ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

# EFFECTS OF BUS PRIORITY METHODS ON ADJACENT MIXED TRAFFIC

**Ph.D. THESIS**

**Nima DADASHZADEH**

**Department of Civil Engineering**

**Transportation Engineering Programme**

**JULY 2019**

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

# EFFECTS OF BUS PRIORITY METHODS ON ADJACENT MIXED TRAFFIC

**Ph.D. THESIS**

**Nima DADASHZADEH**
**(501142403)**

**Department of Civil Engineering**

**Transportation Engineering Programme**

**Thesis Advisor: Assoc. Prof. Dr. Murat ERGÜN**

**JULY 2019**

**ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ**

# KARMA TRAFİK AKIŞINDA OTOBÜS ÖNCELİĞİ YÖNTEMLERİNİN ETKİLERİ

**DOKTORA TEZİ**

**Nima DADASHZADEH**
**(501142403)**

**İnşaat Mühendisliği Anabilim Dalı**

**Ulaştırma Mühendisliği Programı**

**Tez Danışmanı: Doç. Dr. Murat ERGÜN**

**TEMMUZ 2019**

Nima Dadashzadeh, a Ph.D. student of İTU Graduate School of Science Engineering and Technology student ID 501142403, successfully defended the thesis/dissertation entitled "EFFECTS OF BUS PRIORITY METHODS ON ADJACENT MIXED TRAFFIC", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

| | | |
|---|---|---|
| **Thesis Advisor :** | **Assoc. Prof. Dr. Murat ERGÜN**<br>İstanbul Technical University | .............................. |
| **Jury Members :** | **Prof. Dr. Ali Osman ATAHAN**<br>Istanbul Technical University | ............................. |
| | **Assoc. Prof. Dr. Onur TEZCAN**<br>Istanbul Technical University | .............................. |
| | **Assoc. Prof. Dr. Mustafa GURSOY**<br>Yildiz Technical University | .............................. |
| | **Assist. Prof. Dr. Ali Sercan KESTEN**<br>IŞIK University | .............................. |

**Date of Submission : 25 June 2019**
**Date of Defense : 26 July 2019**

***To my beloved spouse, my dear mother,***

***and sole of my father***

## FOREWORD

This thesis is consisting of seven chapters. The first two chapters review the existing studies critically concerning bus priority methods, merging area bottleneck in highways and highlights the research objectives and hypothesis. Chapter 3 describes the history of bus priority methods implementation in Istanbul, Turkey. The design/programming details of a new hybrid model for the calibration of driving behavior parameters using MATLAB and VISSIM software as well as development an integrated model for merging bottleneck area called VSL+ALINEA/B is presented in chapter 4. Chapter 5 defines the case study area (YILDIZ merging in Istanbul, Turkey) selected in order to test the proposed calibration method and merging control models. The performance of the proposed fully-automatic driving behavior parameters' calibration method, and the analysis of different scenarios results to control merging bottleneck in the presence of high bus volume are discussed in detail in chapter 6. Lastly, chapter 7 concludes the research findings and contribution and proposed some directions for further studies.

First of all, I would like to express my gratitude and respects to my thesis supervisor, Assoc. Prof. Murat Ergün for his scientific advice throughout these years, encouragements, and personal support to complete this thesis. He is surely the key to the success of this thesis. Secondly, I'd like to extend my appreciation to my thesis steering committee members Prof. Ali Osman Atahan and Assist. Prof. Ali Sercan Kesten for their valuable suggestions and comments. My warmest gratitude devotes to Prof. Marijan Žura, Assoc. Prof. Peter Lipar and Assist. Prof. Darja Šemrov who provided me with a job opportunity at Traffic Technical Institute, University of Ljubljana (Slovenia) for their limitless supports even when they lack enough time to give. I am honored to be a member of their research/technical team.

I'd like to mention that this study would not have been possible without the emotional encouragement, valuable thoughts, guidance, kindness, and financial support of my lovely parents, my dear sister, and my beloved brothers.

From bottom of my heart, I intend to thank my cute love and kind spouse who encouraged me to pursue my higher educations and paved the way for me with her endless pure love, patients, helps and supports during last three years. She has always been accompanying me to cross over my Ph.D. journey in Istanbul and Ljubljana.

My sincere gratefulness goes to my friends and colleagues who inspired me throughout my Ph.D. program especially Dr. Omid Shokri, Dr. Ahmad Hasanzadeh, Onur Kaya, Serkan Varol, Nezir Özdemir, Simon Detellbach, Yaser Gafoori, Farhad Skandary and all my friends in Iran, Turkey and Slovenia.

June 2019

Nima DADASHZADEH
(Transport/Traffic Engineer, M.Sc.)

**TABLE OF CONTENTS**

**Page**

## ABBREVIATIONS

| | |
|---|---|
| **PT** | : Public Transport |
| **PTP** | : Public Transport Priority |
| **BP** | : Bus Priority |
| **TSP** | : Transit Signal Priority |
| **BL** | : Bus Lane |
| **XBL** | : Exclusive Bus Lane |
| **BRT** | : Bus Rapid Transit |
| **HOV** | : High Occupancy Lane |
| **HOT** | : High Occupancy Toll |
| **DBL** | : Dynamic Bus Lane |
| **IBL** | : Intermittent Bus Lane |
| **BLIP** | : Bus Lanes with Intermittent Priority concept |
| **IMM** | : Istanbul Metropolitan Municipality |
| **MFD:** | : Macroscopic Fundamental Diagrams |
| **EA** | : Evolutionary Algorithm |
| **MANE** | : Mean Absolute Normalized Error |
| **RMSE** | : Root Mean Square Error |
| **SPSA** | : Simultaneous Perturbation Stochastic Approximation |
| **QQMS** | : OptQuest/Multistart Algorithm |
| **NFE** | : Number of objective Function Evaluation |
| **GA** | : Genetic Algorithm |
| **PSO** | : Particle Swarm Optimization |
| **PSOGA** | : Hybrid (combination) model of PSO and GA |
| **GAPSO** | : Hybrid (combination) model of GA and PSO |
| **PCT** | : Parallel Computing Technique |
| **COM** | : Component Object Model |
| **ParGA** | : Parallel Genetic Algorithm |
| **ParPSO** | : Parallel Particle Swarm Optimization |
| **ParGAPSO** | : Parallel GAPSO |
| **ParPSOGA** | : Parallel PSOGA |

