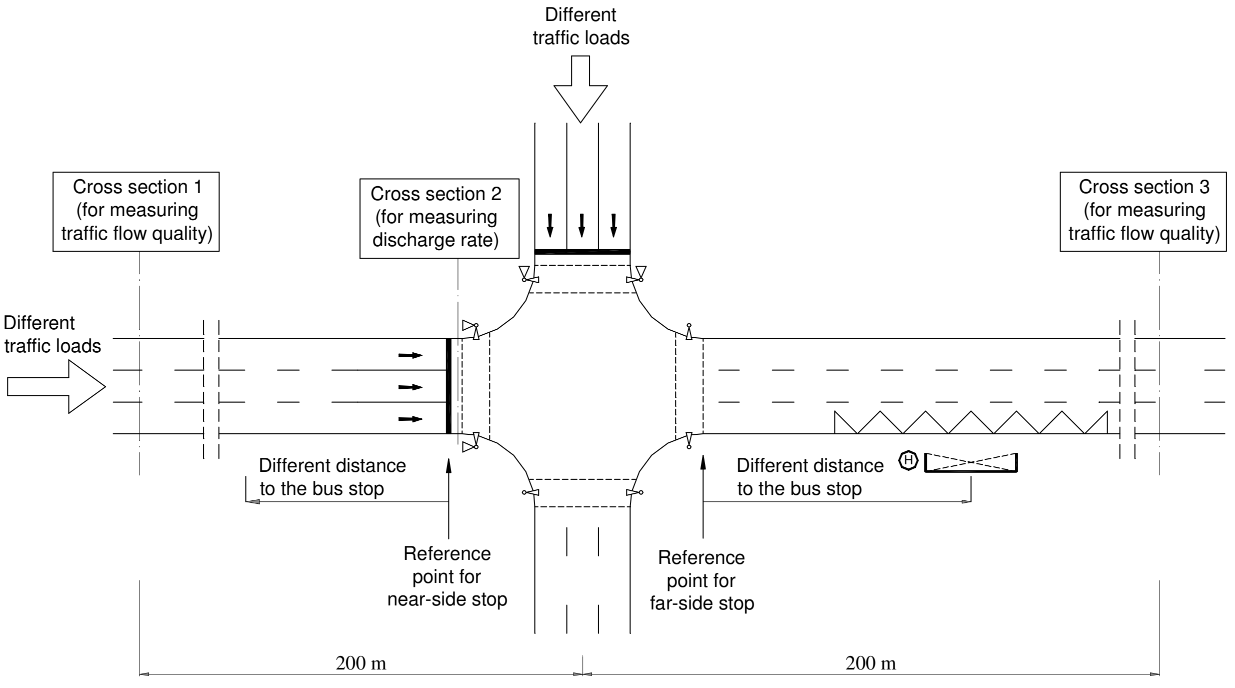

Figure 42: Measurement points of traffic flow quality and discharge rate

The following figure shows the utilisation of the micro-simulation tool for this analysis.

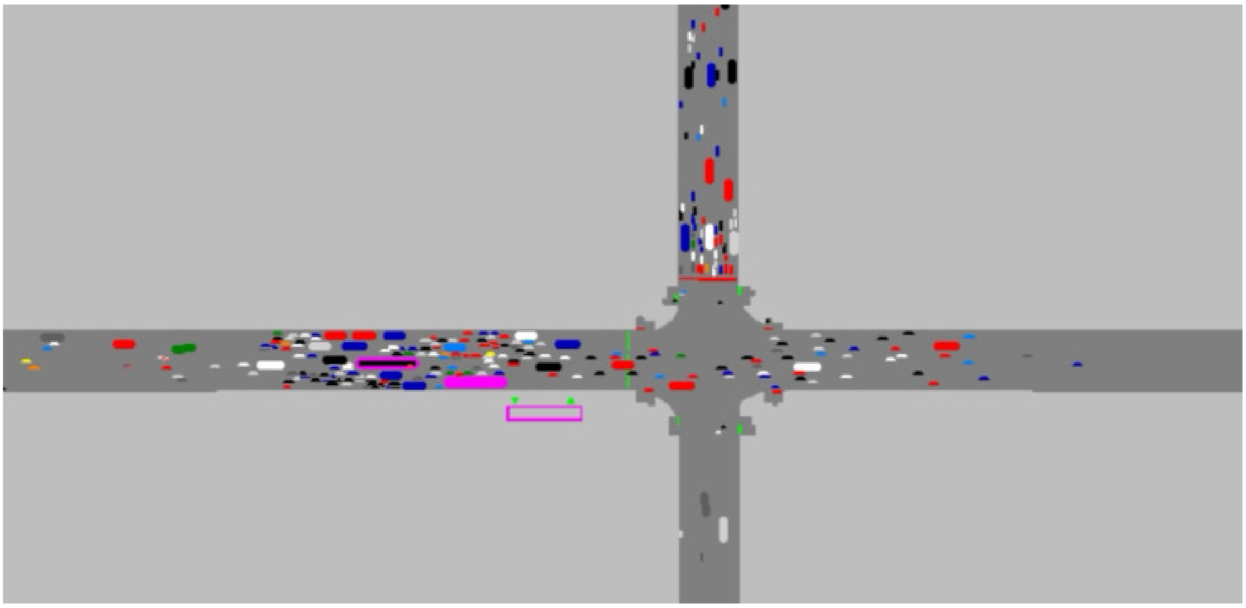

Figure 43: Utilisation of the micro-simulation VISSIM 5.20 for the analysis of the bus stop

In the final stage, each scenario of the analysis was run with 6 different simulation seeds. The warm-up time for the simulation process was 480 s, and the period of assessment was 1600 s (or 20 cycle lengths). All of related parameters were collected for the bus-operating direction after the simulation process. Besides, the same parameters were also observed for the crossing direction in order to notify the impact of temporary queues behind the far-side stop on that direction.

Results

The assessment parameters for this analysis were collected from output files of the simulation. The arithmetic mean of each parameter was calculated from its six values generated by six different simulation seeds. The results of these parameters are provided in Table 9.

Table 9: Results of the analysis for different scenarios of the bus stop

Degree of saturation	Parameters	No stop	Near-side stop					Far-side stop				
			15 m	30 m	60 m	90 m	120 m	15 m	30 m	60 m	90 m	120 m
g = 0.65	Discharge rate (veh/h)	5049	5046	5045	5053	5055	5051	5044	5048	5051	5048	5048
	Delay of buses (s/bus)	36.5	81.9	57.9	50.1	49.4	47.0	56.7	54.1	57.0	56.7	57.8
	Delay of other vehicles (s/veh)	20.6	29.8	24.9	22.8	22.2	21.8	23.4	22.6	22.7	22.4	22.4
	Number of stops of buses (-/bus)	1.3	2.8	2.2	1.4	1.6	1.1	2.5	2.2	1.8	2.0	1.5
	Number of stops of other vehicles (-/veh)	0.7	1.2	1.0	0.9	0.8	0.8	1.0	0.9	0.9	0.9	0.8
g = 0.8	Discharge rate (veh/h)	6198	5983	6161	6194	6214	6196	6196	6179	6197	6187	6204
	Delay of buses (s/bus)	46.0	117.8	84.6	65.6	65.3	63.9	91.7	73.0	73.2	75.8	71.9
	Delay of other vehicles (s/veh)	25.0	54.7	36.3	29.9	27.4	28.0	39.6	30.6	29.7	30.6	29.0
	Number of stops of buses (-/bus)	1.7	4.1	4.0	2.1	2.0	1.9	3.6	2.4	2.5	2.9	2.6
	Number of stops of other vehicles (-/veh)	0.9	2.7	1.6	1.2	1.0	1.0	1.8	1.2	1.2	1.2	1.1
g = 0.9	Discharge rate (veh/h)	6941	6439	6563	6928	6928	6947	6625	6768	6837	6924	6924
	Delay of buses (s/bus)	67.4	207.8	177.3	109.2	105.8	89.8	176.0	145.4	114.6	99.8	101.9
	Delay of other vehicles (s/veh)	34.7	98.6	83.6	51.0	44.7	38.5	82.0	65.0	53.2	45.3	44.7
	Number of stops of buses (-/bus)	2.4	11.5	10.5	4.5	4.0	2.6	9.5	6.7	4.8	4.1	3.8
	Number of stops of other vehicles (-/veh)	1.3	6.0	4.9	2.4	1.9	1.5	4.5	3.2	2.4	1.9	1.8

Thereafter, the difference in value between parameters of the base scenario and those of bus stop scenarios was computed to illustrate the side impact of the bus stop on traffic flow quality and discharge rate. If this difference is positive, corresponding to a certain bus stop position, the stop had a side impact in respect of an examined parameter. Otherwise, the impact of the bus stop is neglected by using the sign "-", i.e. the bus stop at that position did not pose a side impact in terms of the examined parameter; besides, the impact of the stop with a position further than that one is disregarded.

The side impact of the bus stop at different positions on discharge rate and traffic flow quality of the bus-operating direction is provided in Table 10.

Table 10: Side impacts of the bus stop on discharge rate and traffic flow quality

Degree of saturation	Impacts of the bus stop	Near-side stop					Far-side stop				
		15 m	30 m	60 m	90 m	120 m	15 m	30 m	60 m	90 m	120 m
g = 0.65	Decreased discharge rate (veh/h)	3	4	-	-	-	5	1	-	-	-
	Increased delay of buses (s/bus)	45.4	21.4	13.6	12.8	10.4	20.2	17.5	20.4	20.1	21.3
	Increased delay of other vehicles (s/veh)	9.2	4.2	2.2	1.6	1.2	2.8	2.0	2.1	1.8	1.8
	Increased number of stops of buses (-/bus)	1.5	0.9	0.1	0.2	-	1.1	0.9	0.4	0.6	0.2
	Increased number of stops of other vehicles (-/veh)	0.5	0.3	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1
g = 0.8	Decreased discharge rate (veh/h)	215	37	4	-	-	2	19	1	11	-
	Increased delay of buses (s/bus)	71.8	38.6	19.7	19.3	17.9	45.7	27.0	27.3	29.8	25.9
	Increased delay of other vehicles (s/veh)	29.6	11.2	4.9	2.4	3.0	14.6	5.6	4.7	5.6	4.0
	Increased number of stops of buses (-/bus)	2.4	2.3	0.4	0.3	0.1	1.9	0.7	0.8	1.1	0.8
	Increased number of stops of other vehicles (-/veh)	1.8	0.7	0.3	0.1	0.2	0.9	0.3	0.3	0.3	0.2
g = 0.9	Decreased discharge rate (veh/h)	502	378	13	13	-	316	173	104	17	17
	Increased delay of buses (s/bus)	140.4	109.9	41.8	38.3	22.4	108.5	78.0	47.2	32.4	34.5
	Increased delay of other vehicles (s/veh)	64.0	49.0	16.4	10.0	3.8	47.3	30.3	18.6	10.6	10.1
	Increased number of stops of buses (-/bus)	9.1	8.2	2.1	1.6	0.2	7.1	4.3	2.4	1.7	1.4
	Increased number of stops of other vehicles (-/veh)	4.7	3.5	1.1	0.6	0.2	3.2	1.9	1.1	0.5	0.5

To obtain a better visualisation, the variability of each parameter at a specific degree of saturation will be plotted, corresponding to different positions of the bus stop. Afterwards, the curve fitting is applied to some given sets of the data in order to describe the trend of side impacts of the bus stop.

Impacts on Discharge Rate

As shown in Figure 44, at a high degree of saturation (g = 0.9), the discharge rate of the bus-operating approach reduces significantly when the stop is placed closely to the traffic signals. That means a certain number of vehicles were not able to release during the assessment period. For near-side positions, the impact is the most serious when the stop is placed right before the stop line; and a reduction of 502 vehicles/hour (approx. 7%) in discharge rate of the bus-operating approach was measured. For far-side positions, the impact is the most critical when the stop is located right behind the beginning of the downstream intersection, with a decrease of 316 vehicles/hour (approx. 5%) in discharge rate.

Moreover, it should be notified that the far-side stop at the positions 15 m and 30 m caused a corresponding reduction of about 9% and 3% in discharge rate of the crossing approach. This reduction can be interpreted by the interference of temporary queues behind stopping buses. Those queues obviously interfered in the regular release of the crossing approach during its green times.

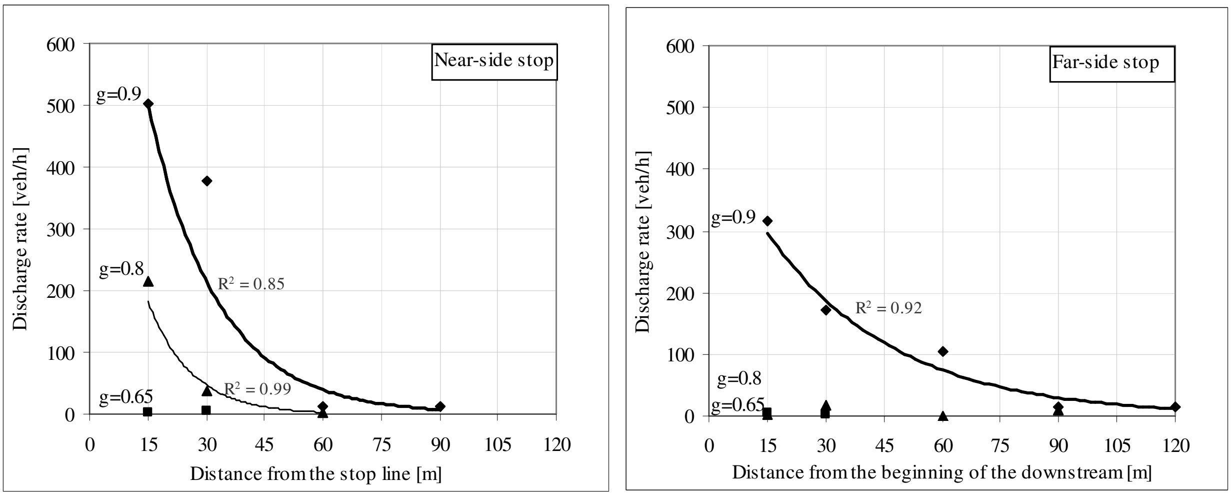

Figure 44: Decreased discharge rate due to the impact of the bus stop

At a medium degree of saturation (g = 0.8), only the positions of the near-side stop close to the traffic signals induce a considerable reduction in discharge rate. For other cases, the impact is almost insignificant. However, it should be noted that the bus-operating approach might still experience its overloaded situation during some cycles.

At a low degree of saturation (g = 0.65), it seems that a reserve capacity of the approach is high enough to keep it not oversaturated or just oversaturated during few cycles. In spite of that capacity, an inadequate bus stop position might still lead to an increment of the degree of saturation and a decrease in traffic flow quality.

A considerable reduction in discharge rate (e.g. greater than 1 %) justifies that the intersection approach became oversaturated at the end of the assessment period. The greater number of vehicles was trapped, the larger number of oversaturated cycles was experienced by vehicles on this approach.

The rate of change of the impact (represented by the slope of approximating curves) is likely variable at different positions of the bus stop and different traffic loads. Particularly at a high degree of saturation, the impact alters rapidly between different bus stop positions in certain ranges close to the intersection; further than those ranges, the impact changes gradually. By placing the stop outside those ranges, the side impact of the stop on discharge rate can be reduced noticeably.

Impacts on Delay of Buses

Remarkably, at a high degree of saturation (g = 0.9) the location of the bus stop has extensive influence on the delay of buses (see Fig. 45). The impact of the bus stop is most critical when it is situated closely to the intersection. Over two thirds of the delay of buses can be saved if the location of the near-side stop is chosen properly. Similarly, over one half of the delay can be reduced with a proper position of the far-side stop.

At a medium degree of saturation (g = 0.8), the impact becomes less severe at most of positions. Only the near-side stop at the positions near traffic signals induces considerable delays.

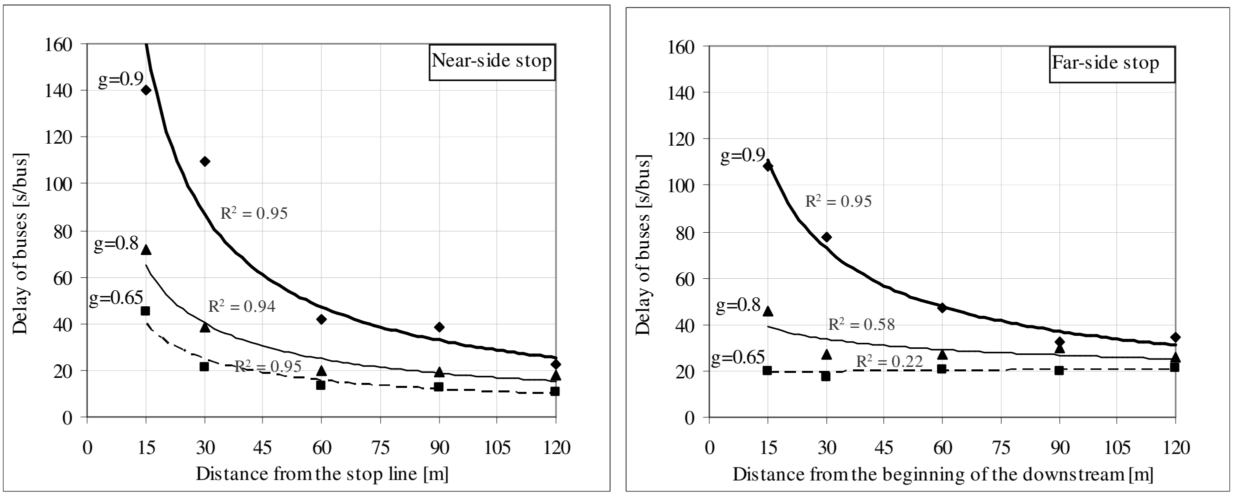

Figure 45: Increased delay of buses due to the impact of the bus stop

At a low degree of saturation (g = 0.65), the impact is marginal for the near-side stop. For the far-side one, the delay of buses is nearly independent of the stop location.

Impacts on Delay of Other Vehicles

At a high degree of saturation (g = 0.9), the impact of the bus stop on the delay of other vehicles is significant at the positions close to the intersection (see Fig. 46). Apart from that impact, it should be noted that the far-side stop at the positions 15 m and 30 m caused additional delays of about 36 and 21 seconds per vehicle respectively for the crossing traffic. By selecting proper positions of the stop, a considerable amount of delay can be reduced for other vehicles.

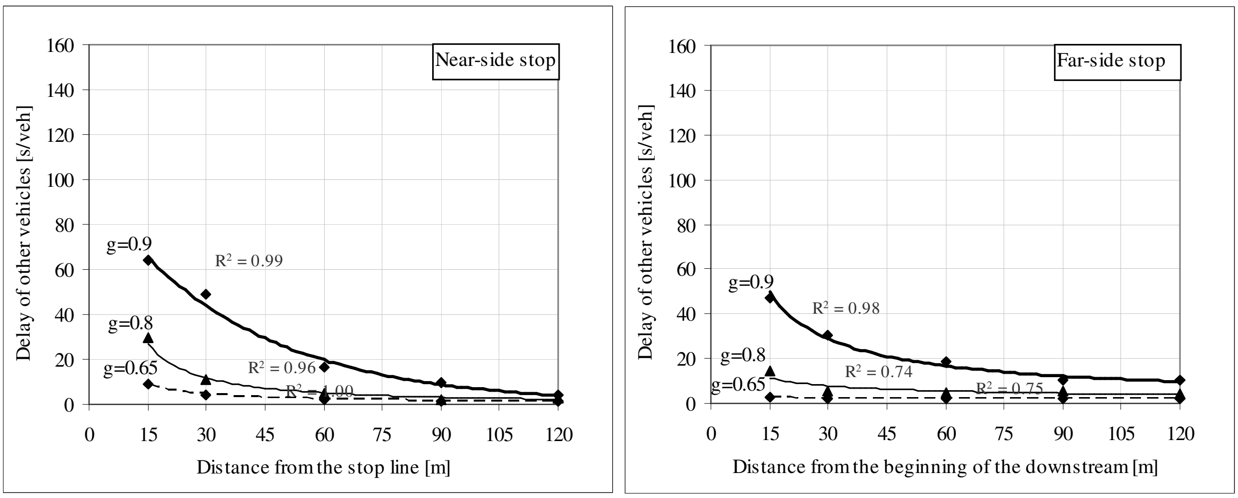

Figure 46: Increased delay of other vehicles due to the impact of the bus stop

At a lower degree of saturation, only the near-side stop directly behind the stop line exposes a sizeable impact. For other cases, the impact is insignificant.

Impacts on Number of Stops of Buses

As seen in Figure 47, at a high degree of saturation (g = 0.9) the impact of the bus stop on number of stops of buses is notable for both far-side and near-side positions, particularly when they are close to the intersection. The impact reduces significantly at the positions of the stop beyond 60 m from its reference points.

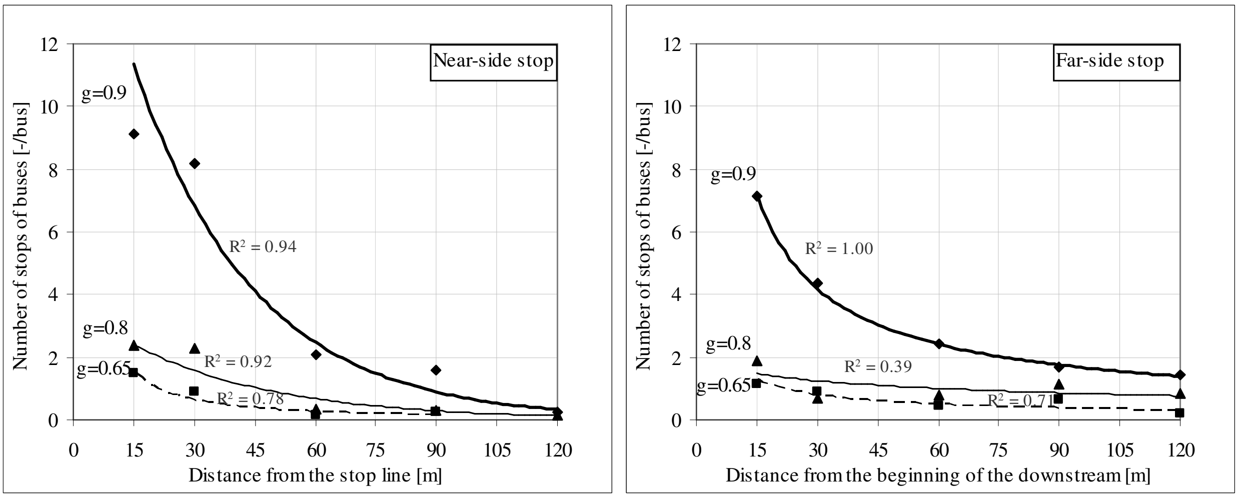

Figure 47: Increased number of stops of buses due to the impact of the bus stop

At a lower degree of saturation, the impact becomes much less critical. However, the positions close to the intersection still show the disadvantage.

Impacts on Number of Stops of Other Vehicles

It is apparent that the impact of the bus stop on number of stops of other vehicles is less severe than on that of buses (see Fig. 48). The impact is most noticeable at a high degree of saturation (g = 0.9) and it declines considerably for a lower degree of saturation. Critical values are still observed at the positions close to the traffic signals in conjunction with high traffic loads.

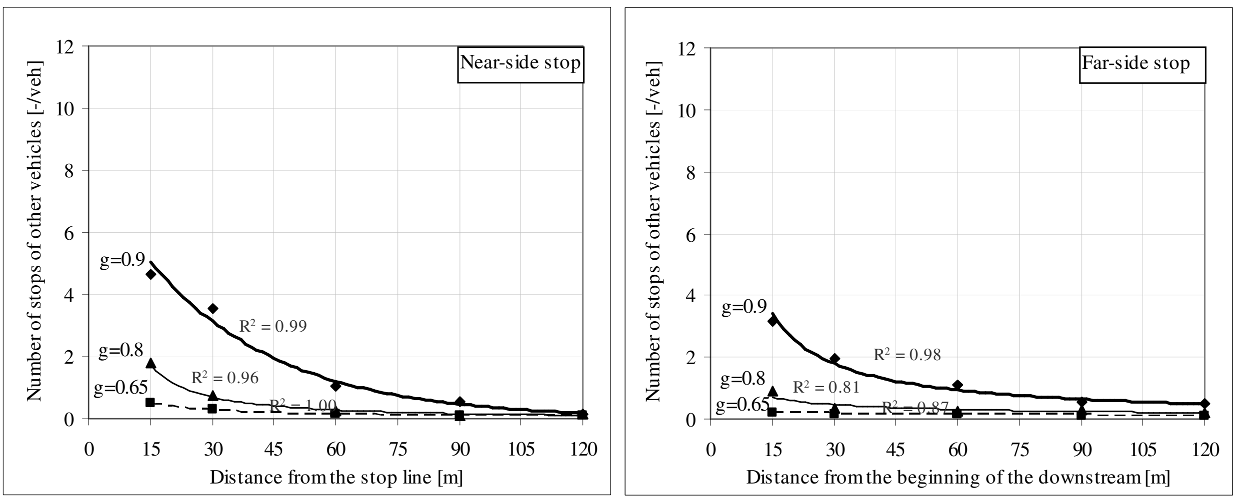

Figure 48: Increased number of stops of other vehicles due to the impact of the bus stop

When traffic loads are low (e.g. g = 0.65), the impact is negligible at nearly all positions of the stop.

5.1.4 Conclusions

When buses operate under mixed traffic conditions of MDCs, on-line bus stops can induce a number of problems which impact adversely on capacity and traffic flow quality of intersection approaches involved. The problems of these bus stops often include (1) the obstruction of buses at bus stops, (2) the obstruction of other vehicles caused by stopping buses, (3) the obstruction due to temporary queues behind bus stops, (4) the impediment due to skewing movements and (5) the perturbation in the range of bus stops.

In order to solve these problems, the measures for bus stops were developed, comprising the adjustment of bus stop location, replacement of on-line stops by bus bays, and implementation of supportive measures. Supportive measures should be carried out at first, then depending on existing problems and local conditions, two remaining measures can be utilised properly. In case an arrangement of bus bays cannot be implemented, the adjustment of bus stop location can be effective for both buses and other vehicles under mixed traffic conditions in MDCs.

From the results of the sensitivity analysis, the impact of the bus stop was clarified to vary from situation to situation, depending largely on the bus stop location and the degree of saturation of the approach involved. Particularly at high degrees of saturation, the critical impact was observed within certain ranges close to the traffic signals. Those ranges were found to extend from the reference points (close to the intersection) to different distances corresponding to different degrees of saturation on the bus-operating approach. Outside those ranges, the impact reduces to moderate or inconsiderable levels. Therefore, the determination of those ranges contributes significantly to select a proper position of the stop. It helps to improve capacity and traffic flow quality of the intersection. Moreover, it can be realised that the impact of bus stops in mixed traffic conditions dominated by motorcycles is different from the calculation in developed countries such as the United States and Germany as mentioned in Chapter 3.

Different conditions, e.g. roadway, traffic, and control conditions might generate different levels of the impact. For general conditions of MDCs, it is suggested that on-line bus stops should not be placed at a distance less than 60 m from the stop line (for near-side stops) or from the beginning of the downstream intersection (for far-side stops). When bus volumes are considerably high (e.g. greater than 60 buses/hour) and traffic loads on bus-operating approaches are high to oversaturated, a distance of more than 75 m from the mentioned reference points is highly recommended for the location of bus stops.

It should be noted that the determination of bus stop location is a process of balancing goal conflicts in the consideration of six major factors (incl. safety, locality, facilities, acceptability, capacity, and traffic flow quality) as mentioned previously. For example, at low loaded signalised intersections, of course, the location of bus stops should be close to the intersections to allow short walking distance and safe crossings of passengers. However, at highly loaded ones, these stops can pose negative impacts not only on capacity and traffic flow quality of intersection approaches but also on safety and quality of bus services. The reason is that when bus stops are unreasonably close to traffic signals, the improper performance of buses at bus stops and the tendency of bus drivers to overuse insufficient dwell times or to skip the service at bus stops are likely arisen. Consequently, those stops potentially endanger the safety of passengers and reduce the reliability, convenience, and comfort of bus services. Therefore, a proper position of bus stops in combination with appropriate supportive measures regarding passenger safety will help to reach a compromise between these kinds of goal conflicts when determining the location of bus stops.

5.2 Measures for Travel Ways

5.2.1 Development of Measures

Priority measures for bus travel ways have been widely proven as an effective way to accelerate bus flow in urban areas. A number of measures have been introduced, such as busways, exclusive bus lanes, time-restricted bus lanes, bus lanes shared with other modes, high-occupancy vehicle lanes, bus lanes with incomplete extension, intermittent bus lanes, queue jump lanes, etc. These measures aim to eliminate or reduce external disturbances caused by other vehicles, which mainly occur on links and at traffic signals. The effectiveness of each measure likely depends much on roadway, traffic, control, and other related conditions.

If roadway conditions are not constrained and traffic demand is not high, the measures regarding full separation between buses and other vehicles, such as busways and exclusive bus lanes, would be the most effective way to speed up bus services. However, these measures often show difficulties to apply to MDCs, in which traffic loads on urban roadways are usually critical during peak periods. As a result, most of buses in these cities are operating on mixed traffic lanes without priority measures for their travel ways.

From this practical issue, it is necessary to develop systematically possible measures which aim to prioritise buses on their travel ways under mixed traffic conditions. For this purpose, three basic factors including "time", "mode", and "space" are used as separation tools for the development of priority measures for bus travel ways (see Fig. 49).