**VSL** : Variable Speed Limits control method

**VMS** : Variable Message Signs

**RM** : Ramp Metering control method

**ALINEA** : Asservissement LINéaire d'Entré Autoroutière (well known RM model)

**VSL+ ALINEA/B** : integrated VSL and ALINEA/B control model

## SYMBOLS

| | | |
|---|---|---|
| **$V_{w.avg}$** | : | Weighted average speed for n lanes, |
| **$v_i$** | : | Speed of $i^{th}$ lane of main road |
| **$q_i$** | : | Traffic volume of $i^{th}$ lane of main road |
| **n** | : | Number of lanes of main road |
| **Z** | : | General form of objective function |
| **$Vtarget_j$** | : | Target (observed) traffic volume collected by detectors |
| **$Starget_j$** | : | Target (observed) traffic speed collected by detectors |
| **$Vsim_j$** | : | Traffic volume simulated by VISSIM |
| **$Ssim_j$** | : | Traffic speed simulated by VISSIM |
| **N** | : | Total number of data collection intervals |
| **$X_{ij}$** | : | The position vector of continuous parameters in GA and PSO |
| **$V_{ij}$** | : | The velocity vector of continuous parameters in PSO |
| **$Lb_{Xi}$** | : | Lower bounde value of parameter $X_{ij}$ |
| **$Ub_{Xi}$** | : | Upper bounde value of parameter $X_i$j |
| **Vmin** | : | Lower bounde value of parameter $V_{ij}$ |
| **Vmax** | : | Upper bounde value of parameter $V_{ij}$ |
| **MaxIt** | : | Maximum Number of Iteration as stoping critrion used by EAs |
| **k** | : | Iteration number in PSO |
| **w** | : | Inertia weight in PSO |
| **$c_1$** | : | Personal learning coefficient in PSO |
| **$c_2$** | : | Population(global) learning coefficient |
| **$r_1$, $r_2$** | : | Random number between 0 and 1 |
| **idx** | : | Counting parametere in Paralle EAs |
| **nPop** | : | Number of populations in EA |
| **pCrossover** | : | Crossover Percentage in GA |
| **nCrossover** | : | Number of Parents (Offspring) in GA |
| **pMutation** | : | Mutation Percentage in GA |
| **nMutation** | : | Number of Mutants in GA |
| **Mu** | : | Mutation rate in GA |
| **phi** | : | Constriction Coefficient in PSO |

**$Pop_c$** : Population made by Crossover operator in GA

**$Pop_m$** : Population made by Mutation operator in GA

**$pop.best_{ij}$** : The personal's best value of parameters in PSO

**global.best** : The best value of parameters among all personal's best in PSO

**LIST OF TABLES**

**Page**

## LIST OF FIGURES

**Page**

# EFFECTS OF BUS PRIORITY METHODS ON ADJACENT MIXED TRAFFIC

## SUMMARY

Nowadays, car-dependent cities with low car occupancy are facing heavy traffic congestion, resulting in delays. A sustainable solution with the aim to simultaneously increase transport capacity and decrease traffic jams is the implementation of effective public transport, e.g. buses.

Globally, bus priority methods, e.g. bus lane (BL), have become popular strategies to increase the utilization of bus transport's capacity. This thesis gives a comprehensive overview of prior studies related to bus priority methods and their implementation challenges and needs together with clustering the most influencing factors in the implementation and operation of BLs.

Under some circumstances, urban transport officials have to operate buses in the mixed traffic based on their road network limitations in providing full bus priority methods. For instance, Istanbul's Metrobus (a segregated BL) has to merge to O-1 highway mixed traffic (known as YILDIZ merging area) to cross the Bosphorus bridge.

This is selected as the best-case study for examining the operational effects of a high rate bus volume in mixed traffic. In order to analyses the effects of this phenomena, YILDIZ merging area is modelled in microscopic traffic simulation software, VISSIM, Traffic data such as speed, volume, and occupancy are gathered through detectors installed in the area.

As most of the microscopic traffic simulation programs used today incorporate car-following and lane-change models to simulate driving behavior across a given area, the first objective of the thesis is to develop an automatic calibration procedure of traffic simulations models using metaheuristic algorithms, in order to find well-tuned driving behavior parameters in the presence of high rate bus volume for the real conditions of Istanbul.

Local search capability of Genetic Algorithm (GA) and swarm's information exchange ability of Particle Swarm Optimization (PSO) are used in order to develop a new combination of the GA and PSO (i.e. hybrid GAPSO and hybrid PSOGA) to overcome the limitations of those algorithms. The calibration procedure is coded using MATLAB and implemented via the VISSIM-MATLAB COM interface on YILDIZ model.

The result of the calibrated model shows that hybrid GAPSO and hybrid PSOGA techniques outperformed the GA-only and PSO-only techniques, and that the lowest value of objective functions (i.e. MANE and RMSE) are achieved with the hybrid GAPSO algorithm. Thus, both are recommended for use in the calibration of microsimulation traffic models, rather than GA-only and PSO-only techniques.

However, the calibration procedure for traffic simulation models can be a time-consuming process in the case of large-scale and complex networks. Another contribution of this study is to develop a quick calibration procedure using EA and parallel computing techniques (PCTs). To this end, two calibration scenarios with/without PCT have been analyzed.

It is found that the implementation of PCT on proposed hybrid models can significantly reduce the total computational time of the optimization process - in these experiments by 45-65%.

Once the best-matched sets of VISSIM’s driving behavior parameters for the case study area is obtained through the proposed calibration procedure, it is necessary to develop new ramp control methods in the presence of a high volume of buses. Ramp metering (RM) e.g. ALINEA and variable speed limit (VSL) are two widely used and effective congestion management strategies, especially for “merging congestion” on highways.

According to the literature review conducted, the implementation of RM and VSL strategies in a separate and combined manner have been thoroughly studied. However, there is no detailed study regarding the combination of these systems in relation to issues with high bus volume.

High bus volume directly affects driving behavior (e.g. lane changing) especially in merging points of urban highways, causing a decrease in the capacity of these areas of highways.

Installation of Transit Signal Priority (TSP) on the YILDIZ ramp can be a simple solution to decrease the interaction of buses with on-ramp vehicles as well as buses delays reduction. It will directly affect on-ramp vehicle delays, which have to give movement priority to buses, however, it cannot control the interaction of buses with highway mixed traffic.

Such a complex condition necessitates an integrated model which is able to control all interactions and avoid conflicts among three types of traffic flow - namely mainline (highway), on-ramp, and buses.

Therefore, the ultimate goal of this study is to address the gap in the literature by developing and proposing a combined VSL and RM strategies in presence of high bus volume (e.g. Metrobus vehicles in YILDIZ merging segment).

Integrated VSL and ALINEA model considering high bus volume (called VSL+ALINEA/B) have been coded and applied to the calibrated model through the VisVAP. Various scenarios with i) no control, and ii) with control (TSP, ALINEA, VSL, VSL+ALINEA/B) have been tested on the calibrated YILDIZ merging simulation model.

For current traffic conditions, proposed VSL+ALINEA/B is able to improve total travel time by 6.6%, average delays of mixed traffic and buses by 28.1% and 48.5% respectively, average speed by 7.4%, bottleneck throughout (capacity) by 2.5%, and fuel consumption, CO, NOx, VOC emissions by 8.4% on average when compared to an existing “VSL+ALINEA” model.

The simulation performs even better when compared to other models such as No Control, VSL, ALINEA, and TSP. Lastly, the proposed VSL+ALINEA/B model performance has been tested with different bus volumes, in order to analyze its effectiveness in different traffic conditions. Results of the scenario analysis confirmed that the proposed VSL+ALINEA/B model is not only able to decrease the delays of buses, but can also improve the adverse effects of high bus volume on mixed traffic flow in highways.

## KARMA TRAFİK AKIŞINDA OTOBÜS ÖNCELİĞİ YÖNTEMLERİNİN ETKİLERİ

## ÖZET

Günümüzde, araç doluluk oranının düşük olduğu otomobile bağımlı şehirler, gecikmelere yol açan yoğun trafik sıkışıklığı ile karşı karşıya kalmaktadır. Ulaşım kapasitesini arttırmak ve aynı zamanda trafik sıkışıklığını azaltmak amacıyla sürdürülebilir çözüm, örneğin otobüs gibi etkili toplu taşıma araçlarının uygulamasıdır.

Ayrıca, otobüslerin kullanım kapasitesini artırmak için dunya çapinda toplu taşıma önceliği yöntemleri, örnekle otobüs şeridi uygulaması popüler hale gelmiştir. Bu çalışma, otobüs önceliği yöntemleri, uygulama zorlukları ve ihtiyaçları ile ilgili çalışmalara kapsamlı bir genel bakış sunmaktadır.

Çalışmada; elde edilen sonuçlar önceki çalışmaların bulgularıyla birleştirilerek, etkili bir otobüs şeridi uygulaması için kapsamlı bir kılavuz formüle edilebilmiştir. Bu calismada önerilen kılavuz; karar vericilerin, planlamacıların, mühendislerin ve operatörlerin yerel bağlamda başarılı bir BL elde etmelerini sağlayacaktır.

Öte yandan, bazı durumlarda şehir içi ulaşım görevlileri, tam otobüs önceliği yöntemlerinin sağlanmasındaki yol ağı sınırlamalarına dayanarak karma trafikte otobüs işletmek zorundadır. Örneğin, İstanbul Metrobüsü Boğaziçi Köprüsününden geçmek için, E5 karayolundaki karma trafiğe katilmak zorundadir (YILDIZ rampasi veya birleşme alanı olarak bilinir).

Bu birleşme alanı, karma trafikte bu denli yüksek oranlı otobüs hacimlerinin operasyon etkilerdi de göz önüne alındığında, seçilebilecek en iyi çalışma yeri olabilir. Bu nedenle, YILDIZ birleşme alanı, bu olayın etkilerini analiz etmek amacıyla, mikroskobik trafik simülasyon yazılımı VISSIM'de modellenmiştir. Hız, hacim ve doluluk dahil olmak üzere trafik verileri, bölgede bulunan dedektörler aracılığıyla toplanmıştır.

Günümüzde kullanılan mikroskobik trafik simülasyon programlarının çoğu, belirli bir alandaki sürüş davranışını simüle etmek için araç takip ve şerit değiştirme modellerini içermektedir. Bu nedenle, tezin birinci amacı; İstanbul için iyi ayarlanmış sürüş davranışı parametrelerini belirlemek icin, metaheuristik algoritmalar kullanarak trafik simülasyonu modellerinin otomatik kalibrasyon prosedürünü geliştirmektir.

Genetik Algoritma'nın (GA) yerel arama kabiliyeti ve Parçacık Sürü Optimizasyonunun (PSO) bilgi alışverişi kabiliyeti kullanılarak, bu algoritmaların sınırlamalarını aşmak için yeni bir GA ve PSO kombinasyonu (yani, hibrit GAPSO ve hibrit PSOGA) geliştirilmıştır.