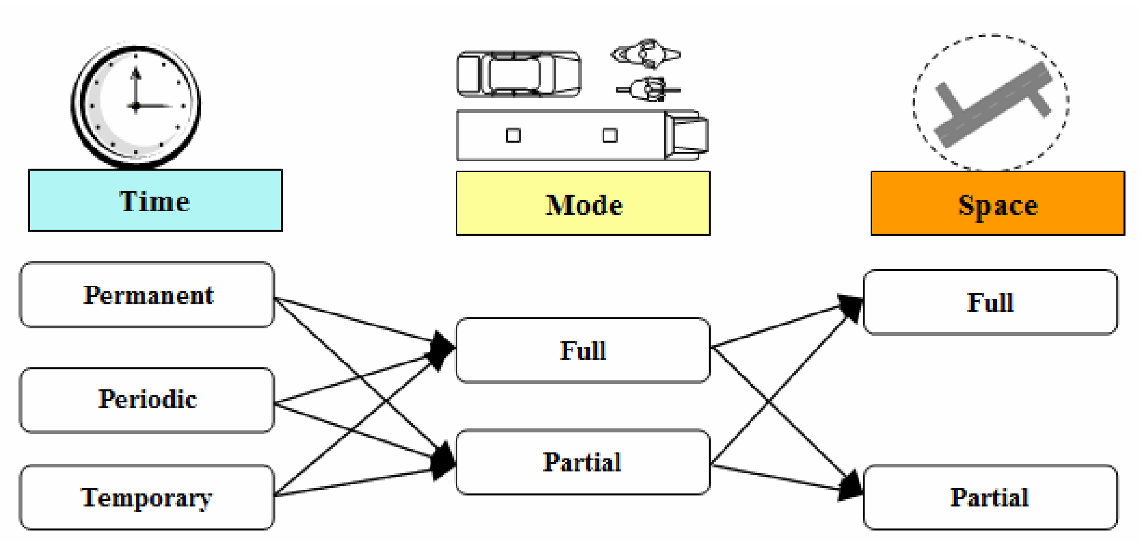

Figure 49: Principle for the development of priority measures for bus travel ways

By making use of the time separation, the priority travel way for buses can be allocated permanently, periodically, or temporarily. In addition, that travel way can be separated fully or partially from other vehicles by utilising the mode separation. By the space separation, furthermore, it can be arranged fully or partially in the length of the section.

In consequence of the alternative combinations as seen in Fig. 49, twelve basic groups of measures have been generated. In each group, measures have been developed based on the specific attributes of the individual separation tools. Thereafter, possible measures are listed in Table 11, whereas impractical measures are disregarded due to their potential ambiguity for road users in MDCs.

Table 11: Possible priority measures for bus travel ways

Group		Level of Separation			Measures
		Time	Mode	Space	
I	1	Permanent	Full	Full	Bus streets
	2				Busways
	3				Exclusive bus lanes
II	1	Permanent	Full	Partial	Bus sluice
	2				Queue jump lanes
	3				Bus lanes with permitted right-turning areas
	4				Incomplete bus lanes
	5				Discontinuous bus lanes
III	1	Permanent	Partial	Full	Streets for buses and bikes
	2				Streets for buses, bikes and taxis
	3				Streets for buses, bikes and motorcycles
	4				Streets for buses, bikes, motorcycles and taxis
	5				Bus lanes shared with bikes
	6				Bus lanes shared with taxis
	7				Bus lanes shared with bikes and taxis
	8				Bus lanes shared with bikes and motorcycles
	9				Bus lanes shared with motorcycles and taxis
	10				Bus lanes shared with bikes, motorcycles and taxis
	11				High-occupancy vehicle (HOV) lanes
IV		Permanent	Partial	Partial	(Impractical for MDCs)
V	1	Periodic	Full	Full	Time-restricted bus streets
	2				Time-restricted bus lanes
	3				Reversible bus lanes
VI		Periodic	Full	Partial	(Impractical for MDCs)
VII	1	Periodic	Partial	Full	Time-restricted streets for buses and bikes
	2				Time-restricted streets for buses, bikes and taxis
	3				Time-restricted streets for buses, bikes and motorcycles
	4				Time-restricted streets for buses, bikes, motorcycles and taxis
	5				Time-restricted lanes for buses and bikes
	6				Time-restricted lanes for buses and taxis
	7				Time-restricted lanes for buses, bikes and taxis
	8				Time-restricted lanes for buses, bikes and motorcycles
	9				Time-restricted lanes for buses, motorcycles and taxis
	10				Time-restricted lanes for buses, motorcycles, bikes and taxis
VIII		Periodic	Partial	Partial	(Impractical for MDCs)
IX	1	Temporary	Full	Full	Full dynamic bus lanes
X	1	Temporary	Full	Partial	Partial dynamic bus lanes
XI		Temporary	Partial	Full	(Impractical for MDCs)
XII		Temporary	Partial	Partial	(Impractical for MDCs)

The selection of measures depends predominantly on existing problems and prevailing conditions. Based on the principles of traffic engineering, the experience from developed countries (as regards Chapter 3, Section 3.3), the problems for buses on roadways in MDCs (as mentioned in Chapter 4, Section 4.2.2), and the specific conditions of MDCs (as regards Chapter 4, Section 4.3.3), the discussions on the suitability of the given measures are provided in the following.

Generally, fully separated travel ways such as *bus streets*, *busways*, and *exclusive bus lanes* will provide buses with the highest priority on roadway segments as well as at signalised intersections. In point of fact, these measures require some prerequisite conditions for their separation. Thereby, they should be introduced in the planning phase of urban road networks. In case they are implemented in the operation phase, supportive measures (e.g. permanent traffic rerouting) are generally required. Otherwise, these measures might be not feasible or their side impacts can be very critical to other traffic.

Bus streets could be a suitable measure for areas suffering heavily loaded traffic but containing only narrow streets. The provision of bus streets will improve substantially the quality of bus services and encourage the use of public transport instead of private vehicles in those areas. Additionally, this measure contributes to improve traffic safety, to protect environment, and to provide the sustainable passenger transport. Thereby, this measure is highly recommended for urban core areas where the permanent traffic rerouting for other vehicles is possible.

If bus streets cannot be implemented, *streets for buses and other specified vehicles* (e.g. bikes, taxis, motorcycles) could be an alternative in order to reduce traffic loads on certain routes deliberately. In this manner, impediments caused by other vehicles on links as well as at traffic signals will be reduced for the purpose of bus prioritisation. The condition for an application of these measures is that traffic rerouting for certain types of vehicles can be disposed.

However, *bus lanes shared with other specified vehicles* are not highly recommended for MDCs because these measures are likely to result in uncertain effects for both buses and other vehicles. Hence, they should not be applied unless their effects are clarified both on roadway segments and at traffic signals.

Time-restricted bus streets and *time-restricted bus lanes* can be considered for an application in practice if delivery and local traffic needs to use the roadway during certain periods of the day. In this way, bus streets or bus lanes are allocated for only buses during certain time of the day, and they can be opened for other vehicles during the remaining time. Periodic traffic rerouting for specific types of vehicles is the main requirement to implement these measures. Besides, extra traffic regulations and enforcement should be provided adequately to avoid the violation of other vehicles during their prohibited time.

If straight-ahead and right-turning vehicles potentially impede left-turning buses on their rightmost lanes, an arrangement of *bus sluice* can be considered for signalised intersections of carriageways. By implementing this measure, buses will perform easily their merging and turning movements at traffic signals. However, a provision of bus lanes is needed for this measure. This requirement is hardly fulfilled under the prevailing conditions of MDCs.

Queue jump lanes are suitable for signalised intersections operating under heavy traffic loads, at which buses often suffer noticeable delays due to severe queues of vehicles. If queue jump lanes are arranged, the waiting time of buses at traffic signals can be reduced to the basic waiting time (i.e. the waiting time caused by the red interval itself). Hence, a large amount of delays can be saved for them since the rear-congestion waiting time is completely eliminated. Besides, mutual impediments between buses and other vehicles in the range of intersections will be also minimised. This measure is highly recommended for MDCs. However, it often requires an expansion of roadways for allocating these lanes, so that it should be introduced in the planning phase of the intersection design. Otherwise, infrastructure measures for an arrangement of queue jump lanes must be basically carried out.

High-occupancy vehicle (HOV) lanes provide vehicles that travel on these lanes with a higher level of service compared to that of other lanes. By regulating vehicular types and the number of occupants, traffic volumes can be apportioned to HOV lanes. As a result, they often operate with a higher traffic flow quality than the other lanes. These lanes are useful for buses and other high occupancy vehicles to avoid traffic congestion, particularly during peak hours. However, the implementation of HOV lanes often needs some prerequisite conditions such as roadway conditions (normally 3 to 4 lanes per direction), proper traffic control and traffic enforcement measures, etc. Under the general conditions of MDCs, this measure is not highly endorsed, particularly for urban streets.

When one travel lane has to be allocated for the operation of buses in both directions, it is considered as a *reversible bus lane*. By allocating different periods of the day for different directions of the operation of buses, reversible bus lanes are formed. In mixed traffic conditions, however, this measure can pose some problems regarding the confusion of road users, safety concerns, arrangement of bus stops, and accessibility of passengers to the stops. Thereby, this measure is not highly recommended for MDCs.

Incomplete bus lanes are specified lanes being allocated on road sections, which end at certain points before stop lines. They can be an alternative solution when exclusive bus lanes cannot be implemented. In this manner, the ending parts (the parts before the stop lines) of bus lanes are shared with other vehicles in order to utilise the capacity of these lanes when buses are absent. That enables to reduce the side impact of bus lanes on capacities of intersection approaches involved. This measure seems to be suitable for streets operating with relatively high traffic loads. However, the drawback of an incomplete bus lane is that it narrows down the outflow cross section for other traffic at the downstream intersection. Consequently, capacity of the intersection approach involved is still affected at some extent. Hence, this measure is not highly encouraged for streets operating with heavy traffic loads.

Similarly, *bus lanes with permitted right-turning areas* entail the similar drawback of incomplete bus lanes. Besides, the movement of turning vehicles can impede straight-ahead buses at traffic signals, particularly when the proportion of right-turning traffic is high. Thereby, this measure is not highly recommended for directions operating under the condition of heavy traffic loads.

To overcome the drawback of both previous measures, *discontinuous bus lanes* will be introduced in this study. This measure is developed on the basis of practical requirements and specific conditions of MDCs. It will be discussed in more detail in the next section.

When certain traffic lanes between two given intersections are activated temporarily for the use of only buses in response to their occurrences, these lanes are considered as *full dynamic bus lanes*. Normally, these lanes are arranged on curb-side lanes. Their activation is carried out by the automatic switching of special signal heads to notify road users that certain lanes on the following sections will be closed for serving forthcoming buses. Detection systems must be required to perceive information of arriving buses beforehand. Then control systems will activate the dynamic lanes for the buses. When the buses are confirmed to pass through their active lanes, the signal will be deactivated and these lanes will return normal traffic lanes for other vehicles. In this manner, dynamic bus lanes are activated/deactivated successively on different sections of a certain direction in response to the presence/absence of buses. This measure might be suitable for streets operating with reasonable traffic loads and low to medium bus volumes. On heavily loaded roadways in conjunction with high bus volumes, however, it might cause critical impacts for other vehicles since a considerable reduction in capacities of intersection approaches will be induced during the activation time of these bus lanes.

In order to reduce the disadvantage of full dynamic bus lanes, *partial dynamic bus lanes* are developed for MDCs. The main differences of these lanes compared to the former ones are the design and control algorithm for their activation. In this way, the side impact on capacity and traffic flow quality of intersection approaches can be minimised while the priority purpose for buses is still achieved. Therefore, this measure might be applied appropriately to streets operating with heavy traffic loads. Further details on this measure will be discussed in another section of this chapter.

5.2.2 Discontinuous Bus Lanes

Basic Principles

Discontinuous bus lanes are developed on the basis of the following principles:

- To minimise external interferences for buses on non-signal affected segments,
- To reduce obstructions of buses due to long or severe queues[21] at traffic signals,
- To increase the number of buses that can be released during one cycle length at traffic signals,
- To provide an adequate level of traffic flow quality for buses at signalised intersections,
- To reduce negative effects of bus lanes on capacities of intersection approaches, and
- To reduce negative effects of bus lanes on traffic flow quality of other vehicles.

[21] Considerations of vehicular queues at traffic signals are given in Appendix A (part A.6).

Arrangement

Basically, a discontinuous bus lane is allocated on the rightmost lane of a direction as presented in Figure 50. This lane is formed by the distances from its first end to the stop line, denoted l_1, and from its second end to the beginning of the downstream intersection, denoted l_2.

The distance l_1 can be calculated if an intended value of degree of saturation is assigned to the bus lane (more details are provided in Appendix A, part A.5). On the one hand, this value should not be too high in order to give precedence to buses over other vehicles; on the other hand, it should not be too low since traffic flow quality of other vehicles might be impacted severely. Thereby, the selection of this value should be consistent with the predefined principles. When traffic-dependent control strategies are applied, different degrees of saturation can be resulted for the bus lane at traffic signals. In that case, the influence of those control strategies should be covered when selecting this distance.

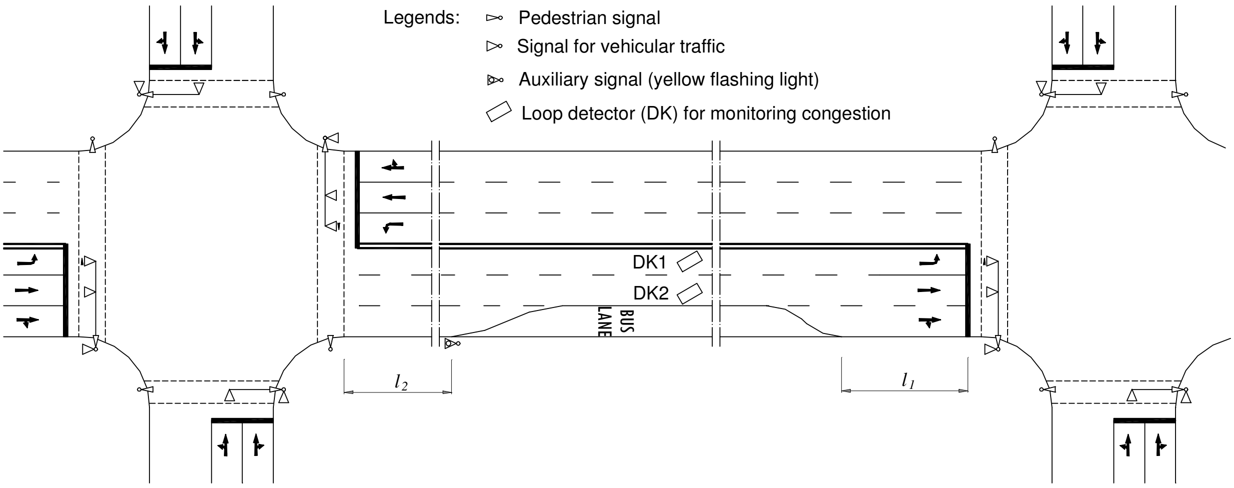

Figure 50: An arrangement of discontinuous bus lane

The distance l_2 is determined so that the narrowing roadway part in the downstream intersection due to the arranged bus lane will not have considerable impacts on capacity and traffic flow quality of the upstream approach. The recommended value for l_2 is given as follows:

$$l_2 = \max \begin{cases} 90\,m \\ l_u \end{cases} \tag{5-1}$$

where

$$l_u = 3 \cdot t_G \qquad \text{(5-2)[22]}$$

l_u = length of unchanged number of lanes on the downstream subsection [m]

t_G = green time of the upstream approach [s]

[22] Reference to the guidance of RiLSA—FGSV (2010b)

If the entry of the bus lane is potentially blocked by queuing vehicles, the use of congestion detectors DK1, DK2 (see Fig. 50) and traffic-responsive control is recommended to monitor the limitation of occurring queues. Depending on certain conditions, these detectors should be placed at relevant positions in order to eliminate a blockage of the bus lane.

Operational Principles

After being discharged from the preceding intersection, buses will join their lane at a certain point on the downstream section (see Fig. 50). On this roadway part, a separate lane is provided for the exclusive use of buses. Thereafter, they will rejoin the mixed traffic lane at another point near the traffic signals. The roadway part ahead of the bus lane is allocated for both buses and other vehicles.

Auxiliary signals (yellow flashing light), relevant traffic signs, and pavement markings must be provided to notify other road users of the discontinuous bus lane being disposed ahead. Consequently, other vehicles on the rightmost lane will divert to adjacent lanes as soon as the information of the forthcoming bus lane is ascertained.

If the bus lane is potentially blocked by extensive rear queues, the use of traffic-responsive control with relevant control strategies (e.g. green time adjustment) must be implemented. In that case, the length of queues on adjacent lanes is monitored by inductive loops (DK1, DK2). As a result, a free entry of buses to their discontinuous lane can be guaranteed.

Recommendations on Application

In order to arrange discontinuous bus lanes, the direction must contain at least two travel lanes. In addition, the length of road sections between consecutive intersections must be long enough to realise these lanes. The minimum value of $3 \cdot l_2$ is recommended for this length. These requirements are considered as prerequisite conditions for an application of this measure.

Generally, this measure could be preferable to directions that operate with a relatively high bus volume (e.g. greater than 20 buses/h) and a low proportion of right-turning traffic (e.g. less than 10%) at the forthcoming traffic signals. When right-turning traffic is noticeable, in particular with its large number of four-wheel vehicles, capacity of intersection approaches can be affected considerably due to impediments of skewing movements. Besides, left-turning buses should not be allocated to operate on these lanes since they can cause impediments for other vehicles due to their skewing movements at traffic signals.

Moreover, this measure is preferably implemented at isolated intersections because of the predefined objectives regarding the utilisation of capacity. For this reason, the areas ahead of bus lanes can be used by both buses and other vehicles in queue or motion.

Traffic control is an important factor for this measure. Traffic engineering installations such as auxiliary signals, traffic signs, guidance panels, strips for bus lane separation, and pavement markings must be implemented properly. Additionally, parking activities and other potential disturbances should be completely restricted on the segments involved. Crossing and accessing traffic from side streets or alleys should be regulated carefully by right-of-way rules or signalisation. Besides, traffic enforcement should be conducted strictly.

5.2.3 Partial Dynamic Bus Lanes

Basic Principles

Partial dynamic bus lanes are developed on the basis of the following principles:

- To allocate certain lanes with lower traffic density to buses,
- To reduce obstructions of buses due to long or severe queues at traffic signals,
- To increase the number of buses that can be released during one cycle time at traffic signals,
- To provide an adequate level of traffic flow quality for buses at signalised intersections,
- To reduce adverse effects of bus lanes on capacities of intersection approaches,
- To reduce adverse effects of bus lanes on traffic flow quality of other vehicles, and
- To reduce impediments caused by skewing movements of unordered right-turning vehicles.

Arrangement

Basically, a partial dynamic bus lane is arranged on the right most lane of a roadway direction. On a road section between two given intersections, this lane starts at a certain point at the downstream intersection and ends at the stop line (see Fig. 51).

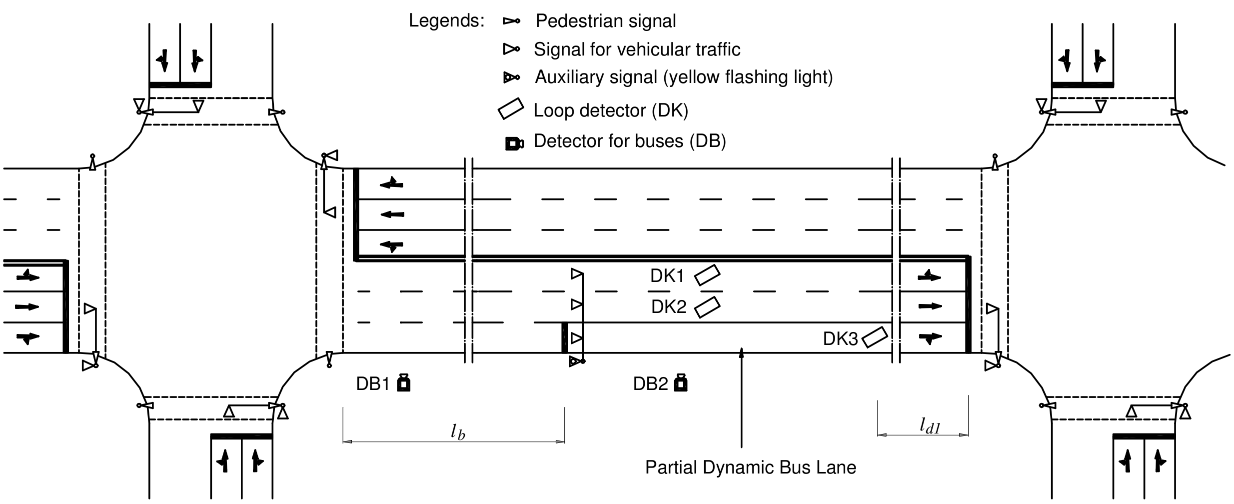

Figure 51: An arrangement of partial dynamic bus lane

The distance from the beginning of the downstream to the starting point of the bus lane (or the secondary stop line) is denoted l_b. The recommended value of l_b is determined by the following equation.

$$l_b = \max \begin{cases} 120\,m \\ l_u + 15\,m \end{cases} \tag{5-3}$$

where

l_b = distance from the beginning of the downstream to the secondary stop line [m]

l_u = length of unchanged number of lanes on the downstream subsection[23] [m]

Apart from the primary signal heads, additional signal heads (considered as secondary signal heads) are required for the partial dynamic bus lane (see Fig. 51). They include the signal heads for the bus lane and the other lanes. The signal head for buses must be a three-unit signal head for the purpose of activating or deactivating the bus lane. However, signal heads for the other lanes might be one-unit signal heads which contain optical units showing green only. Besides, an auxiliary signal head (yellow flashing light) should be used to warn road users when the bus lane is being activated.

To monitor traffic flow quality of the bus lane at the primary traffic signals, a queue detector DK3 is inserted. It is placed at a relevant distance (denoted l_{d1}) from the primary stop line. When a predefined degree of saturation is allocated to this lane, the value of l_{d1} can be determined (more details are provided in Appendix A, part A.5).

The use of bus detectors DB1 and DB2 is recommended to create additionally logical conditions for activating/deactivating the bus lane if their application conditions are favourable. In this manner, sufficient headways between buses and other vehicles can be generated to reduce external disturbances for them. For this purpose, these detectors should be placed at proper positions relative to the secondary stop line.

If the entry of the dynamic bus lane is potentially blocked by queuing vehicles, the usage of congestion detectors DK1, DK2 is recommended. These detectors should be located at relevant positions on the adjacent lanes.

All of these mentioned detectors are used for the activation and deactivation of the dynamic bus lane at the secondary traffic signals.

Operational Principles

The partial dynamic bus lane must be separated from other traffic lanes by proper pavement markings along its length. The aim of this separation is to regulate vehicles moving orderly on their allocated lanes and to avoid spontaneous lane-changing activities from the adjacent lanes to the bus lane. In addition, it enables to provide a certain level of traffic flow quality for buses travelling on the dynamic lane.

When the bus lane is deactivated, it operates like a normal traffic lane. Otherwise, it operates as a dynamic bus lane if activating conditions are met. In the state of its activation, only buses are permitted to access to this lane and other forthcoming vehicles must change to the other lanes or

[23] The calculation of l_u is given in the equation (5-2)

stop before the secondary stop line. For vehicles that already passed over the stop line before the activation moment are allowed to continue their movements towards the primary traffic signals.

Since other vehicles might stop at the secondary stop line during the activation time, buses are recommended to enter their lane from the adjacent lane at a position behind that stop line. Furthermore, to eliminate potential impediments caused by left-turning buses at the primary traffic signals, only straight-ahead and right-turning buses should be permitted to operate on this lane.

In order to activate and deactivate the dynamic bus lane (as regards Fig. 51), the following logical conditions and time conditions are used:

- Check-in bus detector (DB1) for requesting the priority lane: request
- Check-out bus detector (DB2) for terminating the priority lane: request
- Queue monitor detector (DK3): congestion
- Congestion detectors (DK1, DK2): congestion
- Minimum activation and deactivation times to ensure the stable operation of the dynamic bus lane: earliest ends of the activation and deactivation stages

Figure 52 provides the control algorithm for activating and deactivating the partial dynamic bus lane in the form of flow chart.

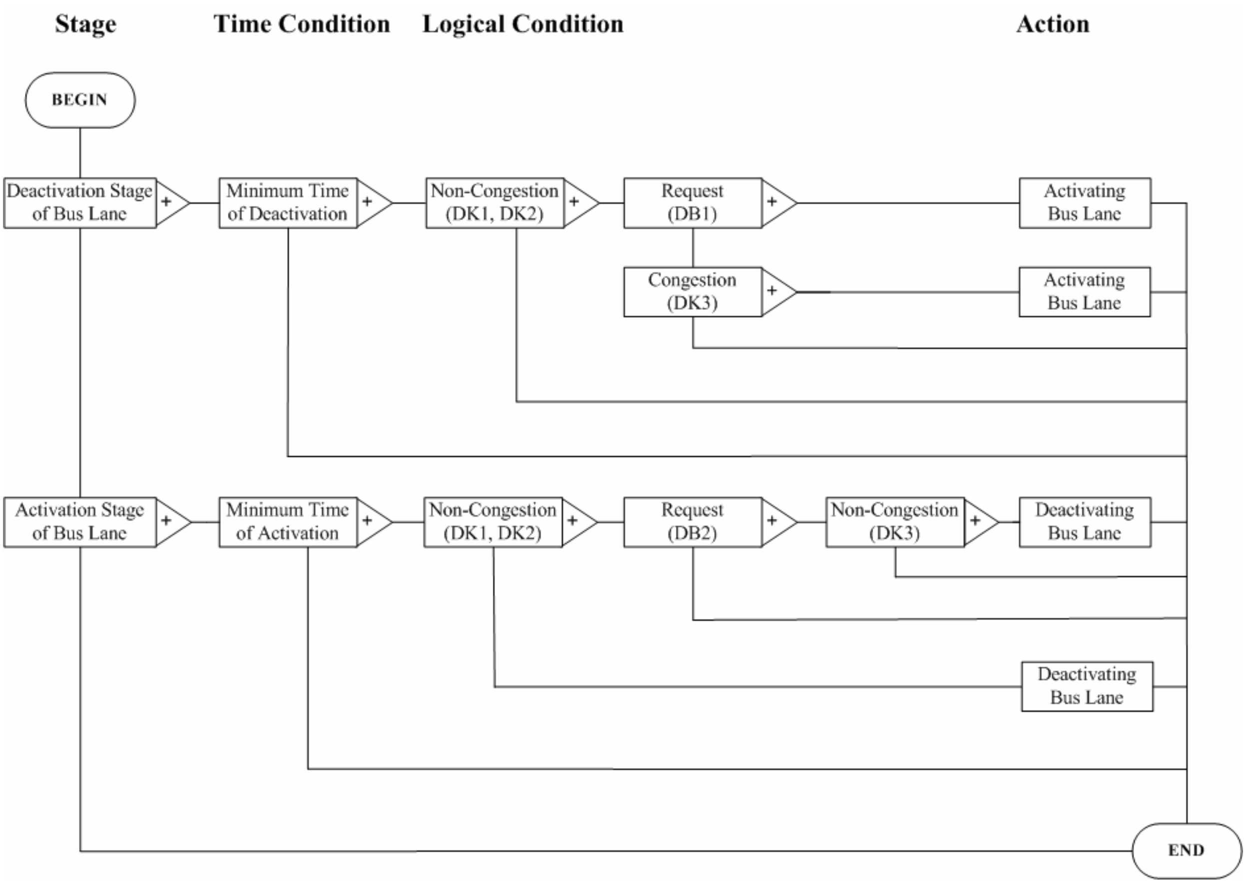

Figure 52: Flow chart of control algorithm for the partial dynamic bus lane

Recommendations on Application

Because lane-changing activities are required for other vehicles when the bus lane is being activated, this measure is recommended for road directions having at least three lanes. Moreover, the length of road sections between two consecutive intersections must be long enough to realise these lanes. The minimum value of $2.5 \cdot l_b$ is recommended for this length. These mentioned conditions are required for an application of partial dynamic bus lanes.

In case prevailing conditions for frequent lane-changing activities are not favourable (e.g. high traffic density within the entrance of dynamic bus lanes, considerable accessing traffic from side streets, or heavy right-turning traffic), partial dynamic bus lanes with restricted switching strategy (i.e. the strategy without the logical conditions of the request of bus detectors) are suggested. For this strategy, bus detectors will not be used. However, the width of the bus lanes should not be less than 4.5 m in order to allow buses to overtake other slow-moving vehicles such as bikes and motorcycles.

It is highlighted that partial dynamic bus lanes are activated through the secondary signal programs. Thereby, this measure can be effective for roadway directions whose intersections bear some of the following complications:

- Constrained signal priority for buses due to conflicting priority in different directions, boundary conditions of signal coordination, and insufficiently reserved green time,
- Heavy traffic loads on intersection approaches,
- High proportion of right-turning traffic on intersection approaches, and/or
- Fixed-time signal programs at the primary traffic signals.

The effectiveness of this measure is influenced significantly by proper traffic engineering installations (incl. auxiliary signals, traffic signs, guidance panels, pavement markings, etc.), appropriate traffic control measures (incl. parking control, control of accessing traffic from side streets, etc.), and steady traffic enforcement. Therefore, all of these concerned issues must be considered carefully before an application. In consequence of these considerations, positive effects of partial dynamic bus lanes can be utilised efficiently.

Since the operational principle of the secondary signal heads for activating dynamic bus lanes is not dissimilar to that of the primary ones, the reaction of road users to these signals is estimated to happen almost in the similar way. Nevertheless, it is important to highlight that an adequate provision of the advance warning and information as well as the clear visibility to installed devices will contribute to the unambiguous reaction of road users.

5.2.4 Estimation of Measure Effects

In order to estimate effects of discontinuous bus lanes and partial dynamic bus lanes, different types of bus delays occurring on urban roadways are considered at first. Then the effects of these lanes are highlighted by comparing them with mixed traffic lanes.

In mixed traffic conditions of urban roadways, apart from signalisation delays and unexpected delays (e.g. delays caused by parking/stopping vehicles, pedestrian crossing, special incidents, etc.), buses basically suffer two additionally distinguishable sources of delays, including:

- Delays on non-signal affected segments: These delays are mainly caused by interactions between buses and other vehicles when they operate in mixed traffic conditions. The level of interactions is basically affected by traffic density, types of vehicles, speeds, acceleration/deceleration rates, and driving behaviour.
- Delays on signal affected segments: The noticeable part of these delays can be a direct consequence of impediments due to severe queues at traffic signals. In addition, the other part can be a result of interactions between buses and other vehicles, particularly in the form of skewing and jerky movements on these segments.

Discontinuous Bus Lanes

Discontinuous bus lanes provide buses with their own lanes on certain parts of road sections. In this manner, impediments due to interactions caused by other vehicles on those parts are removed. As a result, delays of buses on non-signal affected segments will be minimised.

More importantly, their delays at signalised intersections are limited at permissible levels. The main reason is that maximum queues ahead of bus lanes are restricted to the predefined length (l_1). This arrangement helps to eliminate the occurrence of long or severe queues which often obstruct buses at traffic signals during peak periods. Thereby, an increased number of buses being able to release from signalised intersections within one cycle length can be achieved. Moreover, the delay caused by impediments of skewing and jerky movements in the range of traffic signals will be reduced.