Kalibrasyon prosedürü MATLAB programin kullanılarak kodlanmış ve VISSIM-MATLAB COM arayüzü ile YILDIZ modeli uzerinde uygulanmıştır. Kalibre edilmiş modelin sonuçları, hibrit GAPSO ve hibrit PSOGA tekniklerinin yalnızca GA ve PSO

tekniklerinde daha iyi performans gösterdiğini ve her iki amaç fonksyonu icin (yani hem MANE hem de RMSE) en düşük değerinin hibrit GAPSO algoritması ile elde edildiğini göstermiştir.

Bu nedenle, her ikisinin de, yalnızca GA ve yalnızca PSO teknikleri yerine, mikrosimülasyon trafik modellerinin kalibrasyonunda kullanılması önerilmektedir.

Ama, trafik simülasyon modelleri için kalibrasyon prosedürü, büyük ölçekli ve karmaşık bir ağ söz konusu olduğunda çok zaman alan bir işlem olabilir. Bu çalışmanın bir başka katkısı, EA ve paralel hesaplama tekniklerini (PHT'ler) kullanarak hızlı bir kalibrasyon prosedürü geliştirmektir. Bu amaçla, PHT olan/olmayan iki kalibrasyon senaryosu analiz edildi. PHT'nin önerilen hibrit modellerde uygulanmasının, optimizasyon sürecinin toplam hesaplama süresini önemli ölçüde (deneylerimizde %45-65 kadar) azaltabildiği bulundu.

VISSIM'in vaka çalışması alanı için en iyi eşlenen sürüş davranış parametreleri, önerilen kalibrasyon prosedürü ile elde edildikten sonra, yüksek otobüs hacminin varlığında yeni katılım kontrol yöntemleri geliştirilebilir. Katılım kontrolü (KK) örn. ALINEA ve değişken hız sınırı (DHS), özellikle otoyollardaki birleşim tıkanıklıkları için yaygın olarak kullanılan ve etkili sıkışıklık yönetimi stratejileridir.

Yapılan literatür taramasına göre, KK ve DHS stratejilerinin ayrı ve kombine bir şekilde uygulanması üzerine bir çok çalışma yapılmıştır. Ancak, yüksek otobüs hacmi sorunu göz önüne alındığında bu sistemlerin kombinasyonuyla ilgili ayrıntılı bir çalışma yoktur.

Yüksek otobüs hacmi, özellikle şehir içi otoyolların birleşme noktalarındaki sürüş davranışını (örneğin şerit değiştirme) doğrudan etkiliyor olup, bu da otoyol alanlarında kapasite düşüşüne neden olmaktadır. YILDIZ rampasına Transit Sinyali Önceliğinin (TSÖ) kurulması, otobüslerin rampa üstü araçlarla etkileşimini azaltmak ve aynı zamanda otobüs gecikmelerini ortadan kaldırmak için basit bir çözüm olabilir.

Ama, bir yandan, otobüslere hareket önceliği vermek zorunda olan rampa üzerindeki araç gecikmelerini doğrudan etkileyecek olup, diğer yandan otobüslerin karayolunun karma trafiği ile etkileşimlerini kontrol edemeyecektir. Ana yol (otoyol), rampa ve otobüsler gibi üç tür akış arasında çeşitli çakışmaların olduğu bu kadar karmaşık bir durumda, tüm etkileşimleri kontrol edebilen entegre bir modele sahip olmak gerekir.

Bu sebeple, son olarak bu çalışmanın nihai amaçı, yüksek otobüs hacminin varlığında (örnegin E5 otoyoluna giren Metrobüs aracları), birleştirilmiş DHS ve KK stratejileri geliştirerek ve önererek literatürdeki boşluğu ele almaktır.

Yüksek otobüs hacmini dikkate alan entegre DHS ve ALINEA modeli (DHS+ALINEA/O olarak adlandırılmış) VisVAP ile kodlanmış ve kalibre edilmiş modele uygulanmıştır. Kalibre edilmiş YILDIZ birleşim simülasyon modelinde i) kontrolsüz, ii) kontrollü (TSÖ, ALINEA, DHS, DHS+ALINEA, DHS+ALINEA/O) çeşitli senaryolar test edilmiştir.

Önerilen DHS+ALINEA/O modeli kombine DHS+ALINEA gibi mevcut modelle karşılaştırdığında, toplam yolculuk süresini % 6.6 oranında, ortalama hızı % 7.4 oranında, darboğazdan geçiş kapasitesini ortalama % 2.5 oranında, yakıt tüketimini, CO, NOx, ve VOC emisyonlarını ortalama %8.4 oranında iyileştirebilir ve hatta diğer mevcut senariolara gore örn. kontrolsüz, TSÖ, DHS, KK daha iyi performans göstermektedir.

Son olarak, önerilen DHS+ALINEA/O model performansı, farklı olası koşullarda etkinliğini analiz etmek için farklı otobüs hacimleriyle test edilmiştir. Senaryo analizinin sonuçları göstermiştir ki, önerilen DHS+ALINEA/O modeli, yalnızca otobüs gecikmesini azaltmakla kalmaz, aynı zamanda yüksek otobüs hacimlerinin karayollarının ana hatlarındaki karma trafik hareketleri üzerindeki olumsuz etkilerini de iyileştirir.

# 1. INTRODUCTION

Urban transit system consists of multiple travel modes where car and bus are the most common modes among them especially in developing countries. Hence, how to allocate existing road spaces in city-center and suburban corridors among car and bus for improving the operational efficiency of transportation has become a frontier research topic. Achieving mobility and accessibility while maintaining a sustainable urban environment is a common aim of such countries.

City populations and number of registered vehicles are increasing throughout these nations, causing a number of increasingly severe, traffic-related issues: congestion, variability in travel time, environmental pollution, natural resource consumption, and severe-fatal accident rates (Beirão and Sarsfield Cabral, 2007). Improved public transport (PT) efficiency not only plays a vital role in mitigating these problems but also affects the successful development of environmentally-friendly urban areas in developing nations (Kogdenko, 2011; Ibarra-Rojas *et al.*, 2015).

## 1.1 Public Transport Priority

One possible, low-cost measure to improve PT service is to introduce public transport priority (PTP) in particular Bus Priority (BP) measures. BP measures can be clustered into time-based and spatially-based BP schemes. The first of these provides Transit Signal Priority (TSP) to buses at junctions, while the second priorities by designating a space to buses, the bus lane (BL).

According to their location on the road, BLs can be classified into three sub-classes: curbside, offset, and median bus lanes. In turn, each of these can be implemented differently in terms of: i), direction of bus movement (parallel with the flow or contra-flow), ii), separation methods (segregated or unsegregated), and iii) operational type (static or dynamic).

Recent studies have addressed the introduction and performance evaluation of new BL projects in urban areas mostly in developed countries (Xu and Zheng, 2012; Carry *et al.*, 2014; Safran, Beaton and Thompson, 2014; Chen, Chen and Wu, 2016).

The impact of illegal traffic use on BL efficiency has also been studied. Chen *et al.* (2015) researched the interaction between buses and general traffic flow by analyzing variation in lane-changing patterns and driver violations. They found that ‘abnormal’ behaviors such as induce a 16% reduction in the saturation rate of general traffic and a 17% increase in bus travel time. In addition, increased lane-changing maneuvers close to the Bus Rapid Transit (BRT) stations caused an increase in the downstream queue discharge flows of the general traffic.

## 1.2 Merging Congestion, Highway's Bottleneck, and Capacity Drop

### 1.2.1 Bottleneck, and capacity drop

Once the upstream capacity of a given road segment exceeds the downstream capacity, the bottleneck location is created. There is a different kind of reasons to build highway bottlenecks such as work zones and incidents so-called external capacity-reducing events, on-ramp (merging) area, lane drops, specific road buildings e.g. tunnels and bridges. Bottleneck throughput or bottleneck capacity is referred to the maximum number of vehicles that can be crossed the bottleneck location in a given time period only if the upstream flow rate is smaller or equal than the bottleneck capacity. However, if there are a lot of lane-changing behavior or upstream's arriving flow is larger than bottleneck throughput, congestion will be started and spilling-back to the upstream. Consequently, the bottleneck works under its nominal capacity. Researchers have long observed that capacity is not a static feature at bottlenecks and that there is a reduction in the achievable capacity due to the formation of bottlenecks so-called 'Capacity Drop'. Below are the results of empirical observations done by several studies:

- ✓ Upon a bottleneck is started the maximum discharge flow might be 5 – 20 % less than nominal bottleneck throughput (Cassidy and Bertini, 1999; Chung, Rudjanakanoknad and Cassidy, 2007).
- ✓ Upstream queuing and capacity drop in bottleneck area have linear correlation with the acceleration process of slowed vehicles crossed bottleneck location (Hall and Agyemang-Duah, 1991).
- ✓ There are also a strong associations between lane changing and capacity drop in particular in merging segments (Cassidy and Rudjanakanoknad, 2005).

Recently, several congestion control strategies have been proposed and applied like ramp metering and variable speed limit in order to shift or prevent the beginning of a bottleneck related capacity drop (Papageorgiou, Hadj-Salem and Blosseville, 1991; Papamichail and Papageorgiou, 2008; Khondaker and Kattan, 2015). These traffic control measures will be discussed in detail in the following chapters.

### 1.2.2 Lane-changing behavior in merging (on-ramp) area

Lighthill & Whitham (1955) started the first general investigation regarding the relation between lane-changing behaviors and traffic flow conditions. Afterwards, Munjal *et al.* (1971) evaluated the relationship between lane-changing maneuver and speed changes of two vehicles following each other. In addition, by proposing the new models of speed, density, flow and lane-changing rate, it is shown that that lane-changing vehicles had remarkable effects on following vehicles (Laval and Daganzo, 2005, 2006). They concluded that one of the important factors in the activation of merging bottlenecks and in capacity drops is the large number of lane-changing in these area (Banks, 1991; Cassidy, Anani and Haigwood, 2002; Choudhury *et al.*, 2006; Choudhury, Ramanujam and Ben-Akiva, 2009; Daamen, Loot and Hoogendoorn, 2010; Jin, 2010).

The behavior of weaving and lane-changing vehicles at a freeway section has an important effect on freeway performance. Weaving maneuvers can be disruptive to the traffic flow depending on the prevailing conditions. At the microscopic level, lane changing behavior typically deals with an individual vehicle's lateral movement process during lane-changing (Gipps, 1986; Lindgren *et al.*, 2006). The same can also be extended and modeled from a driver behavior perspective where lane-changes are typically first categorized as discretionary or mandatory, and then estimated based on numerous traffic, vehicle and driver characteristic variables (Ahmed, 1999; Toledo and Zohar, 2007; Sun Jian, Ouyang Jixiang and Yang Jianhao, 2014). At a macroscopic level, the lane-changing can be modeled at an aggregate level as exchange of flow across lane boundaries as a derivative of either density perturbations between lanes, or increased utility due to speed differences (Munjal, 1971; Jin, 2010; Wan *et al.*, 2013).