The side impact of this measure might involve slightly increasing the degree of saturation of adjacent lanes compared to the initial one. Besides, traffic flow quality and queue lengths on those lanes might be affected to some extent.

Partial Dynamic Bus Lanes

Partial dynamic bus lanes can provide buses with their temporary lanes according to their occurrences on the sections involved. In this way, traffic density on the bus lanes will be reduced, and time headways between buses and other vehicles will be enlarged in order to reduce external disturbances caused by their interactions. Hence, delays of buses on non-signal affected segments can be reduced noticeably.

In the range of traffic signals, delays caused by vehicular queues are also kept at permissible levels by queue monitor detectors. These detectors guarantee partial dynamic bus lanes to operate not over the predefined degree of saturation and provide buses with non-congested lanes during peak periods. Additionally, this measure also helps to reduce impediments caused by skewing movements, particularly when right-turning traffic is relatively high at traffic signals.

Besides the advantageous aspects, this measure can cause a slight increase in degrees of saturation for adjacent lanes compared to their original circumstances. Thus, delays of other vehicles as well as queue lengths on those lanes might be affected to some extent. Additionally, secondary queues might build up since drivers may stop before the secondary stop lines when these bus lanes are temporarily activated.

Summary of Effect Estimation

Table 12 provides a summary of the estimation of effects for discontinuous bus lanes and partial dynamic bus lanes. The effects of these measures on both buses and other vehicles are highlighted by the relative comparison with mixed traffic lanes.

Table 12: Estimation of effects for discontinuous bus lanes and partial dynamic bus lanes

Effects \ Measures	Mixed traffic lanes	Discontinuous bus lanes	Partial dynamic bus lanes
1. Decrease in bus delays on non-signal affected segments due to			
- Eliminating external disturbances caused by other vehicles		x	
- Reducing traffic density on the lane allocated for buses			x
- Increasing headways between buses and other vehicles			x
2. Decrease in bus delays on signal affected segments due to			
- Restricting queue lengths		x	x
- Minimising the skewing movement of buses		x	x
- Reducing the jerky movement of buses		x	x
3. Possible effects on other vehicles			
Positive effects			
- Minimising impediments caused by skewing movements		x	x
- Reducing impediments caused by jerky movements		x	x
Negative effects			
- Increase in queue lengths on adjacent lanes		x	x
- Decrease in traffic flow quality of other vehicles		x	x
- Formation of secondary queues			x

From the above analyses, discontinuous bus lanes and partial dynamic bus lanes can be considered as two promising measures for MDCs. In order to reveal the level of effects of these measures in different conditions of traffic loads, a sensitivity analysis is conducted in the following section.

5.2.5 Sensitivity Analysis

Under different traffic loads on a certain direction involved, it is estimated that the effect of measures for bus travel ways can vary largely. To clarify this point, a sensitivity analysis is conducted by utilising traffic simulation tool. In this analysis, different scenarios of travel ways for buses are examined. A scenario with mixed travel lanes is formulated firstly. Then scenarios with a discontinuous bus lane, a partial dynamic bus lane, and an exclusive bus lane are created. All of these scenarios are analysed with different traffic loads. Subsequently, the effect of these bus lanes is revealed by comparing between the scenario of mixed travel lanes and the scenarios of these bus lanes. In this manner, the advantage and disadvantage of each bus lane under different conditions of traffic loads will be acquired. This analysis is presented in the following.

Examined Direction

In this experiment, a hypothetical roadway direction together with its isolated signalised intersection was formulated for this analysis (see Fig. 53). Under mixed traffic conditions, buses were allocated to operate in the direction from west to east with a volume of 60 buses/hour. In this direction, buses were assigned to operate on the mixed traffic lanes, and this situation is considered as the initial situation of this analysis.

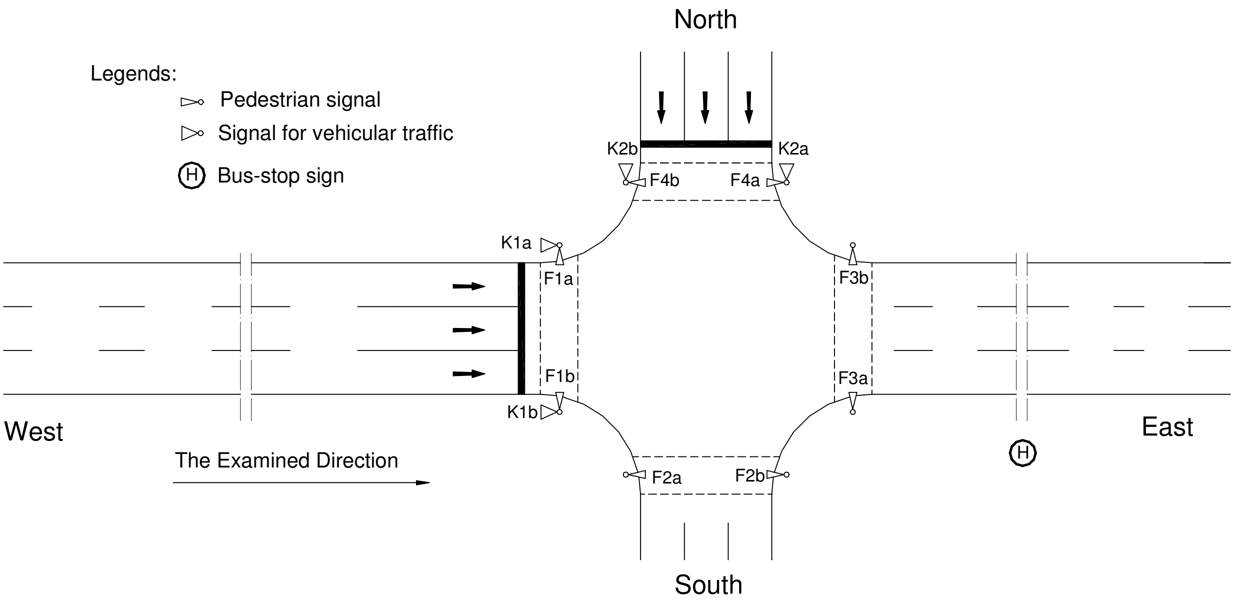

Figure 53: Layout of the examined direction for the sensitivity analysis

At the signalised intersection, a fixed-time signal program and its predetermined elements were implemented. The cycle length of 80 seconds was used, in which 10 seconds were assigned to the total intergreen time (see Fig. 54).

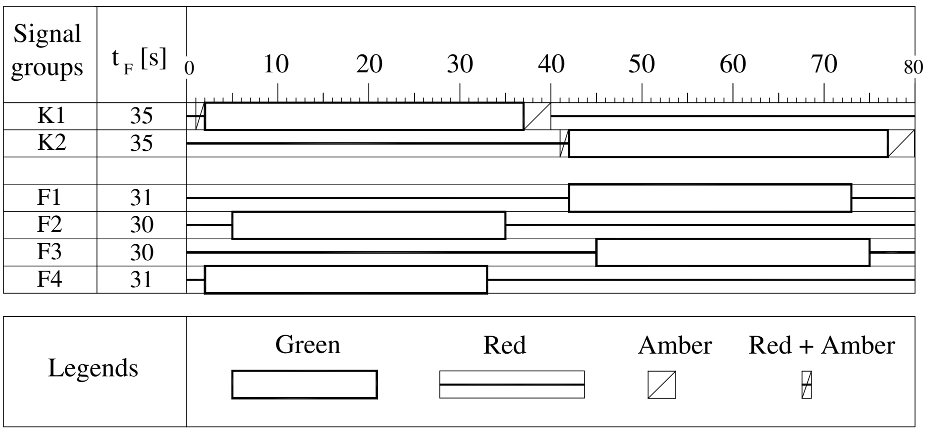

Figure 54: Signal timing plan of the intersection

The intersection approach of the examined direction was allocated a green time (t_F) of 35 seconds at traffic signals. Then green times for the crossing approach and pedestrian traffic were determined.

All of the related factors used in this analysis are summarised in the following table.

Table 13: General factors for the initial situation of the analysis

Factors	Descriptions
1. Geometric Factors	
Number of lanes in the examined direction	3
Number of lanes in the crossing direction	3
Lane width	3.5 m
Gradient of the roadways	0%
2. Signalisation Factors at the Concerned Intersection	
Signal control strategy	fixed-time program
Signal coordination with neighbouring intersections	uncoordinated and isolated intersection
Number of phases	2
Cycle length	80 s
Total intergreen time	10 s
Green time for the examined direction at traffic signals	35 s
Green time for the crossing direction at traffic signals	35 s
3. Traffic Factors	
Traffic composition of the examined direction	85% motorcycles, 10% (cars + buses), 5% bikes
Traffic composition of the crossing direction	85% motorcycles, 10% cars, 5% bikes
Proportion of the straight-ahead movements	100%
Proportion of the turning movements	0%
Traffic loads of the examined direction at traffic signals	different degrees of saturation (g = 0.65, 0.8, 0.9, 1.0)
Traffic loads of the crossing direction at traffic signals	different degrees of saturation (g = 0.65, 0.8, 0.9, 1.0)
Pedestrian volume of each pedestrian crossing	200 pedestrians/h
4. Factors Related to Bus Services	
Directional operation of the bus services	from west to east
Bus volume	60 buses/h
Distribution of the dwell times at the bus stop	$N(15, 4)$
Number of loading areas at the bus stop	2
Type of the bus stop	far-side stop
Location of the bus stop	75 m from the beginning of the downstream
Type of the bus vehicles	standard bus
5. Factors Related to Occupancy Rate	
Buses	52 persons/bus
Cars	1.9 persons/car
Motorcycles	1.3 persons/motorcycle
Bikes	1.0 person/bike

Scenarios of Bus Travel Way

Mixed Travel Way Scenario (Initial Situation)

This scenario is equivalent to the initial situation of the analysis, in which buses operate on their mixed travel way shared with other vehicles (see Fig. 55).

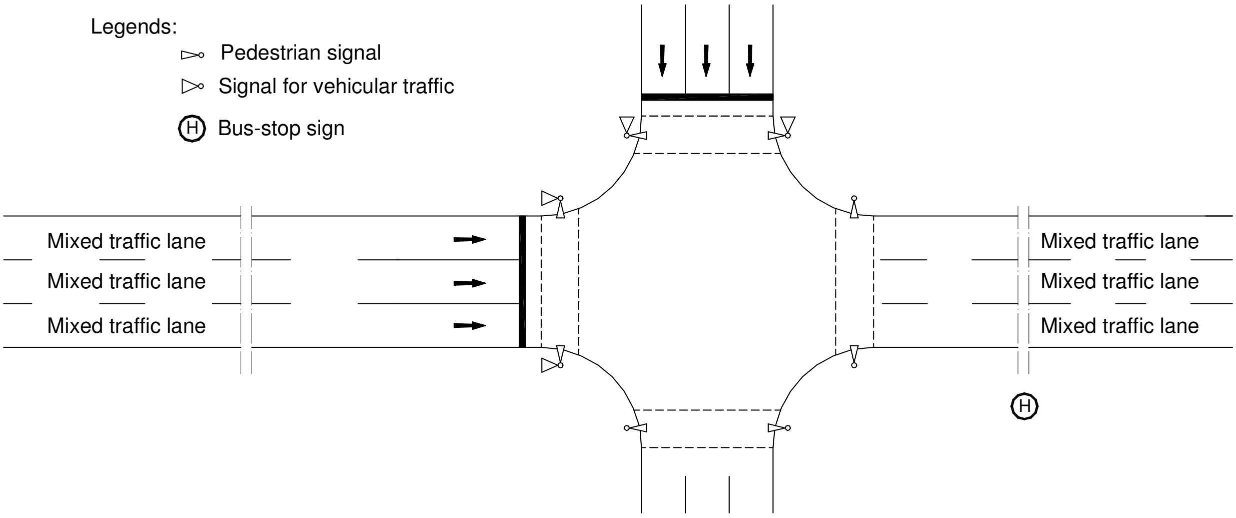

Figure 55: Layout of the mixed travel way scenario

Scenario of Exclusive Bus Lane

This scenario was developed from the initial situation of the analysis by an implementation of an exclusive bus lane while other factors were kept unchanged. This bus lane was allocated for the operation of buses in the examined direction (see Fig. 56). It was arranged on the rightmost lane, extending from the beginning to the end of the sections. On this lane, only buses are allowed travelling. Other vehicles were assigned to travel on the remaining lanes.

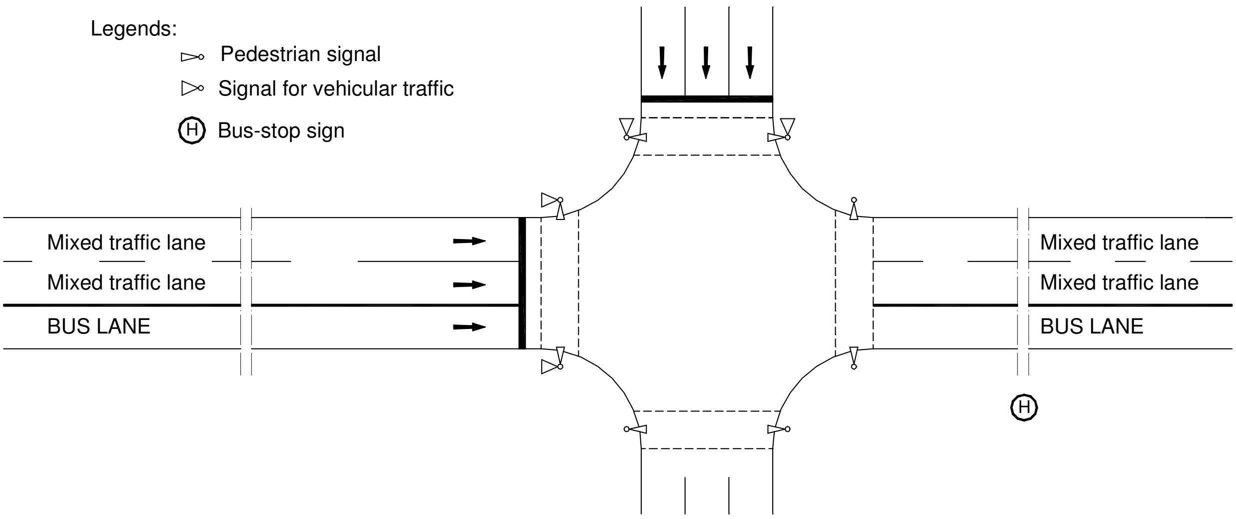

Figure 56: Layout of the exclusive bus lane scenario

Scenario of Discontinuous Bus Lane

As an alternative, this scenario was developed from the initial situation by an implementation of a discontinuous bus lane (see Fig. 57). Because the intersection was formulated as an isolated one, the use of congestion detectors on the adjacent lanes was not necessary.

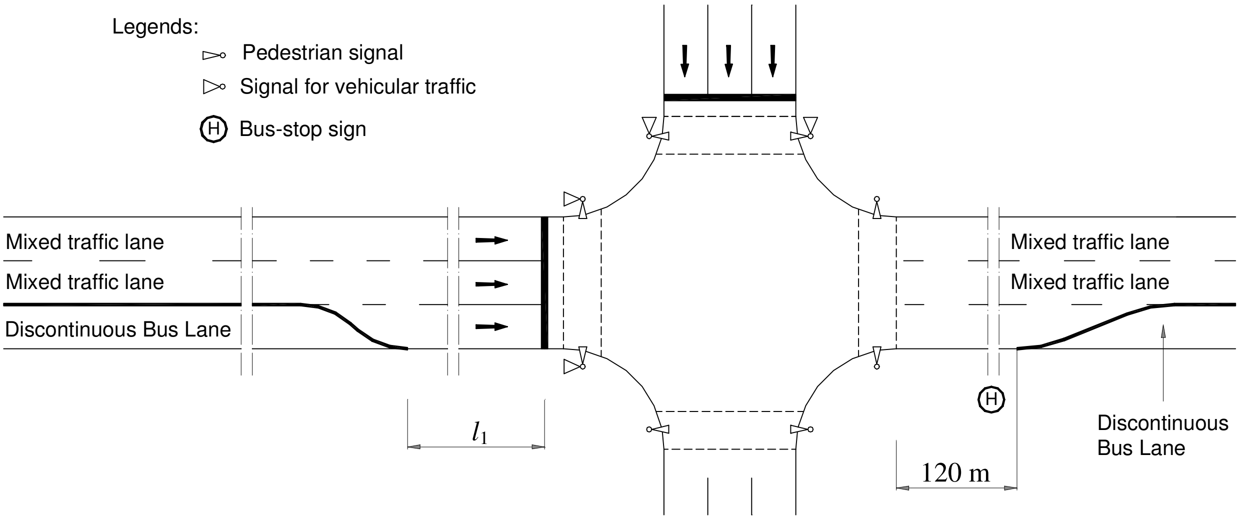

Figure 57: Layout of the discontinuous bus lane scenario

As mentioned previously, the distance l_1 should be set harmoniously in order to limit the front queue but not impact considerably on traffic flow quality of other vehicles. On the basis of this principle, this distance was selected with different values (l_1 = 30, 37, 48 and 60 m) corresponding to different degrees of saturation (g = 0.65, 0.8, 0.9 and 1.0).

The other factors as regards Table 13 will be kept unchanged in this scenario.

Scenario of Partial Dynamic Bus Lane

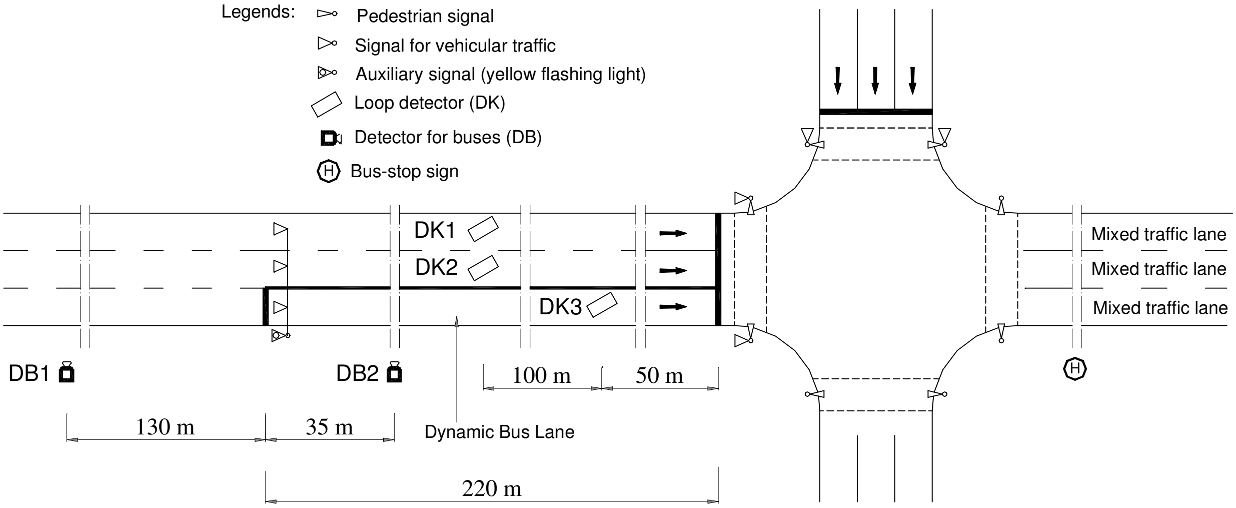

Figure 58: Layout of the dynamic bus lane scenario

In this scenario, a partial dynamic lane was provided for buses on the rightmost lane (see Fig. 58), compared to their mixed travel way of the initial situation. The secondary signal heads were arranged at the distance of 220 m from the primary ones for activating this lane. The other equipment was also installed for this purpose.

Regarding the control algorithm, the minimum times for activation and deactivation stages of the dynamic bus lane were 25 and 20 seconds respectively. Besides, the congestion state on inductive loops was detected if the occupancy period of queues on these loops was greater than 5 seconds.

Assessment Parameters

In order to assess the implemented priority measures for bus travel ways, the following parameters are used in the analysis, including

- Delay of buses[24] (s/bus),
- Average person delay of all modes (s/person),
- Delay of other vehicles (s/veh),
- Queue length[25] (m), and
- Number of stops of other vehicles (-/veh).

Simulation

The micro-simulation VISSIM 5.20[26] was utilised as a simulation tool in this analysis. The first step was for calibrating and verifying this simulation tool (see Appendix B for more details). Then the scenarios of mixed travel way, exclusive bus lane, discontinuous bus lane, and partial dynamic bus lane were modelled similarly in succession.

In the next step, different traffic demands which result in different degrees of saturation (g = 0.65, 0.8, 0.9, 1.0) at the traffic signals were allocated to the bus-operating direction in the mixed travel way scenario. Thereafter, the same traffic demands (taken from the mixed travel way scenario) were in turn allocated to the bus-operating direction in the exclusive bus lane, discontinuous bus lane, and partial dynamic bus lane scenarios.

In order to achieve proper results for comparing effects of the implemented measures, the measurement segment for measuring traffic flow quality must be similar and must cover all affected areas in each scenario. In the scenario of partial dynamic bus lane, for instance, this segment must cover the queuing area at the secondary traffic signals. As presented in Figure 59, measurement points were defined identically for all scenarios, in which traffic flow quality was determined between measurement points 1 and 3, and the queue length was calculated at measurement point 2.

[24] Delay caused by dwell times at the bus stop is not included.

[25] For the scenario of partial dynamic bus lane, queue length is measured at the primary signal heads.

[26] The simulation was used for the assessment of bus stops in Section 5.1.

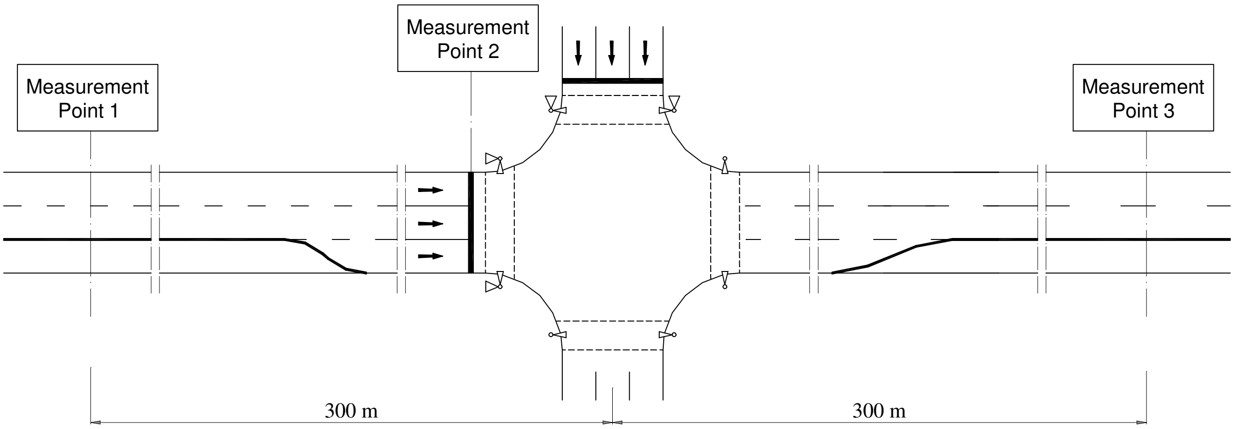

Figure 59: Measurement points for the assessment of bus travel ways

In the last step, each scenario of bus travel ways was run with 6 different simulation seeds. The warm-up time for the simulation process was 240 s, and the period of assessment was 3600 s (or a full hour). All of the assessment parameters were collected after the simulation process.

Figure 60 exemplarily presents the utilisation of the simulation tool for the scenario of partial dynamic bus lane in this analysis.

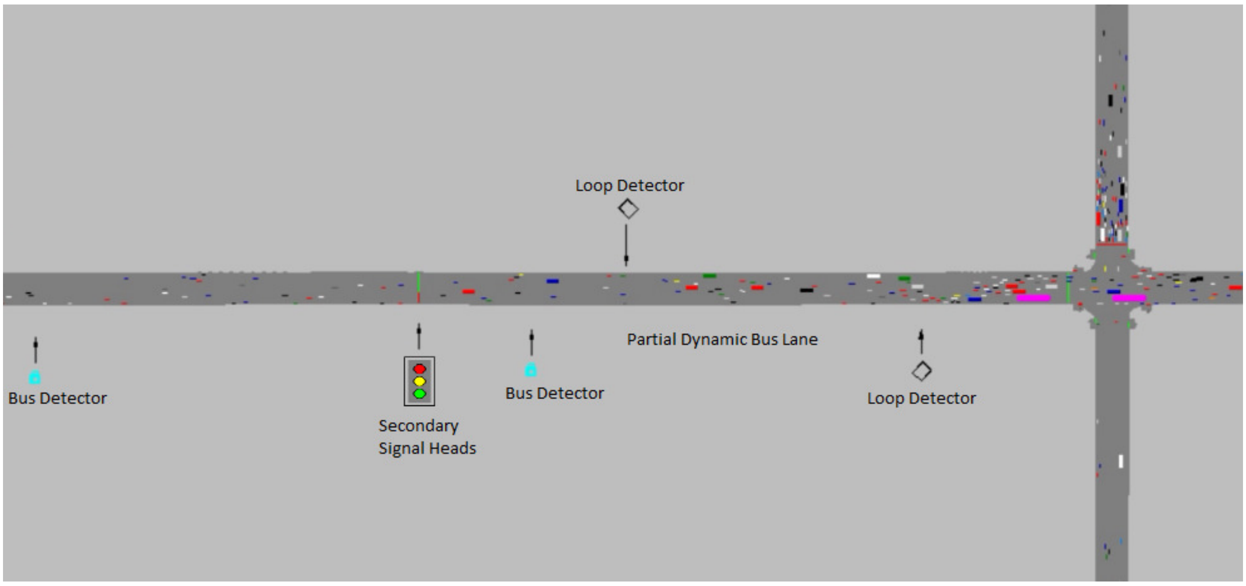

Figure 60: Utilisation of VISSIM 5.20 for the analysis of the partial dynamic bus lane scenario

The results of this analysis are provided in the following.

Results

In the following discussions, the degrees of saturation (g = 0.65, 0.8, 0.9, 1.0) which correspond to different traffic loads of the initial situation (or the mixed travel way scenario) are called the *initial degrees of saturation*, and they will be used as reference values of traffic loads for all scenarios in this analysis.

In addition, for the exclusive bus lane scenario, the data will not be provided at the initial degree of saturation of 1.0 since there was severe congestion on the lanes for other vehicles at this degree of saturation.

Delay of Buses

As seen in Figure 61, the scenario of exclusive bus lane provides the lowest bus delays compared to those of other scenarios. However, when the degree of saturation reaches the value of 1.0, this measure caused severe congestion for the adjacent lanes.

Compared to the mixed travel way scenario, the scenario of discontinuous bus lane resulted in a decrease in bus delays with the value from 27% to 41%. The largest value was measured at the degree of saturation of 1.0.

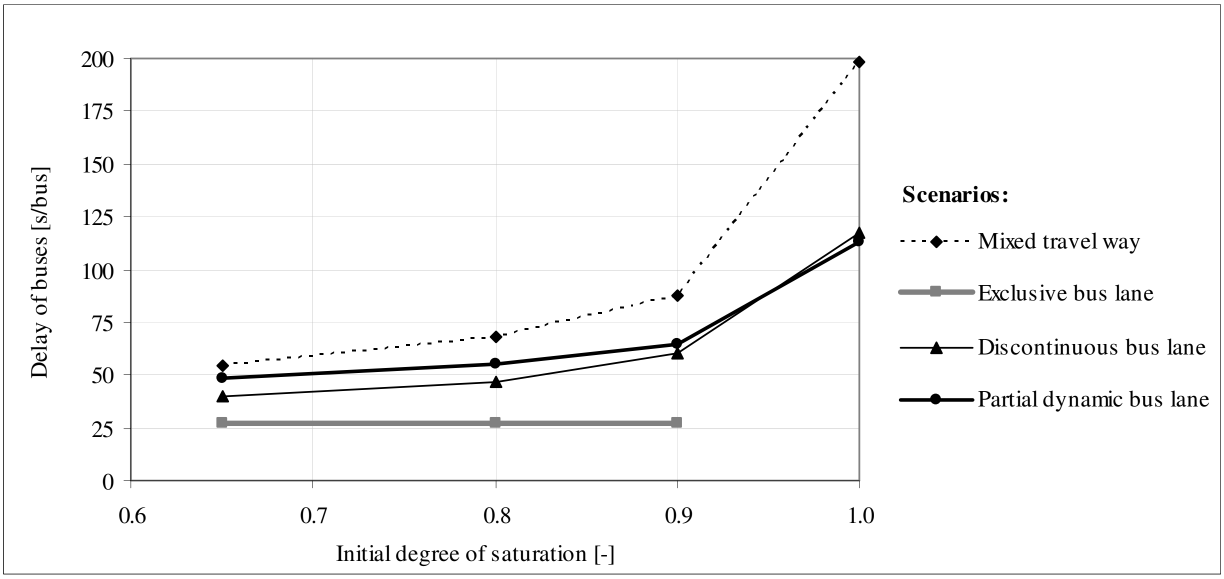

Figure 61: Delay of buses

For the scenario of partial dynamic bus lane, bus delays were reduced by 12% to 43% compared to those of the mixed travel way scenario. The largest amount of delay savings was also recorded at the degree of saturation of 1.0.

Delay of Other Vehicles

As can be seen in Fig. 62, when the degree of saturation on the upstream approach is greater than 0.7, the arrangement of exclusive bus lane can lead to a drastic increase in delays of other vehicles, compared to those of the mixed traffic way. The delays increased by about 146% and 296% at the degrees of saturation of 0.8 and 0.9 respectively.

On the contrary, the scenarios of discontinuous bus lane and partial dynamic bus lane show modest impacts on the delay of other vehicles at most degrees of saturation, compared to the mixed travel way scenario. Significantly, these measures even resulted in benefits to other vehicles at the degree of saturation of 1.0.