Lane changing can also be implemented through hybrid models, treating the lane changing vehicles as moving bottlenecks with respect to their impact on the target lane (Daganzo and Laval, 2005; Laval and Daganzo, 2006). Such hybrid models can show how lane changing can lead to capacity drop (Leclercq, Laval and Chiabaut, 2011; Ramadan and Sisiopiku, 2016). Jin *et al.* (2010, 2013) presented a new framework for modeling the effect of lane changing vehicles on traffic stream. Lane changing was treated as an aggregate multi-lane-group process where all lanes are considered to be balanced in terms of traffic conditions and traffic behavior.

The bus can be considered as an ordinary moving bottleneck. Moving bottlenecks create different traffic conditions upstream and downstream of the bottleneck: the upstream traffic in a congested state and downstream traffic freely flowing at a reduced volume. Another consideration is the effects of buses on the traffic flow in mixed-use conditions. Buses typically travel slower than cars, and could hence create gaps in the traffic flow, which in return would reduce the capacity of the roadway during their presence. This effect, hereafter named capacity reduction due to bus presence, has not been previously quantified in the literature.

## 1.3 Thesis Objective

As can be obtained from existing studies, there are no detailed study regarding existing challenges and needs for the implementation of various spatial bus priority shames, and the effects of giving priority to buses movement in highway merging segments. Therefore, the main objectives of this study can be classified as follows:

- ✓ **Main Objective:** to analyze the effects of giving priority to buses movement in highway merging segments on adjacent mixed traffic compared to existing models.
- ✓ **Sub-objective 1:** to provide an overview on main challenges and requirements to implement different Bus Priority methods? (Worldwide and also in Turkey)
- ✓ **Sub-objective 2:** to develop a hybrid and fast driving behavior parameters calibration procedure in order to have accurate model representing real condition in the presence of high bus volume.
- ✓ **Sub-objective 3:** to develop a combined Variable Speed Limit (VSL) and Ramp Metering (RM) strategies *e.g.* ALINEA in the presence of high bus volume (hereinafter called VSL+ALINEA/B).

### 1.4 Hypothesis

Below is the hypothesis will be evaluated in this thesis:

- Integrated VSL+ALINEA/B control method can improve the merging segments' performance in highways in presence of high bus demand, and decrease the average delay for buses and mixed traffic.

Other sections of thesis are structured as follows:

Chapter two covers the literature studies critically concerning bus priority methods, summarizing minimum requirements for bus priority methods implementation, their challenges, and influencing factors related to their successful implementation. Chapter three describes bus priority methods in Istanbul, Turkey.

Chapter four presents driving behavior parameters definition, traffic simulation models' calibration and optimization algorithms, and objective function definition together with describing the programing (code) details of a new hybrid model for the calibration of driving behavior parameters using MATLAB-VISSIM COM interface integrating with parallel computing techniques. In addition, it describes the development of a novel and integrated VSL+ALINEA/B model for sustainable bus transport in merging segments of highways.

Chapter five defines the case study area (YILDIZ merging in Istanbul, Turkey) in order to test the proposed calibration method and merging control models and relevant observed data collection procedures.

Performance of the proposed driving behavior parameters calibration method and the analysis results of different scenarios for merging control in the presence of high bus volume on case study area are discussed in detail in chapter 6.

Lastly, chapter 7 concludes the research findings and contribution and proposed some directions for further studies.

# 2. LITERATURE REVIEW

## 2.1 Genealogy of Bus Priority Methods

Having embarked on a detailed overview of the literature, it seems that BP methods mainly fall into two distinct categories; those which are time-based, and those which retain a spatial focus. We thus will group BP methods into time-based and spatial methods. All categories and sub-categories of PTP are shown in Figure 2.1 to give researchers a full picture of existing PTP schemes. The present study focuses mainly on spatial based PTP, with time-based PTP explained more briefly.

The first main category of PTP methods shown in Figure 2.1 is time-based PTPs. This refers to those which give a time priority to buses in junctions (e.g. transit signal priority) especially. Time-based methods can be divided into two distinct sub-groups, namely Traffic Signal Priority (TSP) and Pre-Signal Priority (Pre-TSP); as described in Section 3. TSP is implemented in inter-city junctions/intersection and highway on-ramps; while Pre-TSP is setting in a pre-determined distance from main inter-city traffic signals.

The second main category covered pertains to space-based PTP methods, which will be referred to as spatial PTP. This refers to those which provide priority to buses by allocating space in the road to buses (e.g. median-segregated bus lanes) on roads or near junctions. In general, due to their location along roads, spatial strategies can be classified into three sub-classes, including curbside, offset, and median BLs. Each example of these is distinct in terms of direction, separation methods, and operating types. In the following sections, each of these classes and sub-classes will be described in greater detail.