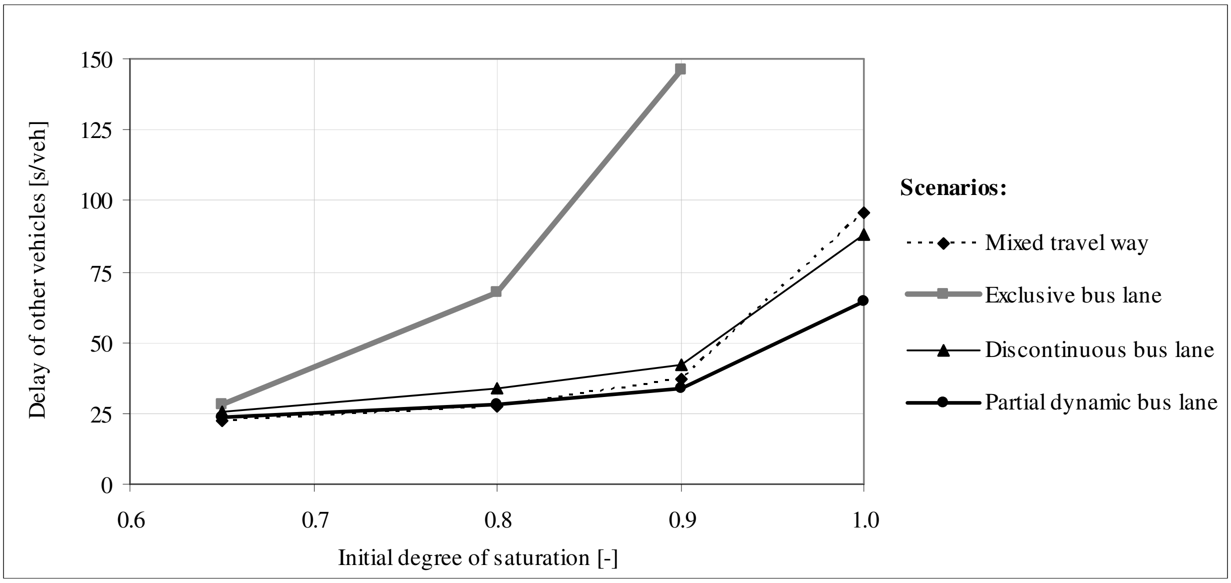

Figure 62: Delay of other vehicles

The reason for those benefits can be explained that these measures have both positive and negative effects on other vehicles as mentioned previously (see Section 5.2.4). The positive effects are to reduce impediments caused by skewing and jerky movements of buses at traffic signals. At a low degree of saturation, those movements might have inconsiderable impacts on capacity and traffic flow quality of the subject approach, but they can be very critical at a high degree of saturation. By the implementation of these measures, the smoother traffic flow and the higher capacity at the intersection can be obtained. For this reason, positive effects of these measures might exceed their negative ones at certain degrees of saturation. In Figure 62, thereby, the total impact of these measures on the delay of other vehicles is observed to shift from the negative side to positive side (compared to the mixed travel way scenario) as traffic loads increase to certain levels.

Average Person Delay

The average person delay can be considered as an important parameter for the assessment of measure effectiveness. This parameter helps to assess the implemented measures more appropriately, particularly when they entail both positive and negative effects.

Compared to the mixed travel way, as seen in Figure 63, the exclusive bus lane resulted in positive effects on the person delay only at a low degree of saturation (e.g. less than 0.65). At a higher one, e.g. $g \geq 0.8$, this measure is no longer effective in terms of this parameter. The average person delay was measured to increase by about 43% and 127% at the degrees of saturation of 0.8 and 0.9 respectively.

In contrast, the discontinuous bus lane reveals considerable benefits in terms of person delay at high traffic loads. The reductions of about 5% and 20% of person delay were achieved at the degrees of saturation of 0.9 and 1.0, respectively.

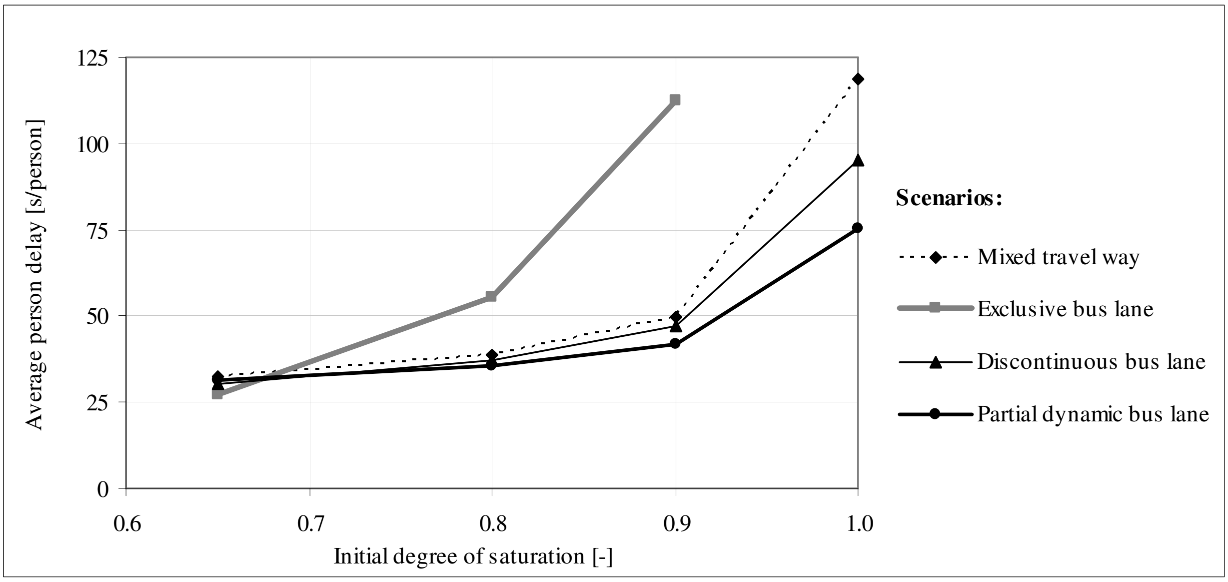

Figure 63: Average person delay of all modes

Remarkably, the partial dynamic bus lane results in significant benefits for the person delay. The reductions of about 16% and 36% of average person delay were observed at the corresponding degrees of saturation of 0.9 and 1.0.

Number of Stops of Other Vehicles

For the scenario of exclusive bus lane, the number of stops increased noticeably, corresponding to the increasing traffic loads. At the degrees of saturation of 0.8 and 0.9, it increased about twofold and fivefold respectively compared to that of the mixed travel way scenario (see Fig. 64).

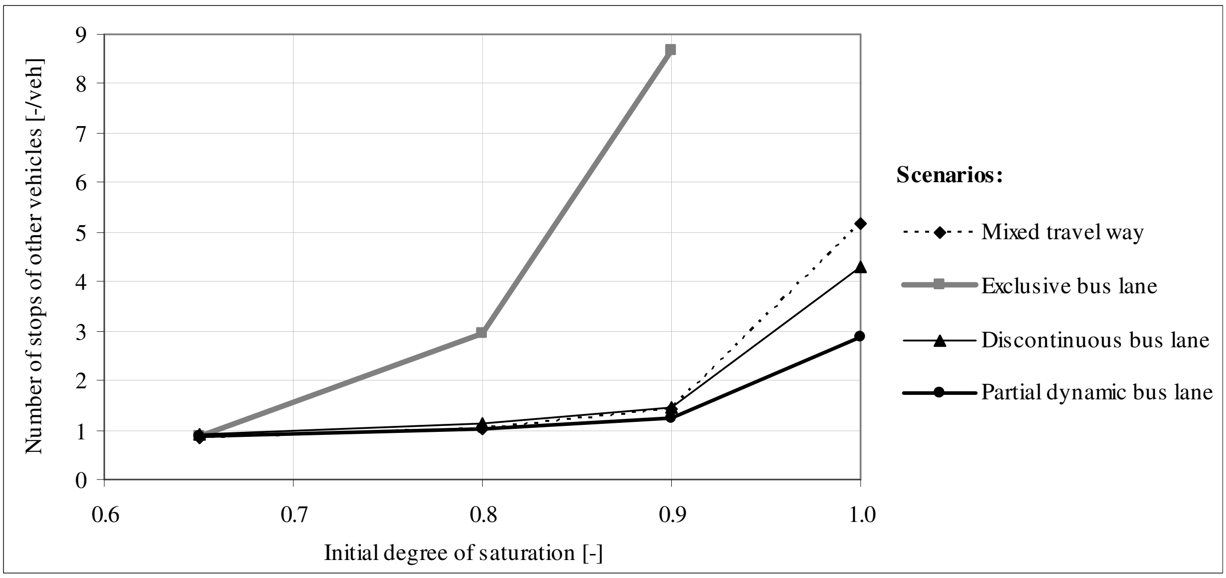

Figure 64: Number of stops of other vehicles

Conversely, the scenarios of discontinuous bus lane and partial dynamic bus lane had negligible impacts on this parameter at almost degrees of saturation. Remarkably, the number of stops is found to reduce at the degree of saturation of 1.0, compared to that of the mixed travel scenario.

Queue Length

There was severe congestion on the adjacent lanes for the scenario of exclusive bus lane when the degree of saturation approached 0.9 (see Fig. 65). The maximum queue length of about 530 m and the average queue length of approx. 360 m were observed at this degree of saturation. In terms of queue length parameter, it can be realised that the exclusive bus lane is not a favourable measure in the condition of heavy traffic loads.

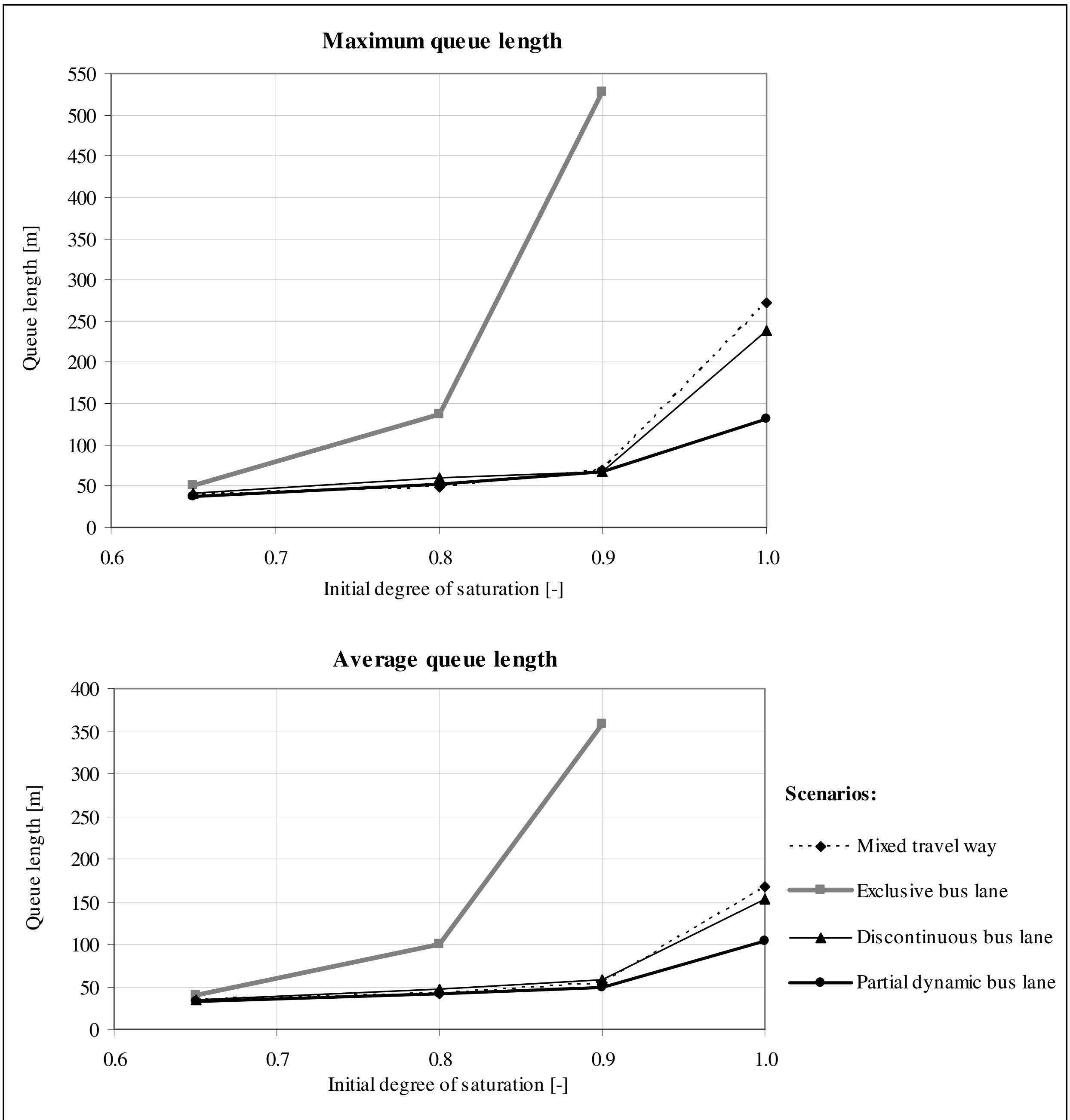

Figure 65: Maximum and average queue length

By contrast, there were small differences in queue length between the mixed travel way scenario and the scenarios of discontinuous bus lane and partial dynamic bus lane at that degree of saturation. In other words, these measures have negligible impacts on the queue length. Particularly, the positive effect is even seen at the degree of situation of 1.0.

5.2.6 Conclusions

Priority measures for bus travel ways are essential to speed up buses in urban streets, especially in heavy traffic conditions. These measures contribute to eliminate or reduce external disturbances caused by other vehicles on links as well as at traffic signals. By implementing these measures, a considerable amount of delay can be saved for buses and therefore the quality of bus services can be improved substantially.

There are a number of measures which have been introduced to prioritise buses. However, most of them have been studied under conditions of cities in developed countries. Consequently, they might not be appropriate to the conditions of MDCs, which are often much different compared to those of other cities.

For this reason, a systematic categorisation of measures has been developed for MDCs. The effect and applicability of measures were analysed based on the basic principles of traffic engineering, the experience from developed countries, the problems for buses on travel ways in MDCs, and the specific conditions of these cities. Thereafter, the most promising measures including discontinuous bus lanes and partial dynamic bus lanes have been studied in detail. These measures show the potential applicability to the prevailing conditions of MDCs, compared to exclusive bus lanes. On the one hand, they were developed to provide certain levels of priority to buses on non-signal and signal affected segments. On the other hand, they were designed to minimise their side impacts on capacity and traffic flow quality of intersection approaches.

Subsequently, the effects of discontinuous bus lanes and partial dynamic bus lanes regarding their benefits for buses and their impacts for other vehicles were estimated. In order to quantify the level of their effects under different traffic loads, the sensitivity analysis has been conducted. In this analysis, the scenarios with a discontinuous bus lane and a partial dynamic bus lane were compared to the mixed travel way scenario in order to reveal their effects. Besides, the scenario with an exclusive bus lane was analysed in order to highlight the advantage of the discontinuous bus lane and the partial dynamic bus lane.

The results of the sensitivity analysis indicated that the exclusive bus lane provided buses with the highest priority compared to that of other measures. However, under heavily loaded conditions, this measure caused critical side impacts for other vehicles, including a sharp increase in delay, number of stops, and queue length. Furthermore, this measure did not bring benefits in terms of person delay under those conditions. Therefore, this measure is basically not favourable if supportive measures are not provided.

Compared to the mixed travel way, remarkably, the discontinuous bus lane and partial dynamic bus lane resulted in positive effects on bus delay and total person delay for the examined direction. Besides, at low or medium degrees of saturation, only modest side impacts on other vehicles were observed. At a high degree of saturation (e.g. g = 1.0), the impacts on other vehicles were even reversed. The main reason for these marginal impacts is that the impediment due to skewing and jerky movements reduced noticeably when these lanes were implemented.

It should be noted that the effectiveness of discontinuous bus lanes and partial dynamic bus lanes might vary depending on local conditions such as roadway, traffic, control, and other conditions. Nevertheless, compared to mixed traffic lanes or exclusive bus lanes, the principal positive aspect of these lanes is basically consistent under the existing conditions of MDCs. Thereby, they are highly recommended for prioritising buses in MDCs, particularly when an arrangement of exclusive bus lanes is not feasible.

5.3 Measures for Traffic Signals

5.3.1 Formulation of Measures

Signal Priority

As mentioned previously in Chapter 3 (Section 3.2), at the intersection level, green extension, early green, phase swapping, phase suppression, actuated phases, and requested phases were recommended as potential measures for MDCs. At the route/network level, in addition, signal coordination of fixed-time programs and adjustment of green bands were suggested as potential measures for these cities. The related measures and their attributes are described in the following table.

Table 14: Potential signal priority measures for buses in MDCs

Level	Measures	Fixed-time program	Variable elements of the responsive signal program corresponding to the request of buses				
			Cycle length	Phase sequence	Number of phases	Green time	Time offset
Intersection	Green extension					X	
	Early green					X	
	Phase swapping			X			
	Phase suppression				X	X	
	Actuated bus phases				X	X	
	Requested bus phases				X	X	
Route/ Network	Coordination of fixed-time signal programs	X					
	Adjustment of green bands					X	X

Moreover, conditional priority is proposed for MDCs, especially under the condition of high traffic loads, considerable bus volumes, or constrained queuing space at signalised intersections. Thereby, minimum green times, permissible traffic flow quality, and maximum queue lengths of non-priority traffic are highly recommended as time and logical conditions for the control algorithm of signal priority.

Other Related Measures

Basically, signal priority helps to reduce delays caused by long red intervals for buses at traffic signals. In MDCs, however, other delays for buses might be derived from other sources such as inadequate signal settings, long vehicular queues, unprotected turning traffic, or congestion at signalised intersections involved.

To deal with those problems, the following measures are additionally proposed for MDCs:

- To improve signal program, including an improvement of intergreen times, phase setting, green times, cycle length, and time offset.
- To improve signal control strategies at both macroscopic and microscopic levels.

5.3.2 Selection of Measures

Signal Priority

In order to select appropriate signal priority measures, the following conditions should be taken into account, including (1) availability of space separation for buses at signalised intersections, (2) degree of saturation at traffic signals, (3) condition of queuing space, (4) signal coordination for other traffic, and (5) bus volume.

Green Extension

This measure provides buses with extended green times if they arrive traffic signals during the last seconds of their phases. In this manner, a considerable amount of delays can be saved for buses if they receive a green extension. In addition, this measure does not require additional clearance intervals, so that capacities of the intersections involved will not be affected.

Based on the experience of industrialised cities, a value from 6 to 10 seconds or about 10% of the cycle length is recommended for a green extension.[27]

Green extension can be relevant to most of roadway and traffic conditions. When non-priority streams suffer high to oversaturated traffic loads, lack of queuing space, or high number of bus requests, conditional priority should be implemented.

Early Green

This measure provides buses with their earlier green times by shortening those of the preceding non-priority phases. It is effective for buses arriving at traffic signals during their red intervals and therefore a larger number of buses can be prioritised by the early green, compared to those by the green extension. Besides, extra clearance intervals are not required, so that capacities of signalised intersections will not be influenced.

Being similar to the previous measure, a value of 6 to 10 seconds or about 10% of the cycle length is suggested for an early green.

The application conditions of this measure are similar to those of green extension. Generally, it can be applied to most of roadway and traffic conditions. If the conditions regarding degrees of saturation or queuing space on non-priority streams are critical, conditional priority should be deployed in order to reduce its side impacts on non-priority traffic.

[27] Reference to UITP (2009)

Phase Swapping

The principle of this measure is that the phase sequence of a signal program can be swapped in order to favour arriving buses during their red intervals. In this case, the signal program will operate with its irregular phase sequence in order to give priority to the buses.

However, this measure contains some concerns for non-priority traffic. The first concern regarding longer waiting times will be suffered by pedestrians and other vehicles belonging to non-priority streams when priority for buses is granted. That can lead to unreasonable waiting times and overloaded situation for them. The second concern is that the signal coordination will be affected adversely by swapped phases.

Thereby, this measure should be applied only if the following conditions are fulfilled, including:

- Availability of space separation for buses at traffic signals,
- Low to medium degrees of saturation on non-priority approaches,
- Sufficient queuing space for non-priority traffic streams,
- Absence of signal coordination, and
- Low bus volume.

In MDCs, moreover, this measure might lead to the misleading behaviour for road users due to its irregular phase sequence and the risk of signal violation because of the longer waiting times suffered by non-priority traffic. Therefore, these issues should be considered carefully in advance.

Phase Suppression

This measure prioritises buses by suppressing one or more of the preceding non-priority phases. The negative impact of this measure can include long waiting times and possibly oversaturated situation for other traffic in the skipped phases. Besides, it can interrupt signal coordination of non-priority traffic. Thereby, phase suppression should be applied if the following conditions are met: available space separation for buses, low degrees of saturation on non-priority approaches, low bus volume, sufficient queuing space, and absence of signal coordination. Additionally, the risk of signal violation due long waiting times should be considered carefully.

Actuated Bus Phases

An actuated bus phase is a predefined phase in the signal program, which is activated only by the requests of buses. By determining a proper time point in the cycle length for allocating this phase, its side impact on non-priority traffic (particularly concerning signal coordination) can be reduced.

However, this measure basically requires a separation between buses and other vehicles; therefore, they should be only implemented in streets where bus lanes, queue jump lanes, or open bus bays are available. In addition, capacities of the intersections involved can be reduced by some extent since this measure needs extra clearance intervals when bus phases are activated.

Apart from those considerations, the following conditions should be met when implementing this measure, including:

- Low to medium degrees of saturation on non-priority approaches,
- Sufficient queuing space for non-priority traffic streams, and
- Low to medium bus volume.

Requested Phases

This measure enables to insert special phases for buses according to their requests nearly within the whole cycle length. In this way, buses can be served at traffic signals with their inconsiderable waiting times. The time needed for an inserted phase (incl. its green time and clearance intervals) is basically taken from non-priority phases by reducing their green times or suppressing one or more of those phases.

However, this measure can cause noticeable impacts for non-priority traffic in terms of long waiting times, oversaturated situation, excessive queue length, and interrupted signal coordination, especially when traffic loads on non-priority approaches remain at critical levels.

Therefore, this measure should be applied only when the following conditions are satisfied, consisting of

- Availability of space separation for buses at traffic signals,
- Low to medium degrees of saturation on non-priority approaches,
- Sufficient queuing space for non-priority traffic streams,
- Absence of signal coordination, and
- Low bus volume.

Coordination of Fixed-Time Programs

In mixed traffic conditions, this measure should be applied only if traffic loads of the intentionally coordinated direction remain at low levels and signal coordination for other traffic is not required. Besides, the conditions regarding a stability of bus speed and dwell times are normally necessary. These conditions are infrequently met in MDCs, and therefore this measure is not encouraged for an application.

Adjustment of Green Bands

This measure enables to grant signal progression to buses along coordinated directions by adjusting existing green bands at their ends. It can be a relevant measure at the route level when the degree of saturation of non-priority traffic is from low to medium and bus volume is not high.

The following table summarises the recommendations on the selection of signal priority measures for MDCs.

Table 15: Recommendations on the selection of signal priority measures

No.	Conditions	Intersection Level						Route/Network Level	
		Green extension	Early green	Phase swapping	Phase suppression	Actuated phases	Requested phases	Coordination of fixed-time programs	Adjustment of green bands
1	**Availability of space separation**								
	Exclusive bus lanes, bus streets	+	+	+	+	+	+	+	+
	Queue jump lanes	+	+	+	+	+	+	+	+
	Unavailability, mixed traffic lanes	+	+	-	-	-	-	(+)	(+)
2	**Degree of saturation**								
	Low	+	+	+	+	+	+	+	+
	Medium	+	+	+	-	(+)	(+)	-	+
	High to oversaturated	(+)	(+)	-	-	-	-	-	-
3	**Queuing space**								
	Sufficient	+	+	+	+	+	+	+	+
	Limited	(+)	(+)	-	-	-	-	-	-
4	**Signal coordination**								
	Required	+	+	-	-	(+)	-	-	(+)
	Not required	+	+	+	+	+	+	+	+
5	**Bus volume**								
	Low	+	+	+	+	+	+	-	+
	Medium	+	+	-	-	(+)	(+)	+	+
	High	(+)	(+)	-	-	-	-	+	-

Legends: + : recommended; (+) : conditionally recommended; - : not recommended

The effectiveness of each priority measure can vary largely depending on specific conditions at individual signalised intersections. For this reason, a selection of relevant measures and their combinations in respect of existing conditions will be an important factor for an effective application of signal priority.

Since general conditions in the road network of MDCs commonly involve mixed traffic conditions in conjunction with high to overloaded traffic demands during peak periods, green extension and early green are found as the most potential measures for signal priority at the intersection level. At the route/network level, however, both signal coordination of fixed-time programs and adjustment of green bands are not preferable for the application to these cities.

Thereby, only green extension and early green as well as their combination are recommended for these cities. Nevertheless, if the mentioned conditions are locally peculiar, other measures and their alternative combinations can be further utilised; but their effects on non-priority traffic and other concerned issues must be examined carefully before an application.

Other Related Measures

At existing signalised intersections where buses operate, a reconsideration[28] of signal program elements (such as intergreen times, number of phases, phase sequence, green times, cycle length, and time offset) and problems for buses at traffic signals should be made. This reconsideration is necessary to identify whether traffic signals were designed properly or not. If not, an improvement of traffic signal design needs to be realised.

To given problems, corresponding measures are suggested for traffic signals as follows:

- If buses are regularly impeded by long vehicular queues during peak periods: Green times should be allocated more for bus-operating approaches in order to avoid their oversaturated situation at traffic signals. Furthermore, an improvement of macroscopic control strategies should be considered to make traffic signals adapt better to the change of current traffic situation. These measures are highly recommended, particularly when a priority lane for buses cannot be arranged on the road section.
- If buses are potentially impeded by long vehicular queues due to the variation of traffic volumes during peak periods: An application of microscopic control strategies for monitoring the queue on bus-operating approaches is highly proposed, especially for directions without a bus lane.
- If buses are noticeably impeded by unprotected turning movements, e.g. by left-turning movements: An improvement of signal programs related to the signal phasing should be conducted by assigning protected phases to those movements.
- If buses are potentially impeded by irregular congestion (e.g. congestion caused by non-unprotected turning traffic or by overloaded queuing space): An improvement of both signal programs and control strategies should be done. Besides, extra traffic regulations and enforcement should be implemented as a supportive measure to enhance traffic discipline in case of congestion.

5.3.3 Estimation of Measure Effects

As mentioned above, the proposed measures for prioritising buses at traffic signals include both signal priority measures and other related measures. On the one hand, signal priority measures help to reduce disturbances caused by the red interval of signalisation itself. On the other hand, the other measures enable to reduce other disturbances caused by improper signal settings, long queues, unprotected turning traffic, and irregular congestion at traffic signals.

Table 16 provides a general estimation of measure effects on both buses and other traffic. It should be noted that the measures related to improvements of signal programs and control strategies generally result in positive effects for buses and parallel traffic. Besides, the side

[28] A reconsideration of an improvement of intersection layout by pavement markings, traffic islands, or infrastructure measures should be made in advance.

effect of these measures on non-priority traffic will not be considered because they are useful for general traffic and they belong to the improvement of traffic signal design.

Table 16: Estimation of effects for traffic signal measures

No.	Measures / Primary Effects	Signal Priority		Other Related Measures	
		Green extension	Early green	Improvement of signal programs	Improvement of control strategies
1	**Positive effects on buses**				
	Reduced delays caused by improper signal settings			x	
	Reduced delays caused by red intervals	x	x		
	Reduced delays caused by long queues			x	x
	Reduced delays caused by unprotected turning traffic			x	
	Reduced delays caused by irregular congestion			x	x
2	**Positive effects on parallel priority traffic**				
	Reduced delays	x	x	x	x
3	**Side effects on non-priority traffic**				
	Increased delays	x	x		
	Increased queue lengths	x	x		
4	**Possibly positive effects on flow of people**				
	Reduced total person delay	x	x	x	x

Signal priority measures including green extension and early green will result in positive effects on delays of buses and other parallel priority traffic. Their side effects on non-priority traffic might consist of increased delays and queue lengths. However, these side effects are often marginal because only some seconds of green times on non-priority approaches are reduced to prioritise buses. Additionally, when conditional priority is applied, these side effects can be monitored at permissible levels.

On the one hand, the effectiveness of traffic signal measures on bus delay and total person delay is evident, and the improvement of quality of bus services (e.g. increased speed, reduced travel time, and enhanced reliability) is clear. On the other hand, the side effects of the selected measures on non-priority traffic are marginal as discussed previously. Therefore, a detailed assessment of these measures will not be given in this chapter. However, an empirical evaluation of bus prioritisation, in which traffic signal measures are involved, will be given in Appendix C of this study.

5.3.4 Conclusions

Measures for traffic signals are essential to prioritise buses at signalised intersections. These measures are classified into two groups: signal priority measures and other related measures.

Regarding signal priority, the potential priority measures at the intersection level comprise green extension, early green, phase swapping, phase suppression, and actuated phases, while at the route/network level they consist of signal coordination of fixed-time programs and adjustment of green bands. In respect of other related measures, improvements of signal programs and control strategies are recommended to deal with problems caused by improper signal setting, long queues, unprotected turning traffic, and irregular congestion at signalised intersections.

A proper selection of signal priority measures and their combinations will help to make use of their positive effects for buses and to limit their side effects on other non-priority traffic. When selecting these measures, both of their primarily positive and negative effects should be taken into account in hand.

Under general conditions of MDCs, green extension and early green were recognised as the most suitable signal priority measures at the intersection level. However, at the route/network level, clear positive effects of signal priority in mixed traffic conditions with high traffic loads have not been seen yet.

Apart from signal priority measures, other related measures (incl. improvements of signal programs as well as control strategies at both macroscopic and microscopic levels) should be carried out at the same time. Since buses often suffer considerable delays caused by improper signal settings, long vehicular queues, unprotected turning traffic, and irregular congestion at signalised intersections, these measures should be considered as an important component of traffic signal measures for prioritising buses in MDCs.

6 Application Process of Bus Prioritisation

6.1 Development of the Process

The application process of bus prioritisation for MDCs was developed, based on the fundamental steps of the transport planning process in Germany. This application process is provided in the following figure.

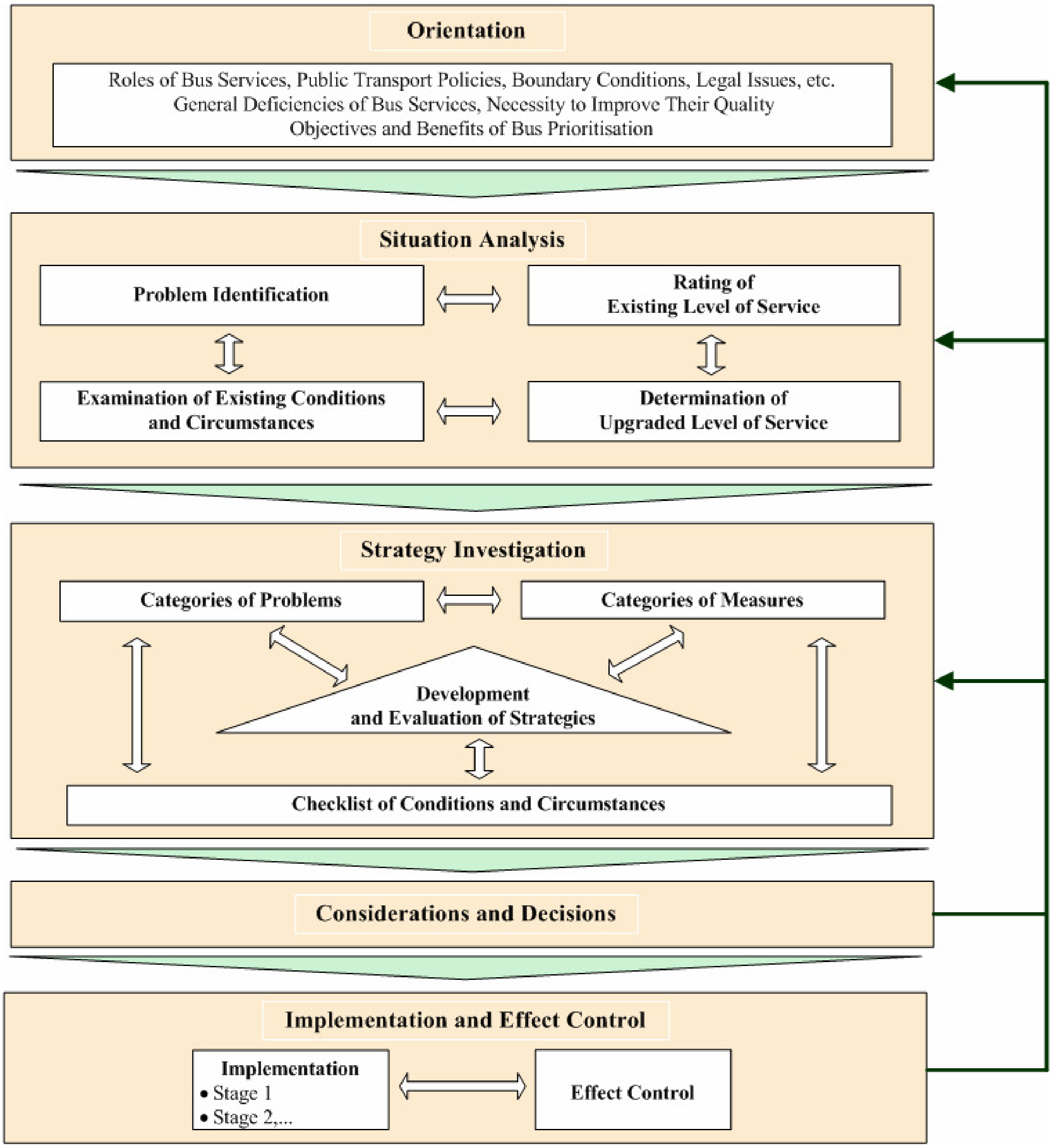

Figure 66: Application process of bus prioritisation[29]

[29] Reference to German transport planning process, FGSV (2001b)

Five basic steps including (1) orientation, (2) situation analysis, (3) strategy investigation, (4) considerations and decisions, and (5) implementation and effect control are determined in this process. In the first step, the role of bus services and other concerned issues in the urban transport system are highlighted in order to clarify the necessity of improving the quality of bus services through bus prioritisation. The second step involves the identification of problems for buses as well as existing conditions and circumstances of urban roadways. Then both existing and upgraded levels of service are determined in this step. The third step deals with the development and evaluation of bus prioritisation strategies, which are based on categories of problems and measures as well as the local conditions and circumstances. Then considerations and decisions are made in the following step. The last step is for the implementation and effect control of bus prioritisation. In the whole process, the effectiveness of bus prioritisation and the quality of bus services can be continually improved by the interrelationships between its steps.

6.2 Problems, Measures, and Strategies

Categorisation of Problems

In mixed traffic conditions, three main categories of possible problems for buses have been summarised based on the analyses in the previous chapters, including problems at bus stops, on travel ways, and at traffic signals. These problems have been condensed to make them ordinarily identifiable on the urban roadway of MDCs. The following table provides the categories of these problems.

Table 17: Categories of possible problems for buses in mixed traffic conditions

No.		Categories	Problems
I		**Bus Stops**	*Operation of buses at their stops*
	1		- Impeded by back queues
	2		- Impeded by densely surrounding vehicles
	3		- Impeded by excessively stopping buses
	4		- Impeded by illegal stopping/parking activities
	5		- Impeded by other activities
			Operation of vehicular traffic at traffic signals
	6		- Impeded by stopping buses
II		**Travel Ways**	*Operation of buses on non-signal affected segments of the section*
	1		- Impeded by other vehicles in mixed traffic flow
	2		- Impeded by local accessing traffic
	3		- Impeded by other activities
			Operation of buses on signal affected segments of the section
	4		- Impeded by long or severe queues
	5		- Impeded by heavy right-turning traffic
	6		- Impeded by illegal stopping/parking activities
	7		- Impeded by other activities
	8		- Impeded by regular congestion
III		**Traffic Signals**	*Operation of buses at traffic signals*
	1		- Impeded by improper signal settings
	2		- Impeded by long queues
	3		- Impeded by long red intervals
	4		- Impeded by unprotected turning traffic
	5		- Impeded by irregular congestion

Categorisation of Measures

In order to deal with the possibly occurring problems as mentioned previously, four major categories of measures have been introduced (see Table 18). Based on the conducted analyses, these measures have been analysed as the most potential measures for MDCs. It should be highlighted that discontinuous bus lanes and partial dynamic bus lanes have been developed specifically for MDCs to provide alternative measures for prioritising buses on their travel ways. Thereby, these measures are highly recommended for an application, particularly when the other ones cannot be implemented efficiently due to lack of necessary conditions.

Table 18: Categories of potential measures for bus prioritisation in MDCs

No.		Categories	Measures
I	1	Bus stops	Adjustment of bus stop location
	2		Bus bays
	3		Increased loading areas
II	1	Travel Ways	Bus streets
	2		Time-restricted bus streets
	3		Streets for buses and other specified vehicles
	4		Time-restricted streets for buses and other specified vehicles
	5		Exclusive bus lanes
	6		Time-restricted bus lanes
	7		Queue jump lanes
	8		Discontinuous bus lanes
	9		Partial dynamic bus lanes
II	1	Traffic Signals	Green extension and early green
	2		Improvement of signal programs
	3		Improvement of control strategies
IV	1	Supportive Measures	Improvement of lane separation
	2		Permanent traffic rerouting
	3		Periodic traffic rerouting
	4		Extra traffic regulations and enforcement
	5		Infrastructure measures

Formulation of Strategies

Under a certain situation, a strategy of bus prioritisation can be defined as an action plan represented by a group of integrated measures which aim to deal with existing problems for buses at bus stops, on travel ways, and at traffic signals. Depending on occurring problems as well as local conditions and circumstances, one or more strategies can be developed alternatively to prioritise buses. The following table provides suggestions on the strategy development of bus prioritisation under general conditions of MDCs.

Table 19: Suggestions on the development of bus prioritisation strategies

	Measures / Problems	Bus Stops: Adjustment of bus stop location	Bus Stops: Bus bays	Bus Stops: Increased loading areas	Travel Ways: Bus streets	Travel Ways: Time-restricted bus streets	Travel Ways: Streets for buses & other specified vehicles	Travel Ways: Time-restricted streets for buses & specified vehicles	Travel Ways: Exclusive bus lanes	Travel Ways: Time-restricted bus lanes	Travel Ways: Queue jump lanes	Travel Ways: Discontinuous bus lanes	Travel Ways: Partial dynamic bus lanes	Traffic Signals: Green extension & early green	Traffic Signals: Improvement of signal programs	Traffic Signals: Improvement of control strategies	Supportive Measures: Improvement of lane separation	Supportive Measures: Permanent traffic rerouting	Supportive Measures: Periodic traffic rerouting	Supportive Measures: Extra traffic regulations & enforcement	Supportive Measures: Infrastructure measures
Bus Stops	*Operation of buses at their stops*																				
	Impeded by back queues	x																			
	Impeded by densely surrounding vehicles	x	$[x]_1$																		$[x]_1$
	Impeded by excessively stopping buses			x																	
	Impeded by illegal stopping/parking activities																			x	
	Impeded by other activities																			x	
	Operation of vehicular traffic at traffic signals																				
	Impeded by stopping buses	x	$[x]_1$																		$[x]_1$
Travel Ways	*Operation of buses on non-signal affected segments*																				
	Impeded by other vehicles in mixed traffic flow				$[x]_2$	$[x]_3$	$[x]_4$	$[x]_5$	$[x]_6$	$[x]_7$		(x)	(x)					$[x]_{2/4/6}$	$[x]_{3/5/7}$	$[x]_{3/5/7}$	
	Impeded by local accessing traffic																			x	
	Impeded by other activities																			x	
	Operation of buses on signal affected segments																				
	Impeded by long or severe queues				$[x]_2$	$[x]_3$	$[x]_4$	$[x]_5$	$[x]_6$	$[x]_7$	$[x]_8$	(x)	(x)					$[x]_{2/4/6}$	$[x]_{3/5/7}$	$[x]_{3/5/7}$	$[x]_8$
	Impeded by heavy right-turning traffic												(x)				$[x]_9$			$[x]_9$	
	Impeded by illegal stopping/parking activities																			x	
	Impeded by other activities																			x	
	Impeded by regular congestion																	x	x		x
Traffic Signals	*Operation of buses at traffic signals*																				
	Impeded by improper signal settings														x						
	Impeded by long queues														$[x]_{10}$	$[x]_{10}$					
	Impeded by long red intervals													x							
	Impeded by unprotected turning traffic														x						
	Impeded by irregular congestion														$[x]_{11}$	$[x]_{11}$				$[x]_{11}$	

Legends:

x : A single measure can be applied properly.

(x) : A single measure with its application conditions can be applied properly.

$[x]_1$: Multiple measures with the same subscript can be applied properly.

$[x]_{2/4/6}$: Multiple measures with the same alternative subscript can be applied properly.

It should be noted that infrastructure measures (e.g. expansion of road space) are basically required when bus bays or queue jump lanes are implemented (see Table 19). However, an arrangement of bus streets or exclusive bus lanes by infrastructure measures is unfavourable at present; thereby, they were not recommended as supportive measures for that arrangement.

After formulating potential strategies for bus stops, travel ways, and traffic signals, the most suitable strategies corresponding to existing problems in individual categories will be selected for an implementation of bus prioritisation. As a result, bus prioritisation can be represented by integrated strategies for bus stops, travel ways, and traffic signals.

6.3 Conclusions

This chapter has provided an integrated process of bus prioritisation, which is based on five basic steps: (1) orientation, (2) situation analysis, (3) strategy investigation, (4) considerations and decisions, and (5) implementation and effect control. As a result, the application of bus prioritisation to MDCs is illustrated with a clear framework.

Thereafter, the categorisations of possible problems for buses and the most potential measures for bus prioritisation were formulated. To facilitate an efficient application of bus prioritisation to MDCs, the detailed suggestions on the development of strategies were given. These suggestions contribute significantly to select effective measures for prioritising buses in different local conditions of MDCs.

7 Conclusions and Recommendations

7.1 Summary of the Research Results

The results of this study have been acquired by solving the research questions which were posed at the beginning of this research work. These results will be summarised in the following.

Justification of the Need of Bus Prioritisation for MDCs

The important roles of bus services in MDCs were identified. They consist of providing equal mobility for all people, saving road space for passenger transport, supporting mode choice, minimising traffic accidents, reducing traffic emissions, and lowering transport costs.

The lack of prioritising buses for many years was discerned as one of the main causes leading to the poor quality of bus services and a number of urban transport problems in these cities. Therefore, the need of bus prioritisation is essential for MDCs.

Consolidation of Bus Prioritisation Measures

Measures for prioritising buses in the urban road network were consolidated based on the experience and research from developed countries. They were categorised into three main groups of measures, including measures for signal priority, measures for travel ways, and measures for bus stops. The major attributes and application conditions of these measures were analysed in order to obtain their advantageous and disadvantageous aspects.

Delineation of Urban Transport Problems

The sophisticated situation of urban transport in MDCs was illustrated, which comprises a bundle of conflicting and interacting problems. These problems were examined in order to comprehend their impacts. As a result, the general situation of urban transport in MDCs was clarified.

Identification of Problems for Buses

The problems for buses on urban roadways were classified and scrutinised. Under mixed traffic conditions, these problems were found to occur at traffic signals, on travel ways, and at bus stops.

At traffic signals, the problems of traffic signal control (incl. inadequate signal program design, lack of priority considerations for buses, and insufficient control strategies), intersection layout, and traffic behaviour were identified to have direct consequences for unreasonable delays of buses.

Due to mixed traffic conditions on travel ways, buses are suffering a number of impediments. On non-signal affected segments of the road section, the interaction between buses and other vehicles in mixed traffic flow was determined as the first component of impediments. On signal affected ones, especially during peak periods, the obstruction caused by extensive queues and skewing movements was observed as the second component. Moreover, the interference of parking/stopping activities, local accessing traffic, and other related activities was potentially the third component of impediments.

The problems at on-line bus stops were examined carefully since these stops are located directly on normal traffic lanes. At bus stops close to traffic signals, obstructions caused by vehicular queues, stopping buses, skewing movements of buses, interactions between buses and other vehicles, and other interference activities were identified as the major external disturbances. These disturbances were observed to impact adversely on traffic flow quality of both buses and other vehicles as well as on capacities of intersection approaches involved.

After considering other problems caused by the general situation of urban transport, the problem sequence was formulated to comprehend how all of the concerned problems are impacting on the quality of bus services. In order to solve the existing problems for buses, the concept of bus prioritisation for MDCs was introduced.

Development, Estimation, and Assessment of Bus Prioritisation Measures

Measures for Bus Stops

Three main measures for on-line bus stops, including the adjustment of bus stop location, replacement with bus bays, and implementation of supportive measures, were developed based on the existing problems of these stops. In addition, the effects of these measures on both buses and other vehicles were estimated.

In order to reveal the level of effects, the sensitivity analysis was conducted. It provided convincing evidence for the influence of bus stop location on traffic flow quality and capacities of the intersection approaches involved. The positions right before the stop line or right after the downstream intersection resulted in the most critical impacts. To avoid sizeable impacts, the critical ranges relatively distant from traffic signals were identified, in which the impact of the bus stop alters rapidly between different positions.

Under high traffic loads, those ranges were found approx. 60 to 75 m extended from the reference points (the stop line for near-side bus stops or the beginning of the downstream intersection for far-side ones). Thereby, it is recommended that bus stops should not be situated too closely to traffic signals.

Measures for Travel Ways

The systematic categorisation of possible measures for bus travel ways was generated. Based on analysing, the potential measures for MDCs were identified. In the consideration of specific conditions in MDCs, discontinuous bus lanes and partial dynamic lanes were introduced in order to provide additional alternatives for prioritising buses on their travel ways. The detailed suggestions on the principles, arrangement, operation, and application of these lanes were established.

The estimation of effects for these lanes was carried out in order to clarify their fundamental effects by comparing with mixed traffic lanes. On the one hand, these lanes result in positive effects on buses on both signal and non-signal affected segments. On the other hand, they can lead to some effects (both positive and negative ones) on other vehicles, and therefore the total effect on those vehicles is most likely insignificant.

In order to clarify the level of effects, the sensitivity analysis was conducted, in which the initial situation involving the mixed travel way of buses was improved in turn by a discontinuous bus lane, a partial dynamic bus lane, and an exclusive bus lane. In the condition of medium to high traffic loads, significantly, the discontinuous bus lane and partial dynamic bus lane resulted in (i) positive effects on the delay of buses, compared to the mixed travel way, (ii) positive effects on the person delay of all vehicular modes, compared to the exclusive bus lane and mixed travel way, and (iii) negligible effects on traffic flow quality of other vehicles and queue length.

Under the saturated condition (g = 1.0) of the mixed travel way, remarkably, about 40% of bus delay was saved by an application of these lanes. In addition, over 20% of average person delay was reduced for the examined direction. Furthermore, traffic flow quality of other vehicles and queue length were slightly improved after the implementation of these lanes. On the contrary, the severe congestion on adjacent lanes was observed after the arrangement of the exclusive bus lane.

The introduction of discontinuous bus lanes and partial dynamic bus lanes provides additional options to prioritise buses in the urban road network of MDCs, particularly when there are a number of roads having application conditions for these lanes but not for exclusive bus lanes.

Measures for Traffic Signals

The potential measures for signal priority were categorised and analysed. In addition, the suggestions on the selection of signal priority measures were provided for different roadway, traffic, and control conditions. Besides, other related measures were formulated. The effects of the most potential measures were estimated to clarify their primary effects on both buses and other vehicles.

Formulation of the Application Process of Bus Prioritisation

The process of bus prioritisation was developed to provide a basic framework for its application. Moreover, to facilitate an efficient implementation of bus prioritisation to MDCs, the possible problems, promising measures, and potential strategies were correspondingly condensed, categorised, and provided.

7.2 Effectiveness of Bus Prioritisation

From the analyses, estimations, and assessments, the effectiveness of bus prioritisation is clarified as follows:

- Effectiveness on the operation of buses: reduced delay, increased speed, reduced travel time, decreased variation of travel time (which results in an improvement of punctuality and reliability), and reduced number of stops.

- Effectiveness on general traffic flow: decreased total person delay and probably improved traffic flow quality.
- Effectiveness on bus services: improvement of the quality of bus services.
- Effectiveness on passenger transport: improvement of safety, mobility, capacity efficiency, environmental sustainability, and economic efficiency.

Since the effectiveness of bus prioritisation comprises a wide range of its influenced elements, a full-scale evaluation of this effectiveness is highly complicated. However, the effectiveness on buses and general traffic flow, such as the delay, speed, travel time, etc., can be quantified.

In respect of the measurable effectiveness, an empirical evaluation of bus prioritisation for a road segment of Nguyen Thi Minh Khai Street in Ho Chi Minh City indicated that the following effectiveness will be achieved after an application of bus prioritisation (see Appendix C for more details):

- 39% of bus travel time will be reduced,
- 53% of bus delay will be reduced,
- 66% of bus speed will be increased,
- 16% of total person delay of all vehicular modes will be saved, and
- The standard deviation of bus travel time will be reduced by 53%.

It is concluded that the effectiveness of bus prioritisation includes the effectiveness on the operation of buses, general traffic flow, bus services, and passenger transport. The measurable effectiveness obtained from the empirical evaluation of bus prioritisation provided extra evidence that bus prioritisation is a key solution to improve the quality of bus services.

7.3 Significance and Limitations of the Study

Significance

This study contributes to establish a key solution for the rising traffic problems in MDCs. This consists of

- Justifying the significant roles of buses and the need of bus prioritisation for MDCs,
- Providing a clear picture of the existing problems for urban transport and buses in MDCs,
- Introducing the concept of bus prioritisation to MDCs,
- Dealing with the latent problems of on-line bus stops in mixed traffic conditions,
- Developing two new measures (discontinuous bus lanes and partial dynamic bus lanes) for prioritising buses on the urban roadway,
- Providing suggestions on the selection of signal priority measures,
- Providing a coherent process for an application of bus prioritisation measures, and
- Clarifying the effectiveness of bus prioritisation in MDCs.

Limitations

Because urban roadway conditions (incl. geometric, traffic, control, and other conditions) vary from location to location, only the most general and typical conditions were selected for the detailed assessments of bus prioritisation measures in this study. Besides, on the basis of minimising turbulence caused by unwanted factors on the effects of measures, some simplifications were made in those assessments, e.g. intersection layout and signal control.

However, these limitations can be uncomplicatedly overcome since the primary effects of measures have been clarified. Moreover, the effect of each measure will be further investigated and controlled for individual situation when bus prioritisation is applied practically in MDCs.

7.4 Recommendations for Further Studies

Studies on Bus Prioritisation

This study has introduced the concept of "Bus Prioritisation" to MDCs and has investigated the potential prioritisation measures in conjunction with their effects. Further research should therefore concentrate on the application of bus prioritisation, including the following aspects:

- Selection of suitable detection and communication systems for related measures of bus prioritisation.
- Implementation of proper traffic guidance and traffic enforcement measures to support the implementation of bus prioritisation.
- Investigations of practical effects of bus prioritisation measures after their implementation.
- Utilisation of non-congested bus lanes (e.g. discontinuous bus lanes and partial dynamic bus lanes) for emergency vehicles.

Other Suggested Research

Apart from bus prioritisation, other research is suggested to improve the quality of bus services in MDCs, consisting of

- Improvement of operational issues related to the bus network, scheduling, vehicle, on-board equipment, etc.
- Application of telematics and other advanced technologies to bus services, including passenger information systems, positioning systems, communication systems, systems for disposition, etc.
- Improvement of intermodal transport in MDCs to encourage the use of public transport and non-motorised transport.

In respect of traffic signal control, the following research directions are recommended for MDCs:

- Improvement of capacity and traffic flow quality at signalised intersections.

- Signal coordination for main directions in the urban road network.
- Application of responsive traffic control to signalised intersections.
- Application of detection systems and communication systems to traffic signal control.
- Modernisation of urban traffic control centres, etc.

Besides, many current problems of urban transport in MDCs need to be solved. Thereby, the studies on managing and monitoring traffic congestion, minimising traffic accidents, reducing traffic emissions, applying traffic information, implementing traffic management, improving traffic discipline, etc. will be necessary for these cities.

Essentially, a number of studies regarding MDCs are being conducted in Vietnamese-German Transport Research Centre (VGTRC) in Ho Chi Minh City, such as “Detailed capacity analysis of signalised intersections” and “Analysis of accidents at signalised intersections and measures for safety improvements”. The promotion of this kind of studies will contribute greatly to solve the rising traffic problems in these cities.

List of Abbreviations

AVL	Automatic Vehicle Location
BMVBW	German Federal Ministry of Transport, Building and Housing
BRT	Bus Rapid Transit
CAN	Controller Area Network
CBD	Central Business District
CO	Carbon Monoxide
dB(A)	A-Weighted Decibel
DFI	Dynamic Passenger Information
DGPS	Differential Global Positioning System
FGSV	German Road and Transport Research Association
GDP	Gross Domestic Product
GNP	Gross National Product
GPRS	General Package Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HBS	German Manual for the Design of Road Infrastructure
HCMC	Ho Chi Minh City
HCMC-PC	Ho Chi Minh City People's Committee
HOV	High-Occupancy Vehicle
HPC	Hanoi People's Committee
IBIS	Integrated On-Board Information System
IBL	Intermittent Bus Lane
ICE	Internal Combustion Engine
IR	Infrared Radiation
IT	Individual Transport
ITCS	Intermodal Transport Control System
IV	Individual Vehicles
JICA	Japan International Cooperation Agency

kJ	Kilojoules
LEDs	Light-Emitting Diodes
LOS	Level of Service
MC	Motorcycle
MDCs	Motorcycle Dependent Cities
MOT	Ministry of Transport of Vietnam
NO_2	Nitrogen Dioxide
O_3	Ozone
PM	Particulate Matter
PM_{10}	Particles with a Diameter of 10 Micrometers or Less
PT	Public Transport
QSV	Level of Service
RF	Radio Frequency
RiLSA	German Guidelines for Traffic Signals
SO_2	Sulphur Dioxide
TSP	Total Suspended Particulates
UITP	International Association of Public Transport
U.S.	United States of America
VDV	German Transport Companies
VGTRC	Vietnamese-German Transport Research Centre
VISSIM	Microscopic Multi-Modal Traffic Flow Simulation Software
VOCs	Volatile Organic Compounds
WHO	World Health Organization
WLAN	Wireless Local Area Network

List of Figures

List of Tables

References

Altenhein, M. (2006).
Umdruck zur Vorlesung: *Planung des öffentlichen Personennahverkehrs.*
Technische Universität Darmstadt.

Asim, M., Kattan, L., Wirasinghe, S.C. (2012).
"Adaptive signal control with LRT preemption".
Traffic Engineering & Control Magazine, TEC June 2012, pp. 230–237.

Asri, D.U., Hidayat, B. (2005).
"Current Transportation Issues in Jakarta and Its Impacts on Environment".
Proceedings of the Eastern Asia Society for Transportation Studies, Vol. 5, 2005, pp. 1792–1798. Retrieved from http://www.easts.info/on-line/proceedings_05/1792.pdf

Barter, P. (1999).
An international comparative perspective on urban transport and urban form in Pacific Asia: the challenge of rapid motorisation in dense cities.
Retrieved from http://researchrepository.murdoch.edu.au/3332/
PhD thesis, Murdoch University.

Basu, D., Maitra, S.R., Maitra, B. (2006).
"Modelling passenger car equivalency at an urban mid-block using stream speed as measure of equivalence". *European Transport, No. 34, 2006*, pp. 75–87.

Bayerisches Landesamt für Umwelt (2007).
Schall- und Erschütterungsschutz im Planfeststellungsverfahren für Landverkehrswege.
Retrieved from http://www.lfu.bayern.de/laerm/doc/verkehr_erschuetterungsschutz.pdf

BMV—Bundesminister für Verkehr (1994).
Verkehrsnachrichten, Heft 10, Oktober 1994.
Bonn.

Boltze, M. (2003).
"A German Example for a Public Private Partnership in Transport Research: ZIV–Institute for Integrated Traffic and Transport Systems at Darmstadt University of Technology".
International Association of Traffic and Safety Sciences (IATSS) Research Vol.27 No.1, 2003, pp. 19–32.

Boltze, M., Wolfermann, A., Schäfer, P. K. (2006).
Leitfaden Verkehrstelematik: Hinweise zur Planung und Nutzung in Kommunen und Kreisen.
Published by Bundesministerium für Verkehr, Bau und Stadtentwicklung.
Bonn.

Boltze, M. (2007).
Materialien zur Vorlesung: *Moderne Verkehrsleittechniken.*
Technische Universität Darmstadt.

Boltze, M. & Kohoutek, S. (2009).
"Environment-Responsive Traffic Control".
International Scientific Conference on Mobility and Transport – ITS for Larger Cities. Munich.

Boltze, M. (2010).
Materialien zur Vorlesung: *Verkehr 1 (A).*
Technische Universität Darmstadt.

Boltze, M., Busch, F., Friedrich, B., Friedrich, M., Kohoutek, S., Löhner, H., Lüßmann, J., Otterstätter, T. (2011a).
"AMONES: Anwendung und Analyse modellbasierter Netzsteurungsverfahren in städtischen Straßennetzen – Teil 1: Problemstellung und Methodik".
Straßenverkehrstechnik 5.2011, pp. 293–300.

Boltze, M., Krüger, P., Reusswig, A., Hillebrand, I. (2011b).
Internationale und nationale Telematik-Leitbilder und ITS-Architekturen im Straßenverkehr.
Berichte der Bundesanstalt für Straßenwesen, Heft F 79.

Bosserhoff, D. (2007).
Bevorrechtigung des ÖPNV an Lichtsignalanlagen.
Handbuch für Verkehrssicherheit und Verkehrstechnik (Kapitel 6.1) der Hessischen Straßen- und Verkehrsverwaltung.

Bradshaw, A. (2010).
"A micro-simulation approach to modelling bus priority".
Traffic Engineering & Control Magazine, TEC October 2010, pp. 339–343.

Brög, W., Erl, E. (1993).
"Die Bedeutung des nichtmotorisierten Verkehrs für die Mobilität in unseren Städten".
Verkehr und Technik 1993, Heft 10, pp. 415–423.

Bundesministerium für Verkehr, Bau-und Wohnungswesen (BMVBW) & Verband Deutscher Verkehrsunternehmen (VDV). (2001).
Telematik im ÖPNV in Deutschland.
Düsseldorf.

Bundesministerium für Verkehr, Bau und Stadtentwicklung (BMVBS)., Deutsche Einsenbahn Versicherung, Sach-und HUK-Versicherungsverein a.G. (DEVK)., Verband Deutscher Verkehrsunternehmen (VDV). (2010).
Sustainable Public Transport, Vol. 1+2.
Düsseldorf.

Central Intelligence Agency (2011).
The World Factbook 2011.
Retrieved from https://www.cia.gov/library/publications/download/download-2011/index.html

Chu, C. M., Matsumoto, S., Sano, K. (2005).
"The Speed, Flow and Headway Analyses of Motorcycle Traffic".
Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, 2005, pp. 1496–1508.

Demetsky, M. J., Lin, B. B. (1982).
"Bus Stop Location and Design". *Transportation Engineering Journal of the American Society of Civil Engineering (ASCE), Vol. 108 No. TE1. Jan. 1982*, pp. 313–327.

Deutsches Institut für Wirtschaftsforschung (DIW) (1999).
"Energieverbrauch im Verkehr in Deutschland - Verringerung der Wachstumsraten in den neunziger Jahren". *Wochenbericht 10/99*, DIW Berlin.
Retrieved from http://www.diw.de/deutsch/99_10_1/30931.html#HDR0

Deutsches Institut für Wirtschaftsforschung (DIW) (2011).
Verkehr in Zahlen 2010/2011.
Berlin.

Dixon, W.J. (1969).
Introduction to Statistical Analysis. Third Edition.
McGraw-Hill Book Company.

Do, Q. C. (2009).
Traffic Signals in Motorcycle Dependent Cities.
Doctoral Dissertation, Technische Universität Darmstadt.