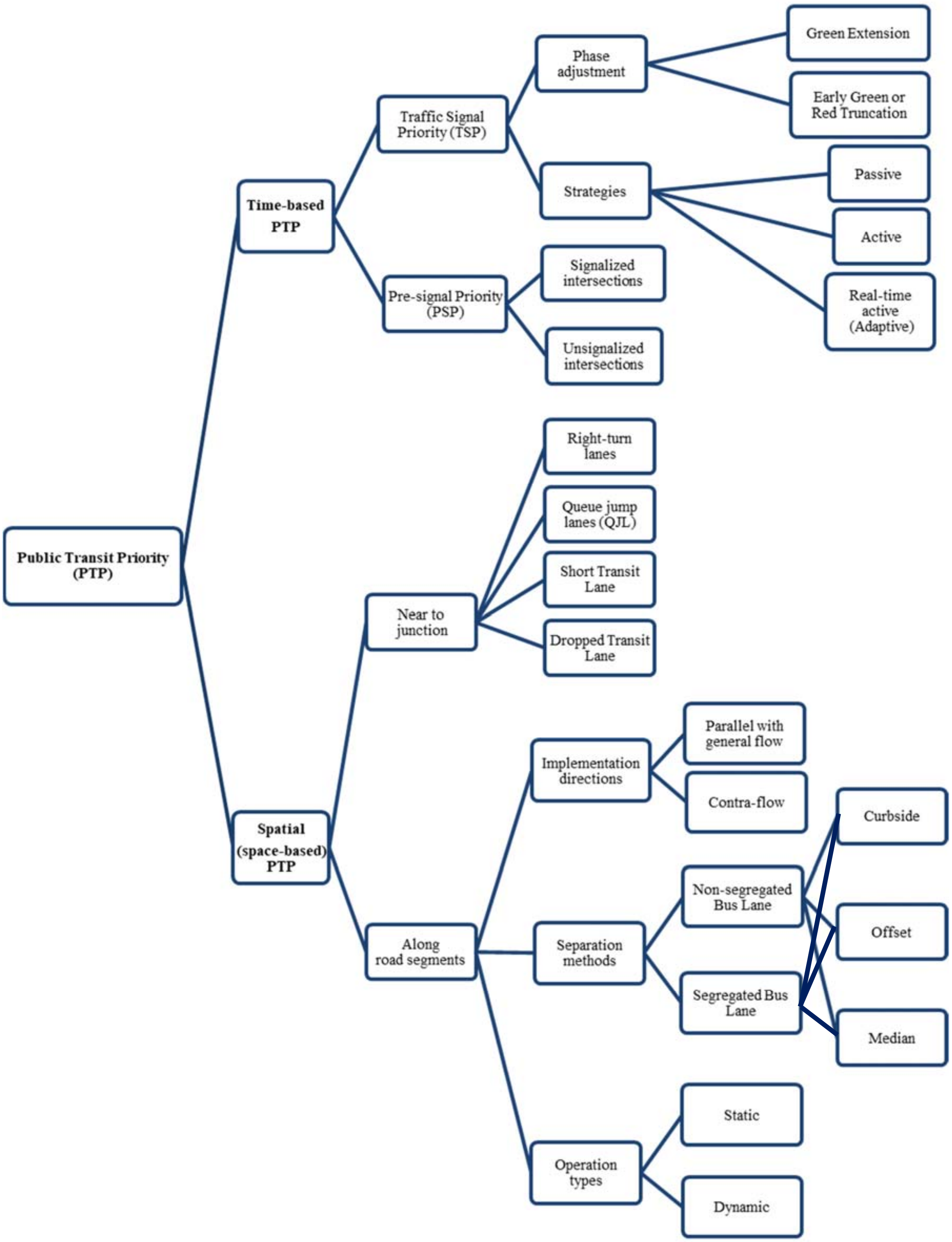


**Figure 2.1 :** Clustering of existing bus priority methods.

### 2.1.1 Time-based BP methods

Urban transit authorities attempt to give time-based priority to buses using traffic signals and Intelligent Transport Systems (ITS), particularly at intersections in which buses are confronted with mixed traffic flows. This section offers a brief overview of time-based BP schemes including signal and pre-signal priority systems. However, detailed information of signal phase adjustments including green extension, early green, and signal operation issues such as passive, active and real-time (adaptive) strategies are beyond the scope of this thesis. For more information regarding signal phasing design, readers are recommended to see (Mirchandani and Lucas, 2004; Zhou, Gan and Shen, 2007; Mahendran *et al.*, 2014; Feng, Figliozzi and Bertini, 2015; Lin *et al.*, 2015; Zhao and Liu, 2016; Lin, Yang and Zou, 2017).

#### 2.1.1.1 Traffic signal priority

TSP is a general term for a set of operational improvements which harness technology in order to reduce the dwell time at traffic signals for transit vehicles, by lengthening the time given for green lights or shortening to time in which red lights remain flashing. As one of the pioneering researchers studying TSP, Duerr (2000) proposed integrated modeling approaches in order to optimize signal control using the dynamic right-of-way for PT. To put it simply, with the application of TSP, buses can request the green phase of traffic signals to offer right of way and proceed unimpeded through an intersection (D'Souza, Hounsell and Shrestha, 2012; Ma, Liu and Han, 2013; He, Guler and Menendez, 2016). TSP may be implemented at individual intersections or across corridors or entire street systems (Skabardonis, 2000). As Smith et al. (2005) point out, the distinction between TSP and signal pre-emption is an important one because: "signal priority modifies the normal signal operation process to better accommodate transit vehicles, while pre-emption interrupts the normal process for special events such as an approaching train or responding fire engine...".

In simpler term, TSP is the process of detecting transit vehicles approaching signalized intersections and adjusting the signal phasing in real time to reduce transit delay (Furth and Muller, 2000). Figure 2.2 shows the required devices to implement TSP system in intersection.