Fornauf, L. (2009).
Priorities for Public Transport at Traffic Signals in Hanoi.
Research Project, Technische Universität Darmstadt.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (1986a).
Verkehrssystem - Management.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (1986b).
Öffentlichen Personennahverkehrs in Räumen und Zeiten schwacher Verkehrsnachfrage.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (1990).
Empfehlungen zur Verbesserung der Akzeptanz des ÖPNV.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (1991).
Hinweise für die Bewertung von Maßnahmen zur Beeinflussung der ÖPNV-Abwicklung.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (1992).
Richtlinien für Lichtsignalanlagen (RiLSA).
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (1992)
Richtlinien für Lichtsignalanlagen (RiLSA). English Version (2003).
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (1993).
Hinweise zur Bevorrechtigung des öffentlichen Personennahverkehrs bei der Lichtsignalsteuerung.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (1999).
Maßnahmen zur Beschleunigung des öffentlichen Personennahverkehrs mit Straßenbahnen und Bussen.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2001a).
Handbuch für die Bemessung von Straßenverkehrsanlagen (HBS).
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2001/2009).
Handbuch für die Bemessung von Straßenverkehrsanlagen (HBS). Ausgabe 2001. Fassung 2009.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2001b).
Leitfaden für Verkehrsplanungen.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2001c).
Merkblatt zum Integralen Taktfahrplan.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2003).
Empfehlungen für Anlagen des öffentlichen Personennahverkehr (EAÖ).
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2006a).
Richtlinien für die Anlage von Stadtstraßen (RASt 06).
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2006b).
Hinweise für die Qualitätssicherung im ÖPNV.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2006c).
Hinweise zür mikroskopischen Verkehrsflusssimulation: Grundlagen and Anwendung.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2008).
Hinweise zur Systemkosten von Busbahn und Straßenbahn bei Neueinführung.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2009).
Hinweise zur Fahrgastinformation im öffentlichen Verkehr.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2010a).
Empfehlung für Planung und Betrieb des öffentlichen Personennahverkehrs.
Köln.

FGSV—Forschungsgesellschaft für Straßen- und Verkehrswesen (2010b).
Richtlinien für Lichtsignalanlagen (RiLSA). Ausgabe 2010.
Köln.

Freie und Hansestadt Hamburg Baubehörde (2000).
Verkehrsentwicklungsplanung Hamburg: Leitlinien und Handlungskonzept für eine an Arbeit und Umwelt orientierte Verkehrspolitik in Hamburg. Retrieved from http://www.nahverkehrhamburg.de/dokumente/sonstiges/VEP_2000_Hamburg.pdf

General Statistics Office (2011).
Statistical Handbook of Vietnam 2010.
Hanoi.

Gorham, R. (2010).
Air Pollution from Ground Transportation: An Assessment of Causes, Strategies and Tactics, and Proposed Actions for the International Community. Division for Sustainable Development, Department of Economic and Social Affairs, United Nations.
Retrieved from www.un.org/esa/gite/csd/gorham.pdf

Gough, C. & Cook, A. (2010).
"Loop detection for bus priority in MOVA & SCOOT – Notts CC come up with a cost effective solution".
Traffic Engineering and Control, September 2010, pp. 285–287.

Hanaoka, S. (2013).
"Transport and the Environment in Asian Megacities".
The World Financial Review, January–February, 2013.
Retrieved from http://www.worldfinancialreview.com/

Hay, W.W. (1961).
An Introduction to Transport Engineering. Second Edition.
John Wiley & Sons.

Hebert, R. (1979).
"Busway - big success in Los Angeles".
International Association of Public Transport (UITP) Revue, Volume 28 - 1979, pp. 215–217.

Highway Research Board (1964).
An Introduction to Traffic Flow Theory. Special Report 79.
Washington, D.C.

Ho Chi Minh City Department of Transport (2010).
Report on Road Transport in 2010.
Ho Chi Minh City.

Ho Chi Minh City Department of Transport (2011).
Report on Road Transport in 2011.
Ho Chi Minh City.

Ho Chi Minh City Fatherland Front Committee (2012).
Report on the Program of Coordinated Actions for the Traffic Safety Year 2012. Retrieved from http://www.ubmttq.hochiminhcity.gov.vn.

Hounsell, N.B., Shrestha, B.P et al. (2008).
"New Strategy Options for Bus Priority at Traffic Signals in London"
Association for European Transport and contributors 2008.
Retrieved from
http://infoscience.epfl.ch/record/158662/files/New%20strategy%20options%20for.pdf

Hsu, T. P., Nguyen, X. D., Sadullah, A. F. M. (2003).
"A Comparative Study on Motorcycle Traffic Development of Taiwan, Malaysia and Vietnam". *Journal of the Eastern Asia Society for Transportation Studies, Vol. 5*, pp. 179–193. Retrieved from http://www.easts.info/2003journal/papers/0179.pdf

Institute for Transportation & Development Policy (2007).
Bus Rapid Transit: Planning Guide.
Retrieved from http://www.itdp.org/microsites/bus-rapid-transit-planning-guide

Institute of Transportation Engineers (1999).
Traffic Engineering Handbook. Fifth Edition.
Washington, D.C.

Intelligent Transportation Society of America (2005).
Transit Signal Priority: A Planning and Implementation Handbook.
Retrieved from http://www.fta.dot.gov/documents/TSPHandbook10-20-05.pdf

Japan International Cooperation Agency (JICA)., Hanoi People's Committee. (1997).
The Master Plan of Urban Transport for Hanoi City in Vietnam.

Japan International Cooperation Agency (JICA)., Ministry of Transport, Socialist Republic of Vietnam (MOT)., Ho Chi Minh City People's Committee (HCMC-PC). (2004).
The Study on Urban Transport Master Plan and Feasibility Study in Ho Chi Minh Metropolitan Area (HOUTRANS).
Vietnam.

Japan International Cooperation Agency (JICA)., Hanoi People's Committee (HPC). (2007).
The Comprehensive Urban Development Programme in Hanoi Capital City of the Socialist Republic of Vietnam (HAIDEP).
Vietnam.

Khuat, V. H. (2006).
Traffic Management in Motorcycle Dependent Cities.
Doctoral Dissertation, Technische Universität Darmstadt.

Kittler, W. (2004).
Fahrgastinformationssyteme für den Öffentlichen Personennahverkehr am Beispiel der Stadt Hanoi.
Diplomarbeit, Technische Universität Darmstadt.

Kittler, W. (2010).
Beeinflussung der Zeitwahl von ÖPNV-Nutzern.
Doctoral Dissertation, Technische Universität Darmstadt.

Kohoutek, S. (2010).
Quantifizierung der Wirkungen des Straßenverkehrs auf Partikel- und Stickoxid-Immissionen.
Doctoral Dissertation, Technische Universität Darmstadt.

Koonce, P. (2012).
"Prioritizing Transit in a Connected Vehicle World".
Institute of Transport Engineers (ITE) Journal, Volume 82, Number 12, December 2012, pp. 18–22. Washington, D.C.

Li, M. (2010).
Development and Applications of Adaptive Transit Signal Priority Systems.
Doctoral Dissertation, Nagoya University.

McLeod, F., Hounsell, N. (2003).
"Bus Priority at Traffic Signals—Evaluating Strategy Options"
Journal of Public Transportation, Vol. 6, No. 3, 2003.

Ministry of Transport of Vietnam (2013).
Report on Summary of Transport Tasks in 2012.
Hanoi.

National Traffic Safety Committee (2002).
Statistical Handbook of Vietnamese Road Accidents in 2001.
Hanoi.

Ngan, V. (2003).
"A Comprehensive Strategy for Transit Signal Priority"
Institute of Transport Engineers (ITE) Journal, Volume 73, Number 11, November 2003, pp. 28–32. Washington, D.C.

O'Flaherty, C.A et al. (2006).
Transport Planning and Traffic Engineering.
CRC Press.

Planung Transport Verkehr AG. (2009).
VISSIM 5.20 User Manual.
Karlsruhe.

Polus, A., Schofer, J. L., ASCE, Members. (1979).
"Contraflow Bus Priority Lane Performance: A Case Study".
Transportation Engineering Journal of the American Society of Civil Engineering (ASCE), Vol. 105 No. TE1. Jan. 1979, pp. 297–305.

Retzko, H. G., Cerwenka, P. (1975).
Optimierungskriterien für die Steuerung des Straßenverkehrs mit Lichtsignalanlagen.
Forschung Straßenbau und Straßenverkehrstechnik, Heft 194.
Bonn-Bad Godesberg.

Retzko, H. G., Boltze, M. (1987).
"Timing of Intergreen Periods at Signalized Intersections: The German Method".
Institute of Transport Engineers (ITE) Journal, Volume 57, Number 9, September 1987, pp. 23–26. Washington, D.C.

Roess, R.P., Prassas, E.S., McShane, W.R. (2004).
Traffic Engineering. Third Edition.
Pearson Prentice Hall.

Rossmark, K., Derstroff, T. (2004).
Public Transport Concepts for Metropolises in Their Early Phase of Private Motorisation: The Case of Hanoi, Vietnam.
Dissertation, University of Kaiserslautern.

Scholz, G. (2012).
IT-Systeme für Verkehrsunternehmen.
IVU Traffic Technologies AG.
Berlin.

Schweigl, A., Düsterwald, M., Reußwig, A., Boltze, M. (2012).
"Qualitätsanalysen im laufenden Betrieb von Lichtsignalanlagen".
Straßenverkehrstechnik 4.2012, pp. 217–224.

Spiegel, M.R. (1961).
Theory and Problems of Statistics.
Schaum Publishing Company.

Statistisches Bundesamt (2013)
" Mehr Fahr- und Fluggäste im öffentlichen Personenverkehr 2012".
Pressemitteilung vom 6. Februar 2013 – 45/13. Retrieved from https://www.destatis.de/

Transportation Research Board, National Research Council (1996).
Guidelines for the Location and Design of Bus Stops. Transit Cooperative Research Program (TCRP) Report 19. Washington, D.C.
Retrieved from http://www.trb.org/Main/Blurbs/153827.aspx

Transportation Research Board, National Research Council (2000).
Highway Capacity Manual (HCM).
Washington, D.C.

Transportation Research Board (2003a).
Bus Rapid Transit, Volume 1: Case Studies in Bus Rapid Transit. Transit Cooperative Research Program (TCRP) Report 90. Washington, D.C.
Retrieved from gulliver.trb.org/publications/tcrp/tcrp_rpt_90v1.pdf

Transportation Research Board (2003b).
Transit Capacity and Quality of Service Manual, 2nd Edition. Transit Cooperative Research Program (TCRP) Report 100. Washington, D.C.
Retrieved from http://www.trb.org/Main/Blurbs/153590.aspx

Transportation Research Board (2010).
Bus and Rail Transit Preferential Treatments in Mixed Traffic: A Synthesis of Transit Practice. Transit Cooperative Research Program (TCRP) Synthesis 83. Washington, D.C.
Retrieved from http://www.trb.org/Main/Blurbs/163890.aspx

UITP—International Association of Public Transport (2009).
Deliverable 1: Review of Bus Priority at Traffic Signals around the World.
Retrieved from http://www.trg.soton.ac.uk/research/bus/term.htm

U.S. Census Bureau (2012).
Statistical Abstract of the United States. Section 23: Transportation.
Retrieved from http://www.census.gov/prod/2011pubs/12statab/trans.pdf

U.S. Department of Transport (2006).
Traffic Detector Handbook: Third Edition—Volume 1
Retrieved from
http://www.fhwa.dot.gov/publications/research/operations/its/06108/06108.pdf

VÖV/VDA—Verband Öffentlicher Verkehrsbetriebe/Verband der Automobilindustrie (1979).
Bus-Verkehrssystem: Fahrzeug, Fahrweg, Betrieb.
Düsseldorf.

Verband Deutscher Verkehrsunternehmen—VDV (1999).
Linienbusse: fahrgastfreudlich – wirtschaftlich – schadstoffarm.
Düsseldorf.

Verband Deutscher Verkehrsunternehmen—VDV (2001).
Verkehrserschließung und Verkehrsangebot im ÖPNV.
Köln.

Viegas, J. M., Roque, Q., Lu, B., Vieira, J. (2007).
"The Intermittent Bus Lane System: Lisbon Demonstration Project". *PTI May/June 2007*, International Association of Public Transport, pp. 40–43.
Retrieved from http://www.uitp.org/mos/PTI//2007/03/09-en.pdf

Vietnamese Ministry of Natural Resources and Environment (2007).
Report on National Environment 2007.
Hanoi.

Vorndran, V. I. (2010).
"Unfallstatistik – Verkehrsmittel im Risikovergleich". *Wirtschaft und Statistik 12/2010*. Statistisches Bundesamt. Retrieved from https://www.destatis.de/

Vuchic, V. R. (1981).
Urban Public Transportation: Systems and Technology.
New Jersey.

Webster, F. V. (1958).
Traffic Signal Settings.
Road Research Technical Paper 39, Road Research Laboratory, London.

Webster, F. V. (1972).
Priority to Buses as Part of Traffic Management.
TRRL Report LR 448, Transport and Road Research Laboratory, Department of the Environment, Berkshire.

Wehberg, I., Schick, P. (2003).
"Systeme der Buspriorisierung".
Der Nahverkehr, 1-2/2003, pp. 14–18. Düsseldorf.

WHO (2004a).
World Report on Road Traffic Injury Prevention.
World Health Organization. Geneva. Retrieved from
http://www.who.int/violence_injury_prevention/publications/road_traffic/world_report/en/

WHO (2004b).
Health Aspects of Air Pollution: Results from the WHO Project "Systematic Review of Health Aspects of Air Pollution in Europe". World Health Organization/Europe. Copenhagen.
Retrieved from http://www.euro.who.int/en/what-we-do/health-topics/environment-and-health/air-quality/publications/pre2009/health-aspects-of-air-pollution-results-from-the-who-project-systematic-review-of-health-aspects-of-air-pollution-in-europe

WHO (2006).
WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide. World Health Organization. Geneva.
Retrieved from http://www.who.int/phe/health_topics/outdoorair_aqg/en/

WHO (2009).
Global Status Report on Road Safety: Time for Action. Geneva.
Retrieved from http://www.un.org/ar/roadsafety/pdf/roadsafetyreport.pdf

Wolfermann, A. (2009).
Influence of Intergreen Times on the Capacity of Signalised Intersections.
Dotoral Dissertation, Technische Universität Darmstadt.

World Bank (2000).
Beyond Economic Growth: Meeting the Challenges of Global Development. The International Bank for Reconstruction and Development/The World Bank. Washington, D.C.
Retrieved from http://www.worldbank.org/depweb/beyond/beyond.htm

World Bank (2007).
Strategic Urban Transport Policy Directions for Bangkok.
Retrieved from http://siteresources.worldbank.org/INTTHAILAND/Resources/333200-1177475763598/2007june_bkk-urban-transport-directions.pdf

Zheng, J., Zhang, G., Wang, Y., Briglia, P. M. (2009).
"Evaluation of Transit Signal Priority Using Observed and Simulated Data".
Institute of Transport Engineers (ITE) Journal, Volume 79, Number 11, November 2009, pp. 42–49. Washington, D.C.

Appendix A: Basic Considerations of Signal Program Design

A.1 Intergreen Times[30]

The interval between the end of the green time for one traffic stream and the beginning of the green time for the next conflicting one is defined as the intergreen time. The necessary intergreen time (t_z) is determined by the crossing time ($t_{ü}$), the clearance time (t_r), and the entering time (t_e) as follows:

$$t_z = t_{ü} + t_r - t_e \tag{A-1}$$

The determination of intergreen times must consider all road user groups such as pedestrians, cyclists, public transport, and individual motorised vehicles. After the calculation of intergreen times between respective signal groups, the relevant (maximum) ones are selected and arranged in an intergreen time matrix.

Crossing Times

The crossing time ($t_{ü}$) is used for considering the overuse of green times of ending signal streams due to the practical braking process of vehicular traffic. Thereby, in the components of the intergreen time, it is the interval between the end of green time and the beginning of the clearance time. Depending on characteristics of traffic streams, the following crossing times are used:

- Straight-ahead moving motorised vehicles are clearing: $t_{ü} = 3$ s
- Turning motorised vehicles are clearing: $t_{ü} = 2$ s
- Public transport vehicles are clearing when they are signalised separately: $t_{ü} = 3$ s for max $V \leq 30$ km/h or $t_{ü} = 5$ s for max $V \leq 50$ km/h if buses are clearing without a near-side stop; $t_{ü} = 0$ s if buses are clearing with a near-side stop.
- Cyclists are clearing: $t_{ü} = 1$ s
- Pedestrians are clearing: $t_{ü} = 0$ s

Clearance Times

The clearance time (t_r) is the time needed for covering a clearing distance (s_r) at a clearance speed (v_r). It is computed by

$$t_r = \frac{s_r}{v_r} \tag{A-2}$$

30 This part is mainly based on the guidance of RiLSA—FGSV (1992) and the study of Do (2009).

where

$$s_r = s_0 + l_{Fz} \quad \text{(A-3)}$$

t_r = clearance time [s]

s_r = clearing distance [m]

v_r = clearance speed [m/s]

s_0 = basic clearing distance [m]

l_{Fz} = vehicle length [m]

The basic clearing distance for vehicles is determined by the distance between the stop line and the intersecting point (conflict point) with the entering path of the starting traffic stream. For pedestrians and cyclists, if jointly signalised, it is the distance between the beginning of the crossing and the end of the conflict area.

The fictitious vehicle length is used for taking account for the clearing of the conflict area. Thereby, the following fictitious lengths are used when calculating the intergreen time:

- Bicycles: l_{Fz} = 2 m
- Motorcycles: l_{Fz} = 2 m
- Other vehicles (incl. trucks, cars, buses, etc.): l_{Fz} = 6 m

In order to compute clearance times, clearing distances and clearance speeds must be determined, corresponding to the following cases.

Case 1: Straight-ahead moving motorised vehicles are clearing

The selected clearance speed: v_r = 8 m/s.

The basic clearing distance [m]: the distance between the stop line and the conflict point, which is measured at the centre of the lane.

The vehicle length: l_{Fz} = 2 m for motorcycles; l_{Fz} = 6 m for other motorised vehicles.

The calculation of the clearance time is given by

$$t_r = \frac{s_0 + l_{Fz}}{8} \quad \text{(A-4)}$$

where

s_0 = basic clearing distance [m]

l_{Fz} = vehicle length [m]

Case 2: Turning motorised vehicles are clearing

The selected clearance speed:

- If a radius of the inner lane edge, R ≥ 10 m: v_r = 7 m/s

- If a radius of the inner lane edge, R < 10 m: $v_r = 5$ m/s

The basic clearing distance [m]: the distance between the stop line and the conflict point, which is measured at the centre of the lane.

The vehicle length: $l_{Fz} = 2$ m for motorcycles; $l_{Fz} = 6$ m for other motorised vehicles.

The calculation of the clearance time is given by

$$t_r = \frac{s_0 + l_{Fz}}{7} \quad \text{if R} \geq 10\text{m} \tag{A-5}$$

or

$$t_r = \frac{s_0 + l_{Fz}}{5} \quad \text{if R} < 10\text{m} \tag{A-6}$$

where

s_0 = basic clearing distance [m]

l_{Fz} = vehicle length [m]

Case 3: Buses are clearing without a near-side stop

If buses are signalised separately, the clearance time is computed by

$$t_r = \frac{s_0 + l_{Fz}}{v_r} = \frac{3.6(s_0 + l_{Fz})}{\max V} \tag{A-7}$$

where

s_0 = basic clearing distance [m]

l_{Fz} = vehicle length [m]

v_r = clearance speed [m/s]

max V = permitted speed [km/h]

If buses are jointly signalised with private traffic, the clearance time can be calculated, corresponding to two optional cases:

- Buses are separately signalised.
- Buses are assumed to operate as other motorised vehicles.

Case 4: Buses are clearing with a near-side stop

For this case, it has to be assumed that at the end of the green time, buses accelerate from the stationary status at their stops to the maximum permitted speed on the subsection. For this reason, the acceleration rate for buses should be chosen from 1.0 to 1.5 m/s^2.

The clearance time in this case is computed by the following formulae:

$$t_r = \sqrt{\frac{2(s_0 + l_{Fz})}{a}} \qquad \text{if} \quad (s_0 + l_{Fz}) \leq \frac{(\max V)^2}{2 \cdot 3.6^2 \cdot a} \tag{A-8}$$

or

$$t_r = \frac{\max V}{3.6 \cdot a} + \frac{s_0 + l_{Fz} - \frac{(\max V)^2}{2 \cdot 3.6^2 \cdot a}}{\frac{\max V}{3.6}} \qquad \text{if} \quad (s_0 + l_{Fz}) > \frac{(\max V)^2}{2 \cdot 3.6^2 \cdot a} \tag{A-9}$$

where

s_0 = basic clearing distance	[m]
l_{Fz} = vehicle length	[m]
max V = permitted speed	[km/h]
a = acceleration from $V = 0$ at the stop line up to $V = \max V$	[m/s^2]

Case 5: Cyclists are clearing

The selected clearance speed for cyclists: $v_r = 4$ m/s.

The vehicle length: $l_{Fz} = 2$ m.

Thereby, the clearance time is computed by

$$t_r = \frac{s_0 + l_{Fz}}{4} \tag{A-10}$$

where

s_0 = basic clearing distance	[m]
l_{Fz} = vehicle length	[m]

Case 6: Pedestrians are clearing

The selected clearance speed for pedestrians: $v_r = 1.2$ m/s [up to maximum value of 1.5 m/s].

The fictitious length of pedestrians: $l_{Fz} = 0$ m.

Thereby, the clearance time is calculated by

$$t_r = \frac{s_0}{v_r} \tag{A-11}$$

where

s_0 = basic clearing distance	[m]
v_r = clearance speed	[m/s]

Entering Times

The entering time (t_e) is the time for covering the entering distance (s_e).

For individual motorised traffic, it is assumed that the first vehicles cross the stop line at the beginning of the green time with an independent entering speed (i.e. regardless of the permissible speed) of 40 km/h. Thereby, the entering time is computed by

$$t_e = \frac{3.6 \cdot s_e}{40} \tag{A-12}$$

where

t_e = entering time [s]

s_e = entering distance [m]

In mixed traffic conditions, buses can be considered to operate as other motorised vehicles when determining the entering time. Otherwise, if buses operate on an exclusive lane, the acceleration process of buses should be taken into account when calculating the entering time.

For cyclists, if they are jointly signalised with motorised vehicles, they are not relevant for the entering process due to their low start-up acceleration and speed. Otherwise, if they are separately signalised, the entering speed of 5 km/h is used.

For pedestrians, if the conflict area between pedestrians and vehicles begins directly at the edge of traffic lanes, the entering process will not be taken into account. Otherwise, the value of 1.5 m/s can be set for the entering speed of pedestrians.

A.2 Transition Times[31]

The transition time is used due to the dynamics reasons of vehicular traffic. Basically, it contains two types: (i) the transition time AMBER (t_G), and (ii) the transition time RED and AMBER (t_{RG}).

The transition AMBER is for the change from green to red of signal indicators. Hereby, it depends on the permissible speed (*zul V*) of motorised traffic on the intersection approach:

- At z*ul V* = 50 km/h, t_G = 3 s.
- At z*ul V* = 60 km/h, t_G = 4 s.

For non-motorised traffic, if cyclists are separately signalised, the uniform transition time AMBER should be 2 seconds; however, signal sequence for pedestrians does not include this transition time.

The transition time RED and AMBER is usually 1 second for motorised traffic, and should not exceed 2 seconds in any cases. For cyclists, 1 second is used for this transition time. However, this transition time is not included in signal sequence for pedestrians.

[31] This part is mainly based on the guidance of RiLSA—FGSV (1992).

A.3 Cycle Length[32]

When selecting a cycle length for signal program, the minimum, optimum, and effective cycle lengths should be considered. Besides, a practical cycle length from 60 to 90 s is also suggested. In some cases, a longer cycle length can be utilised but should not be over 120 s.

Minimum Cycle Length

The minimum cycle length is considered in order to avoid the oversaturated condition at traffic signals. This minimum cycle length is determined by

$$t_{U,\min} = \frac{\sum_{i=1}^{p} t_{Zi}}{1 - \sum_{i=1}^{p} \frac{q_{FS,maßg,i}}{q_{Si}}} = \frac{T_Z}{1 - \sum_{i=1}^{p} \frac{q_{FS,maßg,i}}{q_{Si}}} \qquad \text{(A-13)}$$

where

$t_{U,min}$	= minimum cycle length	[s]
t_{Zi}	= necessary intergreen time for a change of phase	[s]
T_Z	= total necessary intergreen time	[s]
$q_{FS,maß,i}$	= traffic volume on the critical lane of phase i	[veh/h]
q_{Si}	= saturation flow rate of the critical lane of phase i	[veh/h]
p	= number of phases	[-]

Optimum Cycle Length

The optimum cycle length basically results in minimum waiting times for vehicular traffic. It is computed by

$$t_{U,opt} = \frac{1.5 \cdot T_Z + 5}{1 - \sum_{i=1}^{p} \frac{q_{FS,maßg,i}}{q_{Si}}} \qquad \text{(A-14)}$$

where

$t_{U,opt}$	= optimum cycle length	[s]
T_Z	= total necessary intergreen time	[s]
$q_{FS,maß,i}$	= traffic volume on the critical lane of phase i	[veh/h]
q_{Si}	= saturation flow rate of the critical lane of phase i	[veh/h]
p	= number of phases	[-]

[32] This part is mainly based on the guidance of HBS—FGSV (2001a).

Effective Cycle Length

The effective cycle length is recommended for the condition of high traffic loads, particularly when signal coordination is required for certain directions. This cycle length is calculated as follows:

$$t_{U,pref} = \frac{T_Z}{1 - \sum_{i=1}^{p} \frac{q_{FS,maßg,i}}{g_i \cdot q_{Si}}} \quad \text{(A-15)}$$

where

$t_{U,pref}$ = effective cycle length [s]

T_Z = total necessary intergreen time [s]

$q_{FS,maß,i}$ = traffic volume on the critical lane of phase i [veh/h]

q_{Si} = saturation flow rate of the critical lane of phase i [veh/h]

g_i = degree of saturation for the critical lane of phase i [-]

[Suggested value: g ≤ 0.85 (max. 0.9)]

p = number of phases [-]

A.4 Green Times and Red Times[33]

Green Times

The allocation of green times is generally based on the equalisation of degree of saturation for the critical lanes. The allocated green time is determined by

$$t_{Fi} = \frac{b_{maßg,i}}{B}(t_U - T_Z) \quad \text{(A-16)}$$

where

$$b_{maßg,i} = q_{FS,maßg,i} / q_{S\,i} \quad \text{(A-17)}$$

$$B = \sum_{i=1}^{p} b_{maßg,i} \quad \text{(A-18)}$$

t_{Fi} = green time for the critical lane of phase i [s]

$b_{maß,i}$ = flow ratio for the critical lane of phase i [-]

B = sum of flow ratios of the critical lanes in all phases [-]

t_U = selected cycle length [s]

T_Z = total necessary intergreen time [s]

[33] This part is mainly based on the guidance of HBS—FGSV (2001a).

$q_{FS,maß,i}$ = traffic volume on the critical lane of phase i [veh/h]

q_{Si} = saturation flow rate of the critical lane of phase i [veh/h]

p = number of phases [-]

In MDCs, apart from the green time allocation based on the equalisation of degree of saturation, it is recommended that weighted factors for priority directions such as bus-operating directions, signal coordinated directions, and major streets should be considered in this allocation.

The minimum green time for vehicular traffic should be 10 seconds. For the main direction, the minimum value of 15 seconds is recommended. For intersection approaches having low traffic loads, this minimum green time can be reduced to 6 seconds.

The minimum green time for pedestrians should be sufficient enough to enable them to cover more than half of pedestrian crossings with the green signal indicator.

Red Times

The maximum red time should be considered to avoid the following disadvantages at traffic signals:

- Overloaded waiting areas for non-motorised traffic.
- Overloaded queuing space for motorised traffic.
- Unreasonable waiting time for pedestrians and cyclists.
- Unreasonable waiting time for public transport vehicles.
- Unreasonable waiting time for individual motorised vehicles.

A.5 Degree of Saturation

The degree of saturation for certain lanes should be divided into "input" and "output" values. The output degree of saturation is computed from the selected cycle length and green times as well as other parameters. Otherwise, the input degree of saturation is used as an input parameter in order to determine cycle length, to allocate green times to certain signal groups, or to provide special design for certain traffic lanes (e.g. discontinuous bus lanes, partial dynamic bus lanes).

In the condition of high traffic loads, particularly in MDCs, the input degree of saturation is more significant than the output one. Thereby, this study utilised an approach to traffic loads by using different input degrees of saturation. Noticeably, it is realised that the degree of saturation, g = 0.9, is an effective degree of saturation for MDCs due to its certain advantages regarding both capacity utilisation and traffic flow quality.

The relationship between the degree of saturation and other parameters for certain approach lanes at traffic signals is given as follows:

$$g_j = \frac{q_j}{C_j} = \frac{q_j}{\frac{t_{Fj}}{t_U} \cdot q_{Sj}} = \frac{q_j}{f_j \cdot q_{Sj}} \tag{A-19}$$

where

g_j = degree of saturation for lane j [-]

q_j = traffic volume on lane j [veh/h]

C_j = capacity of lane j [veh/h]

q_{Sj} = saturation flow rate of lane j [veh/h]

t_{Fj} = green time of lane j [s]

t_U = cycle length [s]

f_j = green time ratio of lane j [-]

Equation (A-19) can be rewritten in the generalised form for an approach lane at traffic signals as follows:

$$g = \frac{q}{C} = \frac{q}{\frac{t_F}{t_U} \cdot q_S} \tag{A-20}$$

Substituting $q_S = \dfrac{3600}{t_B}$ to Equation (A-20), then it becomes

$$g = \frac{q}{\frac{t_F}{t_U} \cdot \frac{3600}{t_B}} = \frac{q \cdot t_U}{3600} \cdot \frac{t_B}{t_F} = \frac{m \cdot t_B}{t_F} \tag{A-21}$$

where

$$m = \frac{q \cdot t_U}{3600} \tag{A-22}$$

m = average number of vehicles arriving during one cycle length on the subject lane [veh]

g = degree of saturation for the subject lane [-]

C = capacity of the subject lane [veh/h]

q = traffic volume on the subject lane [veh/h]

t_F = green time of the subject lane [s]

t_U = cycle length [s]

t_B = saturation headway [s]

Extending the principle of homogeneous flow for heterogeneous flow, Equation (A-21) can be rewritten for mixed traffic flow as follows:

$$g_{Mix} = \frac{f_{Mix} \cdot (m_{Car} \cdot t_{B,Car} + m_{MC} \cdot t_{B,MC} + m_{BC} \cdot t_{B,BC} + m_{Bus} \cdot t_{B,Bus})}{t_F} \tag{A-23}$$

where

$$m_{Car} = \frac{\rho_{Car} \cdot q \cdot t_U}{3600} \qquad \text{(A-24)}$$

$$m_{MC} = \frac{\rho_{MC} \cdot q \cdot t_U}{3600} \qquad \text{(A-25)}$$

$$m_{BC} = \frac{\rho_{BC} \cdot q \cdot t_U}{3600} \qquad \text{(A-26)}$$

$$m_{Bus} = \frac{\rho_{Bus} \cdot q \cdot t_U}{3600} \qquad \text{(A-27)}$$

g_{Mix}	= degree of saturation for the mixed traffic lane	[-]
f_{Mix}	= adjusted factor for mixed traffic flow	[-]
m_{Car}	= average number of cars arriving during one cycle length	[veh]
m_{MC}	= average number of motorcycles arriving during one cycle length	[veh]
m_{BC}	= average number of bikes arriving during one cycle length	[veh]
m_{Bus}	= average number of buses arriving during one cycle length	[veh]
$t_{B,Car}$	= saturation headway of car flow	[s]
$t_{B,MC}$	= saturation headway of motorcycle flow	[s]
$t_{B,BC}$	= saturation headway of bike flow	[s]
$t_{B,Bus}$	= saturation headway of bus flow	[s]
ρ_{Car}	= proportion of cars in mixed traffic flow	[-]
ρ_{MC}	= proportion of motorcycles mixed traffic flow	[-]
ρ_{BC}	= proportion of bikes mixed traffic flow	[-]
ρ_{Bus}	= proportion of buses in mixed traffic flow	[-]
q	= traffic volume on the mixed traffic lane	[veh/h]
t_F	= green time of the mixed traffic lane	[s]
t_U	= cycle length	[s]

The following table provides suggestions on selecting the saturation headway of homogenous flow.

Table A.1: Suggestions on the selection of saturation headways[34] [35]

Lane width [m]	Saturation headways of homogeneous flow, t_B [s]			
	Car	Motorcycle	Bike	Bus
3.0	2.24	0.38	0.38*	3.5*
3.5		0.35	0.35*	
4.0	1.8*	0.31	0.31*	
4.5	1.6*	0.25	0.25*	

Legends: - The values without an asterisk are observed values.
- The values with an asterisk are assumed values.
- These saturation headways are recommended for the green time ≥ 10 s.

The adjusted factor, f_{Mix}, depends on both traffic composition and the suitability of lane separation at traffic signals. For a certain mixed traffic composition, it is estimated that this value ranges from 1.0 to 1.1 if lane separation is proper (i.e. there is inconsiderable interference from vehicles on adjacent lanes when signal turns green). However, an inappropriate lane separation at traffic signals (e.g. occurring conflicts with straight-ahead and/or turning vehicles on adjacent lanes when signal turns green) can lead to a much higher value.

If a certain degree of saturation is allocated to a mixed traffic lane, the number of intended vehicles arriving on that lane during one cycle length can be determined by solving Equation (A-23) because traffic composition, cycle time, green time, saturation headways, and f_{Mix} (assumed 1.05) are generally known. Furthermore, by considering the dimension of different types of vehicles (e.g. bus, car, motorcycle, and bike) and their proportion in mixed traffic flow, the intended queue length (corresponding to that degree of saturation) during red intervals can be estimated. This estimation is utilised to determine the distance l_1 of discontinuous bus lanes, and the distance l_{d1} of partial dynamic bus lanes.

In addition, Equation (A-23) can be utilised to estimate the factor f_{Mix} for oversaturated flow at traffic signals to examine whether the current lane separation is proper or not. If not, an improvement of lane separation at traffic signals should be carried out.

A.6 Priority Considerations for Buses

Considerations of Green Time Allocation

The allocation of green times for bus-operating approaches should be sufficient in order to ensure these approaches not being oversaturated. At heavily loaded signalised intersections, the

[34] Since the dimension of motorcycles and bikes is almost equivalent and the proportion of bikes is much smaller than that of motorcycles in mixed traffic flow, it is assumed that their saturation headway is identical at traffic signals. In addition, their saturation headway can be considered as fictitious headway.

[35] The adjusted factor for saturation headway of car flow can be considered if necessary, which depends on heavy vehicles' proportion, turning radius, gradient, and pedestrian traffic as mentioned in HBS—FGSV (2001a).

allocated green time resulting in a degree of saturation not over 0.9 for these approaches is highly recommended.

Considerations of Signal Priority

If buses suffer unreasonable waiting times due to the long red time at traffic signals, signal priority should be provided for them. Green extension and early green with their values from 6 to 10 s (or about 10% cycle length) are suggested.

Considerations of Queues

Since buses operate based on their schedule, critical impediments caused by vehicular queues at traffic signals should be avoided for them. From this consideration, a classification of vehicular queues at traffic signals into "normal", "long", and "severe" queues is recommended.

Normal Queues

The normal queue is defined as the queue that is dissipated during one cycle length only. Thereby, the maximum number of vehicles in this queue is computed by

$$N_{\max RE.1} = \frac{q_S}{3600} \cdot t_F \qquad \text{(A-28)}$$

where

$N_{max\ RE.1}$ = maximum number of vehicles in the normal queue on the subject lane [veh]

q_S = saturation flow rate of the subject lane [veh/h]

t_F = green time for the subject lane [s]

For bus-operating approaches, the design of signal program should result in normal queues. Under this condition, buses can be released at traffic signals during one cycle length only. In addition, this condition will help to increase the effectiveness of signal priority.

Long Queues

The long queue is defined as the queue that needs more than one cycle length but not over two cycles to be dissipated. Therefore, the maximum number of vehicles in this queue is calculated by

$$N_{\max RE.2} = \frac{q_S}{3600} \cdot (2t_F) \qquad \text{(A-29)}$$

where

$N_{max\ RE.2}$ = maximum number of vehicles in the long queue on the subject lane [veh]

q_S = saturation flow rate of the subject lane [veh/h]

t_F = green time of the subject lane [s]

These queues should be avoided for bus-operating approaches since they induce rear-congestion waiting times for buses and reduce the effectiveness of signal priority (i.e. they increase the failure of receiving signal priority for buses).

Depending on the frequency of these queues during a certain observation period, an improvement of signal program or control strategies should be considered.

Severe Queues

The severe queue is defined as the queue that needs more than two cycle lengths to be dissipated. Thereby, the number of vehicles in this queue is given as follows:

$$N_{RE.3} > \frac{q_S}{3600} \cdot (2t_F) \quad \text{(A-30)}$$

where

$N_{RE.3}$ = number of vehicles in the severe queue on the subject lane [veh]

q_S = saturation flow rate of the subject lane [veh/h]

t_F = green time of the subject lane [s]

These queues should be totally avoided for bus-operating approaches by implementing priority measures for bus travel ways and applying supportive measures to bus-operating directions if necessary.

When the dimension of different types of vehicles (e.g. bus, car, motorcycle, and bike) and their proportion in mixed traffic flow are considered, the length of normal, long, and severe queues for certain lanes at traffic signals can be uncomplicatedly estimated.

A.7 Other Considerations

Apart from the above considerations, other considerations need to be concerned at the same time when designing signal programs, consisting of

- Considerations of signal phasing, including segregation of traffic streams (non-conflicting streams and conflicting streams), allocation of movements (e.g. protected or permitted left-turning movements, signalised or non-signalised right turning movements, etc.), number of phases, phase sequence, and phase transitions.
- Considerations of signal coordination, particularly for arterials, major streets, or directions with closely spaced traffic signals.
- Considerations of queuing space condition for general traffic.
- Considerations of permitted turning movements, especially when they induce critical impediments for straight-ahead movements.
- Considerations of signal program elements (incl. cycle length, green time, number of phases, phase sequence, and time offset) which can be influenced by control strategies at both macroscopic and microscopic levels.

Appendix B: The Utilisation of Micro-Simulation Tool

B.1 Traffic Simulation

Traffic simulation is a technique which enables the study of a complex traffic system (such as road networks, signalised intersections, etc.) in the laboratory rather than in the field. It helps to reduce significantly time and costs needed for testing that system, compared to the testing of a real one. In many cases, more importantly, traffic simulation enables a study of system characteristics prior to its construction. [Highway Research Board (1964)]

According to Transportation Research Board (2000), in respect of modelling level of detail, there are basically three simulation models: microscopic, macroscopic, and mesoscopic models. The main attributes of these models will be briefly discussed as follows:

- The microscopic model captures the movement of each vehicle in traffic flow. Thereby, individual vehicles can be traced through the road network. For this reason, this model contains certain processing logic that describes how vehicles behave. The behaviour of vehicles is basically represented by their activities such as acceleration, deceleration, lane changes, passing maneuvers, turning movements, and gap acceptance.
- The macroscopic model tends to employ traffic flow parameters (e.g. speed, density, flow, etc.) and other descriptors to describe how the traffic flow is moving. The principle equations of traffic flow, such as conservation-of-flow equations and equations for boundary conditions, are used in this model. In addition, equations for describing shock wave[36] phenomena are typical used in this model.
- The mesoscopic model having its level of modelling detail falls between the microscopic and macroscopic models. It models the movement of traffic flow in the form of clusters or platoons of vehicles in conjunction with their interactions.

For the study of bus priority, an utilisation of the microscopic model is essential since the characterisation of buses in mixed traffic flow is required to assess the effect of bus priority on both buses and other traffic. As a result, a number of studies utilised micro-simulation tool for the study of bus priority, such as McLeod et al. (2003), Ngan (2003), Hounsell et al. (2008), Zheng et al. (2009), Bradshaw (2010), etc.

Thereby, this study selected VISSIM 5.20 as a micro-simulation tool for assessing the level of effects of bus prioritisation measures in the condition of MDCs, particularly for new measures which were developed in this research work. The following part will provide some discussions on this simulation tool.

[36] The shock wave is the compression or decompression wave due to the abrupt change in traffic flow condition, which is often influenced by queuing or slow moving vehicles.

B.2 The Utilisation of Micro-Simulation VISSIM 5.20

Overview[37]

VISSIM is a microscopic, time step, and behaviour-based simulation model, which was developed to model urban traffic and public transport operations. This simulation tool facilitates the analysis of private and public transport operations under different conditions such as lane configuration, traffic composition, traffic signals, public transport stops, pedestrians, etc. In addition, it enables to develop user-defined signal control logic such as traffic-dependent signal control, signal priority for public transport vehicles, etc.

The core model of VISSIM is the psycho-physical driver behaviour model, which was developed by Wiedemann (1974). The basic concept of this model is that the driver of a faster moving vehicle will start decelerating as he/she reaches his/her individual perception threshold to a slower moving vehicle. Depending on front to rear distance and difference in velocity, the driver might perform conscious or unconscious reaction to his/her speed, resulting in an interactive process of acceleration and deceleration.

Simulation of Mixed Traffic Flow in MDCs

Since VISSIM allows each vehicle unit in mixed traffic flow to be described by its technical specification (e.g. dimension, speed, acceleration, and deceleration), behaviour (such as psycho-physical sensitivity thresholds, acceleration based on current and desired speeds), and interdependence of other vehicle units (e.g. reference to leading and following vehicles, etc.), the utilisation of this simulation tool for motorcycle dependent flow is feasible.

The following figure presents an example of the utilisation of VISSIM 5.20 for modelling mixed traffic flow in MDCs.

Figure B.1: Example of modelling mixed traffic flow in MDCs by VISSIM 5.20

[37] This part is mainly based on Planung Transport Verkehr AG (2009).

Calibration of Simulation Tool

Before the calibration process, the following data were collected and entered as input data into the simulation program:

- Vehicle types,
- Dimensions of vehicles,
- Acceleration and deceleration distribution,
- Desired speed distribution,
- Stand still distances in queue at traffic signals, and
- Lateral distances between vehicles.

Then the root mean square error (RMSE), root mean square percent error (RMSPE), mean error (ME), and mean percent error (MPE) are used in the calibration process. These indexes are given as follows [FGSV (2006c)]:

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(x_n^{sim} - x_n^{obs})^2} \tag{B-1}$$

$$RMSPE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left[\frac{x_n^{sim} - x_n^{obs}}{x_n^{obs}}\right]^2} \tag{B-2}$$

$$ME = \frac{1}{N}\sum_{n=1}^{N}(x_n^{sim} - x_n^{obs}) \tag{B-3}$$

$$MPE = \frac{1}{N}\sum_{n=1}^{N}\left[\frac{x_n^{sim} - x_n^{obs}}{x_n^{obs}}\right] \tag{B-4}$$

where

$RMSE$ = root mean square error

$RMSPE$ = root mean square percent error

ME = mean error

MPE = mean percent error

x_n^{sim} = examined parameter generated from the simulation

x_n^{obs} = examined parameter observed from the field.

N = number of observations

The following table provides the results of these indexes after the calibration process for saturation headways of motorcycle flow and car flow.

Table B.1: Results of the calibration for saturation headways

Lane width	Motorcycle flow					Car flow				
	Number of observations	RMSE [s]	RMSPE [%]	ME [s]	MPE [%]	Number of observations	RMSE [s]	RMSPE [%]	ME [s]	MPE [%]
3 m	67	0.017	4.0	0.004	0.9	-	-	-	-	-
3.5 m	30	0.021	5.8	-0.013	-3.5	102	0.102	4.3	-0.021	-0.6
4.0 m	70	0.011	3.4	-0.006	-1.8	-	-	-	-	-

The results from the above table indicate that VISSIM 5.20 is capable of modelling motorcycle flow and car flow in MDCs.

In addition, the relationship of speed and flow rate of mixed traffic flow was used to verify this simulation tool under mixed traffic conditions in MDCs. Since the measurement of speed and flow rate is often limited in certain range, the measured data collected by Chu et al (2005) were compared to the simulation data. The following figure presents the relationship of speed and flow rate of mixed traffic flow (incl. 79.4% motorcycle, 17.7% bike, 1.7% car, and 0.2% bus), which was obtained by the measured data and simulation data.

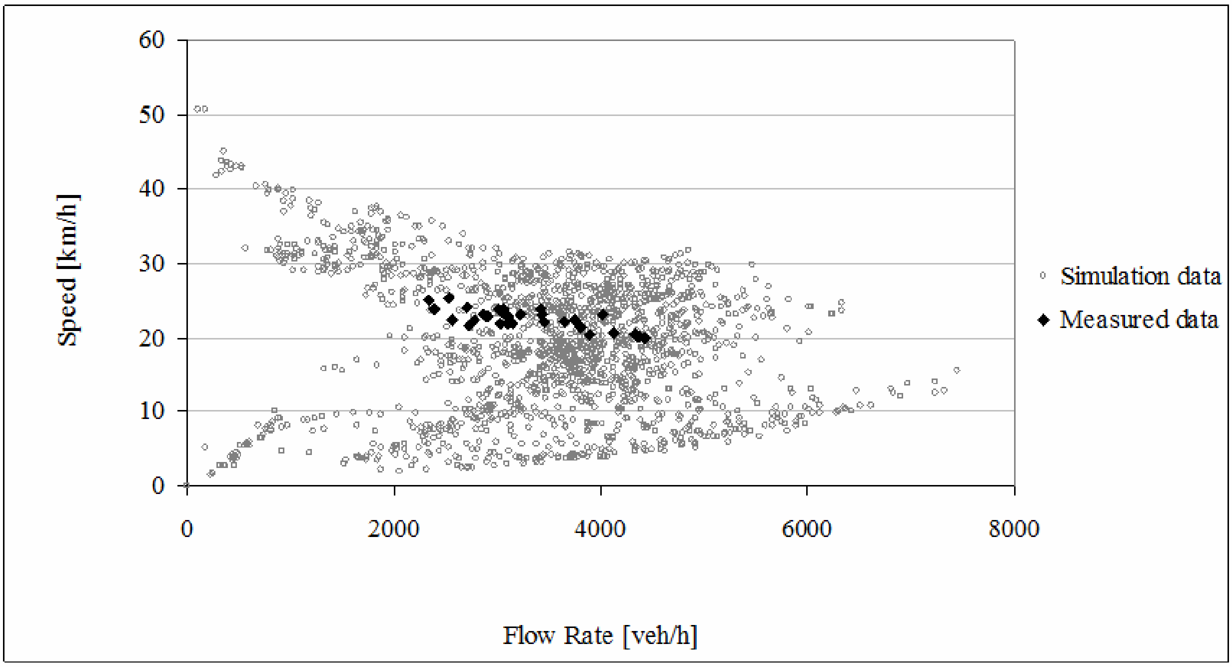

Figure B.2: Comparison between the measured data[38] and simulation data

From the results of the calibration process, it can be realised that VISSIM 5.20 is capable of modelling mixed traffic flow dominated by motorcycles.

[38] The measured data were collected by Chu et al (2005) on the mixed traffic lane (3.27 m wide).

Appendix C: An Empirical Evaluation of Bus Prioritisation

C.1 Aims

The aim of this work is to provide an empirical evaluation of bus prioritisation under practical conditions of MDCs. From this work, a deeper understanding about inherent problems for buses and the effectiveness of bus prioritisation are acquired.

C.2 Study Site

A signalised intersection and its approaches in Ho Chi Minh City (HCMC) were selected for the evaluation of bus prioritisation. This intersection is the crossing of Nguyen Thi Minh Khai Street and Nam Ky Khoi Nghia Street located in District 1 (the core centre) of HCMC. Both of the mentioned streets are one-way streets. Apart from the main intersection, there is another un-signalised intersection from side street (Le Quy Don Street) at the upstream of the main intersection (see Figure C.1). In this study, Nguyen Thi Minh Khai Street was selected for an application of bus prioritisation.

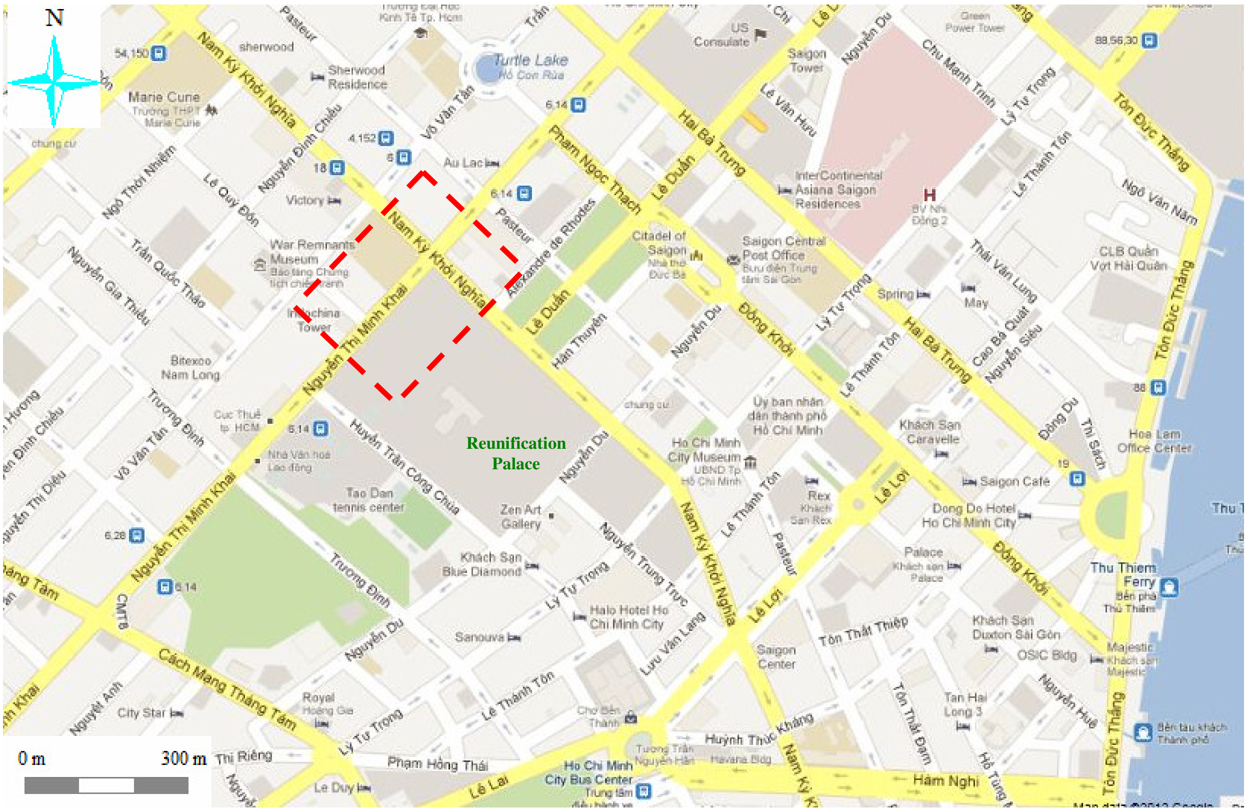

Figure C.1: The study site for bus prioritisation (marked by the dashed rectangular)
[Source of the background image: Google maps (2012)]

At present, buses are operating in mixed traffic conditions and under high traffic loads, and there are no priority measures for them. Consequently, they are suffering unreasonable and unpredictable delays on the roadway as well as at the traffic signals, particularly during peak periods. For this reason, the buses with a volume of 25 buses/h operating in Nguyen Thi Minh Khai Street were chosen for an application of bus prioritisation (see Figure C.2).

Figure C.2: Bus services operating in Nguyen Thi Minh Khai Street

C.3 Data Survey

Tasks

The main tasks of the survey are to describe the problems for buses as well as the existing traffic situation in this site. For this purpose, the following survey tasks were done, including:

- Identification of problems for buses.
- Determination of travel times of buses between two measurement points.
- Determination of traffic volumes.
- Collection of other related data (incl. geometric factors, traffic signal control, traffic operation, existing conditions, etc.)

Methods

The following main methods were utilised to collect the data:

- Field observations and analyses were applied to identify problems for buses.
- Digital watches were used to measure travel times of individual buses.
- Video observations were applied to determine traffic volumes.

C.4 Data Collection and Situation Analysis

In order to obtain the data, the main survey was conducted during a peak period (from 7:45 to 8:45 a.m.) of a working day (Tuesday, December 27, 2011) and in good weather condition. The results of data collection in conjunction with the analysis of existing situation are presented in the following.

Identification of Problems for Buses

Categorisation of Problems

Since bus stops were absent, problems of the mixed travel way and the unfavourable traffic signals were observed at the study site. These problems were identified and summarised in the following table.

Table C.1: Problems for buses at the study site

Categories	Problems	Level of impediments			
		Absent	Low	Medium	High
Bus Stops	*Operation of buses at their stops*	x			
Travel Ways	*Operation of buses on the non-signal affected segment*				
	- Impeded by other vehicles in mixed traffic flow				x
	- Impeded by local accessing traffic			x	
	- Impeded by other activities		x		
	Operation of buses on the signal affected segment				
	- Impeded by severe queues			x	
	- Impeded by heavy right-turning traffic				x
	- Impeded by illegal stopping/parking activities		x		
	- Impeded by other activities		x		
	- Impeded by regular congestion		x		
Traffic Signals	*Operation of buses at traffic signals*				
	- Impeded by improper signal settings				x
	- Impeded by long queues				x
	- Impeded by long red intervals			x	
	- Impeded by unprotected left-turning traffic	x			
	- Impeded by irregular congestion		x		

Problems of Travel Time, Speed, and Waiting Time

Travel times of buses operating in Nguyen Thi Minh Khai Street were measured between two measurement points in the range of the signalised intersection. One measurement point was located at the intersection upstream and the other was situated right after the stop line. The distance between these points is 148.60 m. The following figure provides the measured data of bus travel times.

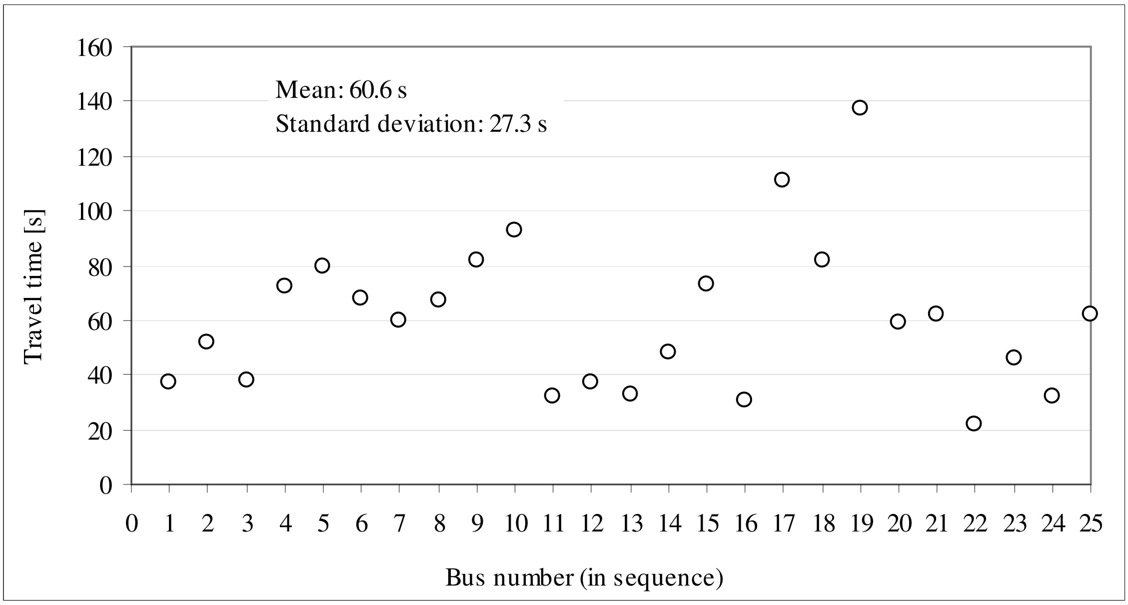

Figure C.3: Travel times of buses

As can be seen in Figure C.3, travel times of buses vary largely due to impediments of other vehicles in mixed traffic flow, vehicle queues at the traffic signals, right-turning traffic, and unfavourable signal settings.

From the measured travel times, the average speed of bus flow is computed by

$$V_{Bus} = \frac{L}{\frac{1}{n}\sum_{i=1}^{n} t_i} \qquad \text{(C-1)}$$

where

V_{Bus} = average speed of buses [m/s]

L = distance between two measurement points [m]

t_i = travel time of the i^{th} bus between two measurement points [s]

n = number of observed buses [-]

The result of the speed calculation gives V_{Bus} = 2.45 m/s = 8.8 km/h. This average speed is too low for bus services.

Furthermore, the average waiting time of buses at the traffic signals can be estimated from the measured data. By assuming a desired bus speed of 40 km/h, the average delay of buses between two measurement points is 47.3 s. Since the measurement segment was situated at the intersection upstream, this delay is mainly caused by traffic signals due to impediments of red intervals and vehicular queues. It is assumed that the average waiting time of buses (w_{Bus}) at traffic signals accounted for 90% of this delay, and therefore this waiting time was estimated approx. 43 s. In general, this waiting time is not reasonable for public transport.

Examination of Existing Conditions and Circumstances

Traffic Volumes

For the examined direction, traffic volumes were counted in one full hour. For other directions, the volumes were measured during sub-hour period, and then they were converted to hourly volumes. These volumes are provided in Figure C.4.

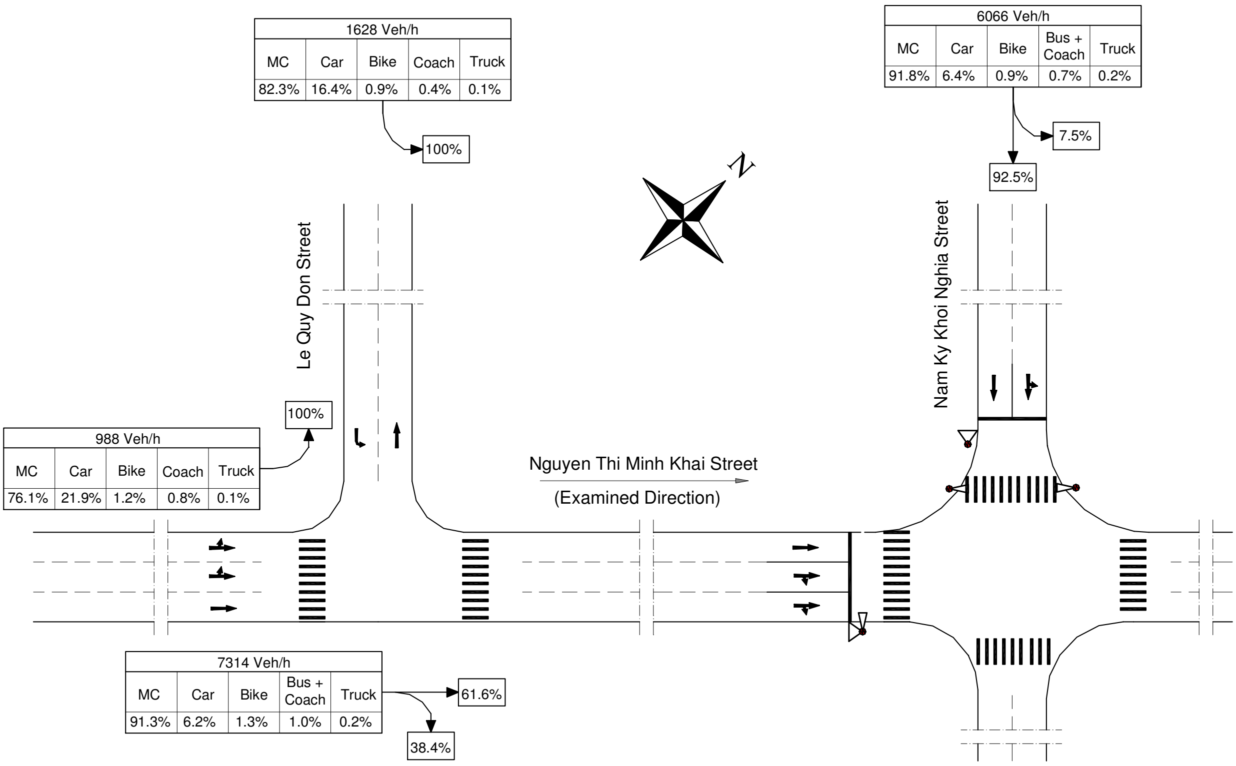

Figure C.4: Traffic volumes[39] at the study site

Traffic Control and Operation

Traffic signals at the main intersection operated with a fixed-time program. Two-phase control was applied to this intersection. The cycle length was 90 s, in which 50 s were allocated to Nguyen Thi Minh Khai approach, 35 s were allocated to Nam Ky Khoi Nghia approach, and 5 s were for intergreen times.

Signal coordination with the preceding intersection in Nguyen Thi Minh Khai Street was not recognisable due to high traffic loads and distant traffic signal spacing. Besides, during the survey time, there was inconsiderable impact of the succeeding intersection.

The main problems at the signalised intersection were identified, consisting of

- Inadequate lane separation (i.e. right-turning traffic impeded straight-ahead movements),
- Improper markings of the intersection layout,

[39] During the observation time, pedestrian volume at each pedestrian crossing was low (< 50 pedestrians/h). "MC" stands for motorcycle.

- Improper intergreen times,
- Lack of signal priority for buses, and
- Insufficient pedestrian signals.

Apart from the mentioned intersection, there is another un-signalised intersection (the crossing of Le Quy Don Street) located at the upstream of the traffic signals. During the observation time, the unregulated accessing traffic from the side street had some interference in the movement of buses.

Other Issues

Traffic loads at the study site remained at high levels during the observation period. It is estimated that the degree of saturation on the subject approach at traffic signals was over 0.9. Therefore, an implementation of exclusive bus lanes or queue jump lanes without supportive measures is basically unfavourable. Besides, an expansion of roadways for these lanes is almost impossible because the study site is located in the city centre of HCMC. Thereby, infrastructure measures will not be applied to this site.

Alternatively, time-restricted streets for buses operating with other specified vehicles as well as time-restricted bus lanes basically require a lower traffic volume. For this reason, traffic rerouting can be considered to facilitate these measures if necessary. However, it should be noted that traffic rerouting in practice is often under a certain constraint and therefore it needs a careful consideration of the road network.

Considerations of Level of Service

As seen in Table C.2, the existing level of service for the operation of buses is rated according to their average waiting time at traffic signals and average travel speed. In addition, the expected level of service is determined for an intended improvement of the quality of bus services through bus prioritisation.

Table C.2: Determination of level of service for buses

Level of service (LOS)	Average waiting time at traffic signals [s]			Average travel speed [km/h]		
	Reference value	Existing LOS	Upgraded LOS	Reference value	Existing LOS	Upgraded LOS
A	≤ 5		(X)	≥ 24		(X)
B	≤ 15		(X)	≥ 22		(X)
C	≤ 25		(X)	≥ 19		(X)
D	≤ 40			≥ 15		(X)
E	≤ 60	X		≥ 10		(X)
F	> 60			< 10	X	

Legends: X : Existing level of service
(X) : Expected level of service (optional)

C.5 Investigation of Bus Prioritisation Strategies

Development of Strategies

Based on the analysed problems for buses and existing local conditions and circumstances, the following strategies are selected for prioritising buses on the travel way and at the traffic signals:

- Improvement of the roadway layout (particularly the layout of the signalised intersection) by pavement markings,
- Arrangement of a partial dynamic bus lane,
- Arrangement of additional signals for pedestrians,
- Recalculation of intergreen times,
- Implementation of conditional signal priority, including green extension (6 seconds) and early green (6 seconds),
- Improvement of microscopic signal control strategies, and
- Implementation of supportive measures for improving traffic discipline.

Application of Strategies

Improvement of Layout

The following figure presents the roadway layout after an application of bus prioritisation to Nguyen Thi Minh Khai Street.

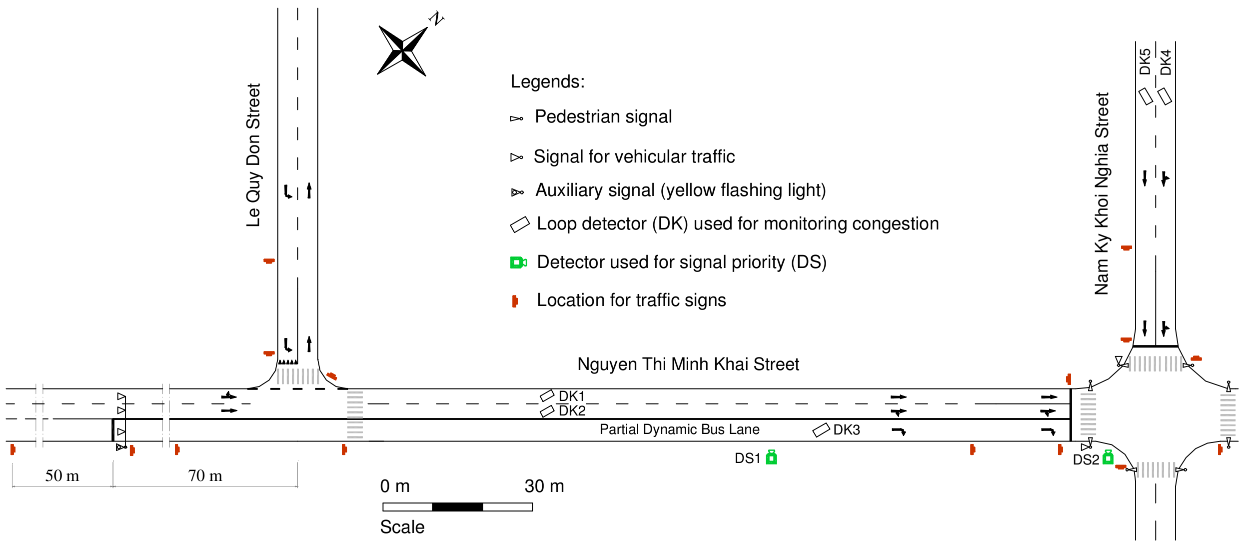

Figure C.5: Roadway layout after an application of bus prioritisation

Application of Partial Dynamic Bus Lane

As seen in Figure C.5, a partial dynamic bus lane with the width of 4.5 m was arranged for prioritising buses in the direction of Nguyen Thi Minh Khai Street. Only buses and right-turning vehicles at the traffic signals are allowed operating on this lane. Due to high traffic density and a considerable volume of accessing traffic from the side street, only logical conditions from detectors DK1, DK2, and DK3 were used for activating and deactivating the bus lane (i.e. bus detectors were not used for switching this bus lane). The following figure presents the algorithm for activating and deactivating this bus lane.

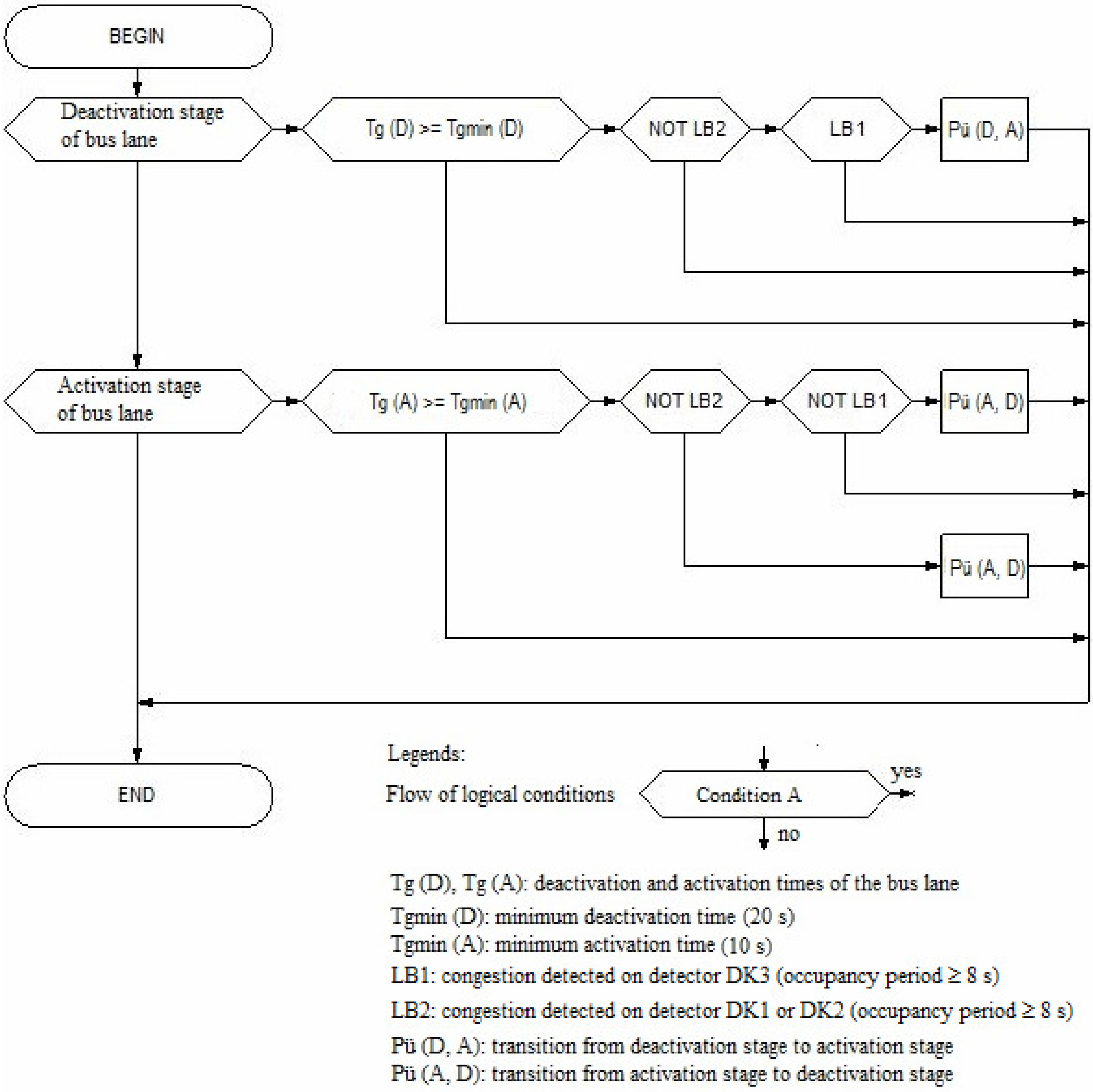

Figure C.6: Flow chart of control algorithm for activating and deactivating the bus lane

Improvement of Signal Timing Plan

In combination with an improvement of the intersection layout, the recalculation of intergreen times was performed in order to determine the proper values. Figure C.7 presents the signal phasing and signal timing plan after the reconsideration of traffic signal design.

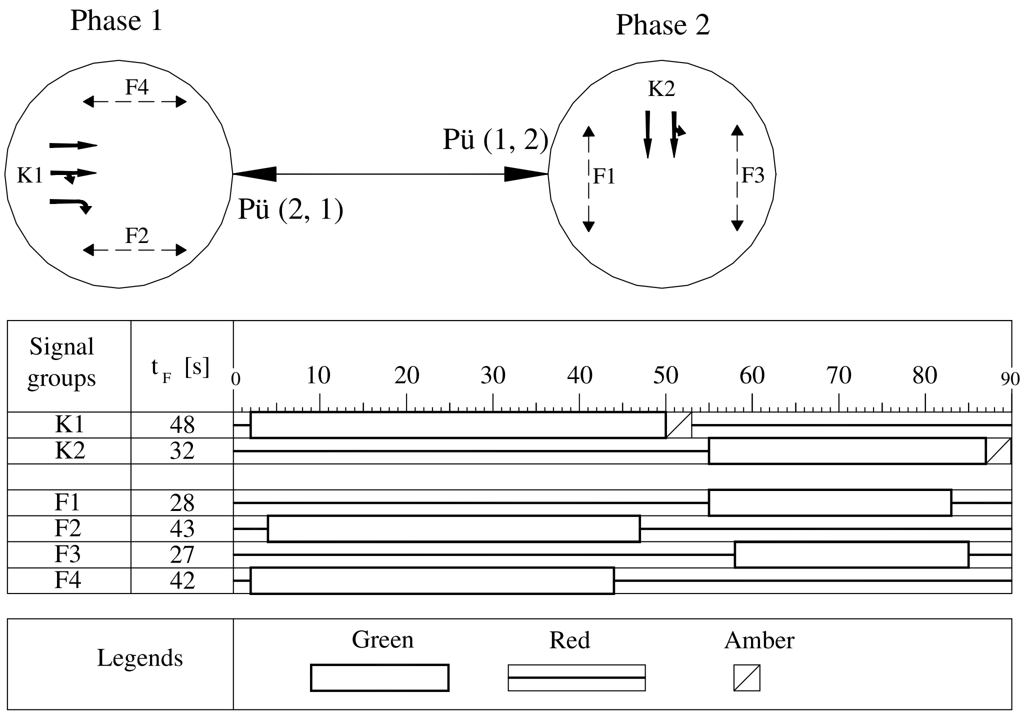

Figure C.7: Signal phasing and signal timing plan of the signalised intersection

Application of Signal Priority

As mentioned previously, green extension and early green were proposed to implement as signal priority at the traffic signals. The request of signal priority is generated by the check-in detector (DS1), and the cancellation of that priority is undertaken by the check-out detector (DS2) as seen in Figure C.5. The following figure presents the signal timing plan with signal priority for buses.

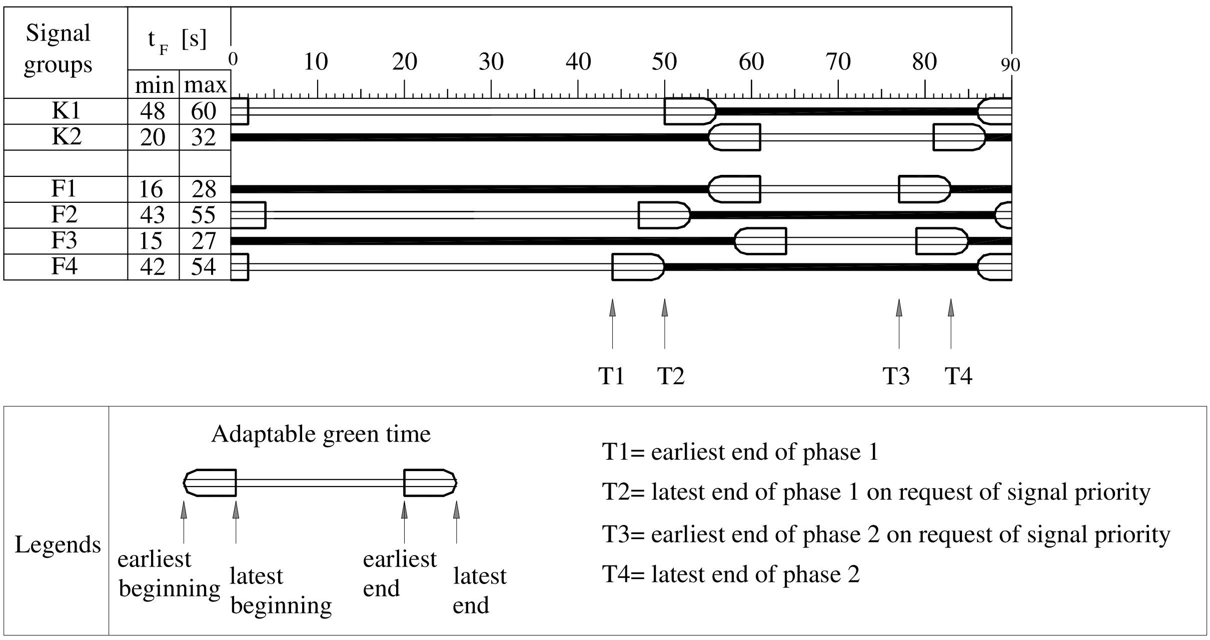

Figure C.8: Signal timing plan with green extension and early green

The conditional signal priority is used, in which the green extension will be granted to buses only if the congestion on detector DK4 or DK5 does not occur. The control algorithm for signal priority is provided in the following figure.

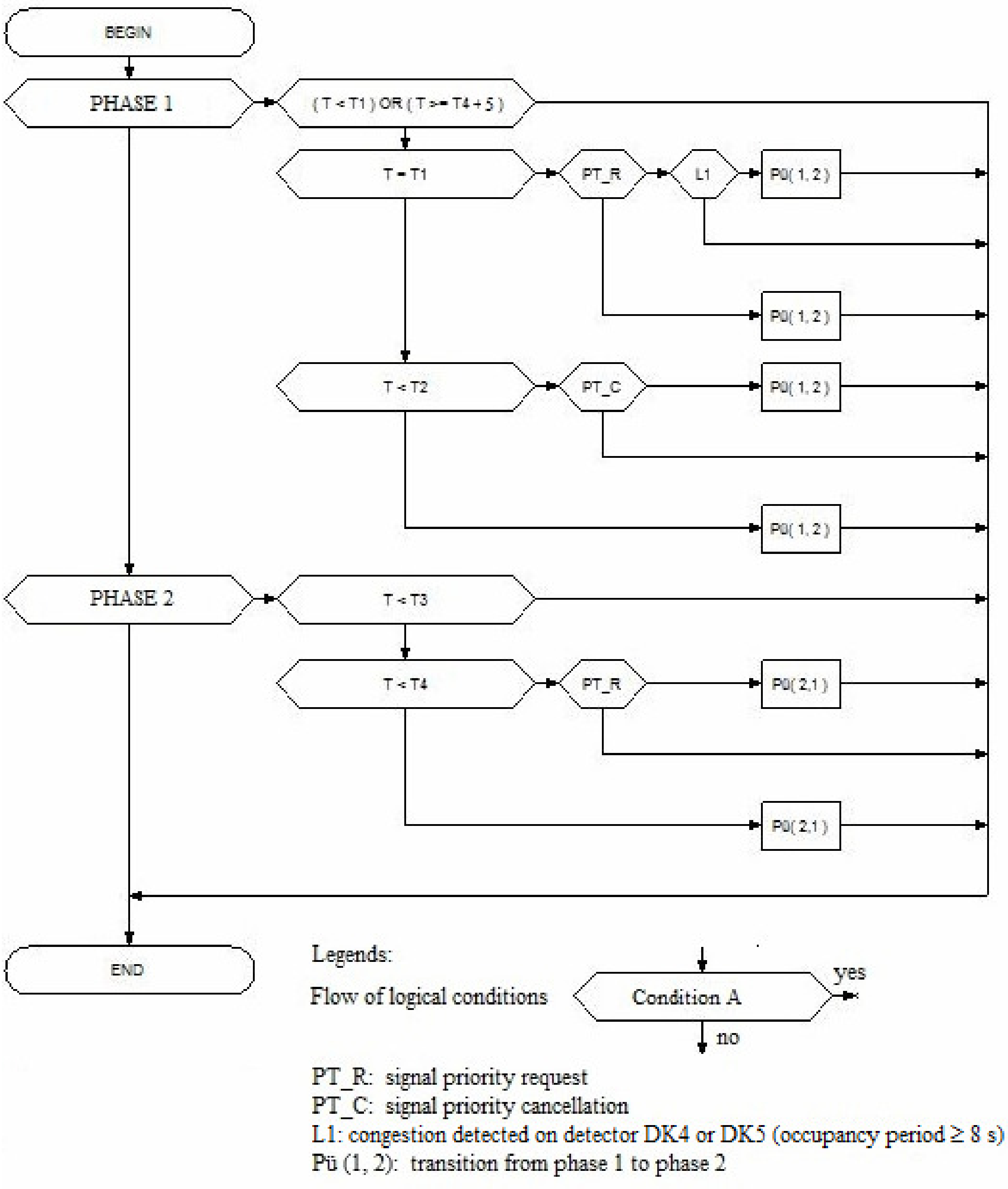

Figure C.9: Flow chart of the control algorithm for signal priority[40]

[40] A priority request (PT_R) is generated and stored in control unit when a bus is detected at the check-in detector (DS1), and this request will be removed when the bus is confirmed to cross over the stop line by the check-out detector (DS2).

C.6 Evaluation of Bus Prioritisation

Evaluation Parameters

The following parameters are used for evaluating the effectiveness of bus prioritisation:

- Travel time of buses (s),
- Delay of buses (s),
- Travel speed of buses (km/h),
- Total person delay[41] of all vehicular modes (s), and
- Standard deviation of bus travel time (s).

Simulation Tool

The micro-simulation VISSIM 5.20 was utilised for this evaluation. In this simulation, two scenarios were formulated, including the "initial scenario" and "bus prioritisation scenario". The initial scenario is the existing situation or the scenario without bus prioritisation, whereas the bus prioritisation scenario is the scenario with an application of bus prioritisation.

Apart from the basic calibration process as mentioned in Appendix B, additional calibration with the travel time of buses was performed. Thereafter, both scenarios were separately simulated in VISSIM 5.20 (see Figure C.10). Each scenario was run with 6 different simulation seeds. The warm-up time for the simulation was 300 s, and the period of evaluation was 3600 s (one hour).

Figure C.10: Example of simulating the initial scenario in VISSIM 5.20

[41] The total person delay is calculated for all vehicular modes in the study site. The occupancy rate is assumed with reference to JICA et al (2004): 1.3 persons per motorcycle, 1.0 person per bike, 1.9 persons per car or truck, and 39 persons per bus or coach.

Results

The results of evaluation parameters were obtained after the simulation process. The arithmetic mean of six out-put values generated by six different simulation seeds was computed for each parameter. Then the improvement of individual parameters was calculated. In addition, the test of significance might be applied to check whether the improvement is significant or not. The following table summarises these results.

Table C.3: Results of the evaluation

Parameters	Initial scenario	Bus prioritisation scenario	Improvement [%]	Test of significance (*t* -Test)
Travel time of buses (s)	60.6	36.7	39%	significant
Delay of buses (s)	47.3	22.3	53%	significant
Travel speed of buses (km/h)	8.8	14.6	66%	significant
Total person delay (s)	39.4	33.0	16%	-
Standard deviation of bus travel time (s)	27.3	12.9	53%	-

Notes: Student's *t*- test (one-tailed test) at the 5% level of significance is used for the test of significance of the improvement.
"-": the test of significance is not applied.
The given travel time, delay, and speed are the average value per vehicle or person.

As can be seen in Table C.3, the travel time, delay, speed, and variation of travel time of buses are improved noticeably after an implementation of bus prioritisation. Besides, the total person delay is reduced considerably. As a result, the level of service (LOS) for the operation of buses is increased, from LOS E to LOS C for the criterion of average waiting time, and from LOS F to LOS E for the criterion of average travel speed.

From the results of this empirical evaluation, it is concluded that bus prioritisation is a key solution to improve the quality of bus services in MDCs.

In der Schriftenreihe des Instituts für Verkehr an der Technischen Universität Darmstadt sind bisher folgende Hefte erschienen:

Fachgebiet Verkehrsplanung und Verkehrstechnik (ISSN 1613-8317):

V1 G. Faust
Entwurf und Bau von stark überhöhten Fahrbahnen
1999

V2 C. Korda
Quantifizierung von Kriterien für die Bewertung der Verkehrssicherheit mit Hilfe digitalisierter Videobeobachtungen
1999

V3 State of the Art of Research, Development and Application of Intelligent Transport Systems (ITS) in Urban Areas
Proceedings of the Japanese-German Symposium, April 27, 2001

V4 Verkehrssystem auf dem Weg zur freien Marktwirtschaft
Vorträge im Rahmen des Kolloquiums im Verkehrswesen am 11.06.2001

V5 V. Blees, M. Boltze, G. Specht
Chancen und Probleme der Anwendung von Qualitätsmanagement in Verkehrsplanungsprozessen
2002

V6 C. Lotz
Ermittlung von Detektorenstandorten für den Straßenverkehr innerorts
2002

V7 N. Desiderio
Requirements of Users and Operators on the Design and Operation of Intermodal Interchanges
2002

V8 S. Hollborn
Intelligent Transport Systems (ITS) in Japan
2002

V9 M. Boltze, G. Specht, D. Friedrich, A. Figur
Grundlagen für die Beeinflussung des individuellen Verkehrsmittelwahlverhaltens durch Direktmarketing
2002

V10 M. Boltze, A. Reußwig
First Review of Available Data: Modal Split in Different Countries
2000

V11 P. Schäfer
Bürgerinformation, ein wichtiges Element der Bürgerbeteiligung
2003

V12 M. Boltze
Fachgebietsbericht - September 1997 bis Dezember 2002
2003

V13 R. Stephan
Einsatzbereiche von Knotenpunkten mit der Regelungsart "rechts vor links"
2003

V14 V. Blees
Qualitätsmanagement in Verkehrsplanungsprozessen
2004

V15 P. Schäfer
Alternative Methoden zur Überwachung der Parkdauer sowie zur Zahlung der Parkgebühren
2004

V16 A. Reusswig
Qualitätsmanagement für Lichtsignalanlagen
2005

V17 P. Pujinda
Planning of land-use developments and transport systems in airport regions
2006

V18 M. Bohlinger
Grundlagen, Methodik und Verfahren der Verkehrsmanagementplanung
2006

V19 V. H. Khuat
Traffic Management in Motorcycle Dependent Cities
2006

V20 St. Krampe
Nutzung von Floating Traveller Data (FTD) für mobile Lotsendienste im Verkehr
2007

V21 A. Minhans
Traffic Management Strategies in Cases of Disasters
2008

V22 N.Roth
Wirkungen des Mobility Pricing
2009

V23 Q.C. Do
Traffic Signals in Motorcycle Dependent Cities
2009

V24 A. Wolfermann
Influence of Intergreen Times on the Capacity of Signalised Intersections
2009

V25 H. Jentsch
Konzeption eines integrierten Qualitätsmanagements für den Stadtverkehr
2009

V26 Y. Ni
Pedestrian Safety at Urban Signalised Intersections
2009

V27 W. Kittler
Beeinflussung der Zeitwahl von ÖPNV-Nutzern
2010

V28 S. Kohoutek
Quantifizierung der Wirkungen des Straßenverkehrs auf Partikel- und Stickoxid-Immissionen
2010

V29 V. N. Nguyen
Bus Prioritisation in Motorcycle Dependent Cities
2013

Fachgebiet Bahnsysteme und Bahntechnik (ISSN 1614-9300):

B1 F. Lademann
Bemessung von Begegnungsabschnitten auf eingleisigen S-Bahn-Strecken
2001

B2 J. Becker, E. Schramm
Barrierefreier Schienenpersonennahverkehr
Beschreibung und Bewertung der Anforderungen mobilitätseingeschränkter Menschen
2003

B3 C. Axthelm
Umweltbahnhof Rheinland-Pfalz
2004

B4 T. Muthmann
Rechnerische Bestimmung der optimalen Streckenauslastung mit Hilfe der Streckendurchsatz-leistung
2004

B5 J. Becker
Qualitätsbewertung und Gestaltung von Stationen des regionalen Bahnverkehrs
2005

B6 C. Axthelm
Kriminalität im Schienenverkehr in Ballungsräumen
2006

B7 M. Frensch
Ermittlung von wirtschaftlich und betrieblich optimalen Fahrzeugkonzepten für den Einsatz im Regionalverkehr

B8 M. Pächer
Pünktlichkeitsbewertung im Straßenbahn- und Stadtbahnverkehr
2007

Fachgebiet Straßenwesen mit Versuchsanstalt (ISSN 1614-9319):

S1 J. S. Bald
Risikoanalysen im Straßenwesen
2001

S2 U. Stöckert
Ein Beitrag zur Festlegung von Grenzwerten für den Schichtenverbund im Asphaltstraßenbau
2002

S3 M. Socina
Griffigkeit
2002

S4 H.-F. Ruwenstroth
Auswirkungen von wiederverwendeten Fräsasphalten mit polymermodifiziertem Bitumen und stabilisierenden Zusätzen auf Asphalteigenschaften
2003

S5 K. Fritscher
Aufnahme von Wegweisungsinformationen
2004

S6 B. Bach
Untersuchungen der Auffälligkeit von Verkehrszeichen und Werbung im Straßen auf der Grundlage inhaltlicher Eigenschaften und ihrer psychologischen Wirkung
2005

S7 S. Riedl
Rückrechnung dynamischer Tragfähigkeitswerte aus den Messdaten des Falling Weight Deflectometer (FWD)
2006

S8 V. Root
Entwicklung eines Prüfverfahrens zur Beurteilung des Widerstandes von Asphaltdeckschichten gegen Schubbeanspruchung an der Oberfläche
2008

S9 Huyen, Le Thu:
Risk Analysis, Driver Behaviour and Traffic Safety at Intersections in Motorcycle-Dominated Traffic Flow
2009

S10 Weidich, Peter:
Entwicklung eines Prüfverfahrens zur Beurteilung des Widerstandes von Asphaltdeckschichten gegen Schubbeanspruchung an der Oberfläche
2009

S11 Abesha Feyissa, Berhanu:
Analysis and modelling of long life asphalt concrete pavement
2009

S12 Huyen, Le Thu:
Risk Analysis, Driver Behaviour and Traffic Safety at Intersections in Motorcycle-Dominated Traffic Flow
2009

S13 Huyen, Le Thu:
Bewertung der Tragfähigkeit und der Standfestigkeit bestehender Asphaltstraßen zur Wahl zweckmäßiger Erhaltungsmaßnahmen
2009

S14 Rosauer, Verena:
Abschätzung der herstellungsbedingten Qualität und Lebensdauer von Asphaltdeckschichten mit Hilfe der Risikoanalyse
2010

S15 Wolf, Thorsten:
Ein prozessorientierter Ansatz zur Qualitätssicherung des Asphalt-Prüfprozesses
2010

S16 Farag Khodary Moalla Hamed:
Evaluation of Fatigue Resistance for Polymer Modified and Unmodified Asphalt Binders and Mixtures
2010

S17 Romy, Reinisch
Beitrag zur Bewertung der Komplexität des Straßenumfeldes bei Nachtfahrten im übergeordneten Straßennetz unter Berücksichtigung wahrnehmungspsychologischer Aspekt
2010

Curriculum Vitae

Full name:	**Nguyen** Van Nam
Date of birth:	December 26th, 1979
Place of birth:	Nam Dinh, Vietnam
Nationality:	Vietnamese
Address:	Section of Highway and Airport Engineering, University of Transport and Communications, Hanoi, Vietnam
Email:	ngvnamgtvt@yahoo.com

Education

10/2009 – 5/2013

Doctoral Candidate
Transport Planning and Traffic Engineering,
Darmstadt University of Technology, Germany

10/2004 – 8/2007

Master Degree: Urban Transport Planning and Highway Construction
University of Transport and Communications (UTC), Hanoi, Vietnam

9/1997 – 6/2002

University Degree: Civil Engineering, Road and Highway Construction
University of Transport and Communications (UTC), Hanoi, Vietnam

9/1994 – 6/1997

Pham Hong Thai High School, Hanoi, Vietnam

9/1990 – 6/1994

Thanh Cong Secondary School, Hanoi, Vietnam

Occupation

8/2002 – 5/2004

Teaching Assistant
Section of Road and Highway Engineering, Department of Civil Engineering,
University of Transport and Communications, Hanoi, Vietnam

5/2004 – 8/2009

Lecturer
Section of Highway and Airport Engineering, Department of Civil Engineering,
University of Transport and Communications, Hanoi, Vietnam

Prize

The Second Prize in National Mechanics Olympic (2000)
Merit for Excellent Graduate Students (2002)