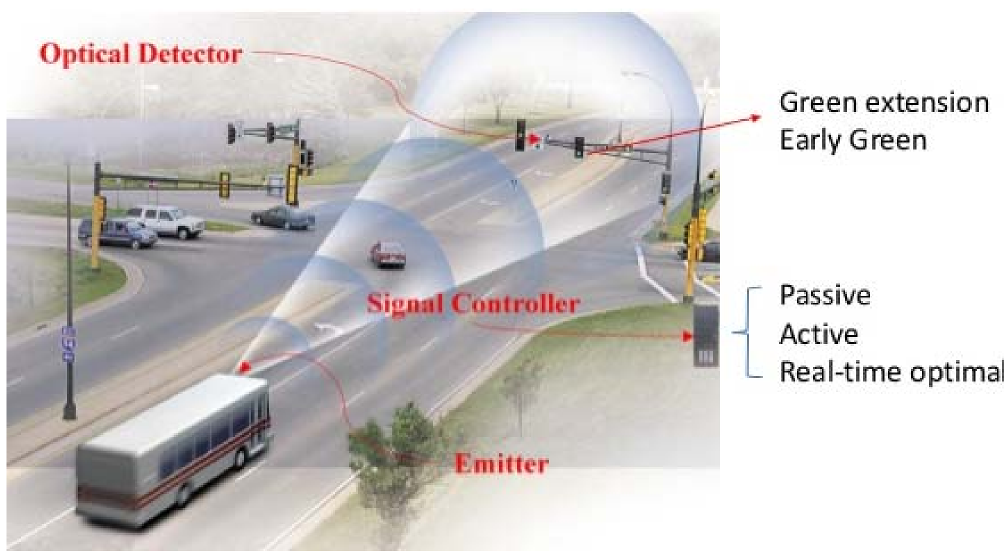


**Figure 2.2 :** TSP system components in the intersection (NACTO, 2016).

#### 2.1.1.2 Pre-signal priority or bus gates concept

The most worrying issue regarding PT operations is that buses can be delayed by car queues, leading to more unreliable transit service. Mitigating the impacts of these harmful interactions on transit vehicles is essential in promoting PT as a solution to urban traffic congestion. One strategy to help minimize negative bus–car interactions at signalized intersections is the installation of an additional traffic signal upstream to help manage conflicts between the two vehicle types.

These additional signals, called pre-signals or bus gates, are used on approaches with segregated BLs. The pre-signals are typically installed at the locations where BLs end to help buses transition out of the segregated BLs with minimal interruption (Wu and Hounsell, 1998).

The idea of setting up a signal in front of the main signal (i.e. a pre-signal) is not new and has been studied before. However, Guler and Menendez (2014) have provided guidelines to determine the pre-signal timing for minimizing the system delay (see Figure 2.3).

The proposed operating strategy was for intersections without bus detection infrastructure. This has been implemented in a number of UK cities, such as in London in 2009. Sometimes, signaled bus gates attempt a similar strategy (UK Department for Transport, 2003). Pre-Signals are also used to provide priority to buses utilizing opposite lanes (Guler and Menendez, 2015; Guler, Gayah and Menendez, 2016).

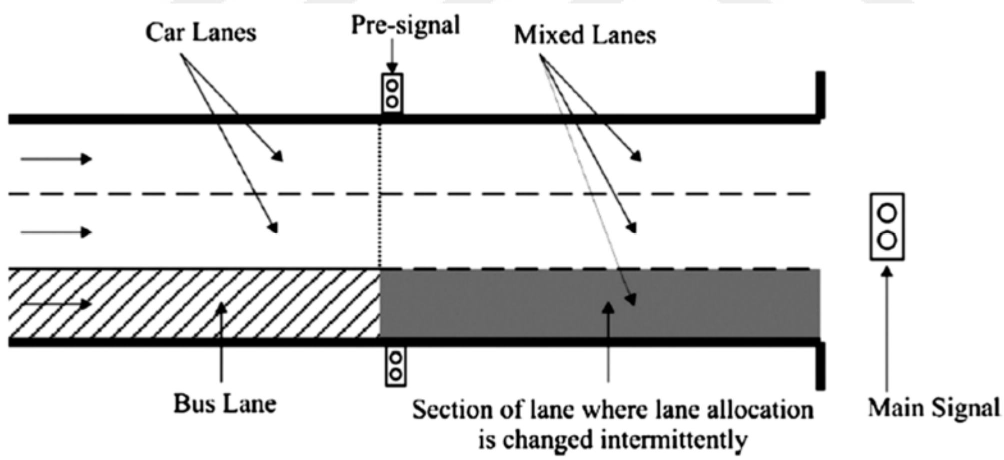


**Figure 2.3 :** Schematic view of pre-signal installation near to signalized intersection.

### 2.1.2 Spatial BP methods

The following sub-sections will examine spatial methods as an important aspect of BP, and consider the operational conditions in which they may improve traffic conditions. Since the world's first designated Exclusive Bus Lane (XBL) was created in Chicago in 1939 (APTA, 2008), more and more XBLs have been put into service to give priority to buses and save travel times in places where roads are congested with general traffic in both developed and developing countries.

In terms of implementation locations, XBLs fall into two main groups: those implemented on roads near junctions, and those implemented along roads themselves. These shall be examined further below.

#### 2.1.2.1 XBLs located near junctions

The allocation of exclusive spaces for buses near intersections so that they may proceed without delay regardless of traffic conditions, significantly increases the average speed and reliability of buses as well as reducing bus delays (Levinson, 2001; Levinson *et al.*, 2002, 2003). Types of XBLs located near junctions – sometimes combined with time-based priority methods – include;

- ✓ Right-turn lanes (virtual transit lane, right-turn pocket lanes, shared transit lane)
- ✓ Bus Queue jump lanes (QJL)
- ✓ Short Transit lane
- ✓ Dropped transit lane

**Virtual Transit Lane**

Virtual right-turn lanes permit right turns only when a transit vehicle is not present. When a transit vehicle approaches, right turns are prohibited (see Figure 2.4-a). Transit signals are triggered to allow transit vehicles to pass through the intersection.

**Right-turn Pocket**

Where right-turn volumes are high enough to interfere with transit operations but cannot be prohibited, providing a right-turn pocket to the right of the through transit lane reduces bus and streetcar delays (see Figure 2.4-b). This lane provides segregated space for right turns while giving priority to through-moving transit, and permits dedicated right-turn phases, potentially beneficial for pedestrian and bicyclist safety and operations at high-pedestrian intersections.

**Shared Transit/Right-Turn Lane**

On streets with a right-side segregated transit lane that accommodates a moderate volume of right-turn movements, the transit lane can permit right turns approaching an intersection (see Figure 2.4-c). At locations where right-turning vehicles can typically clear through the intersection quickly. This lane can accommodate moderate right-turn volumes at intersections where right turn on red is permitted and pedestrian volumes are low and can be applied to streets with or without segregated transit lanes. Shared transit/right-turn lanes allow vehicles to make right turns across a transit lane.

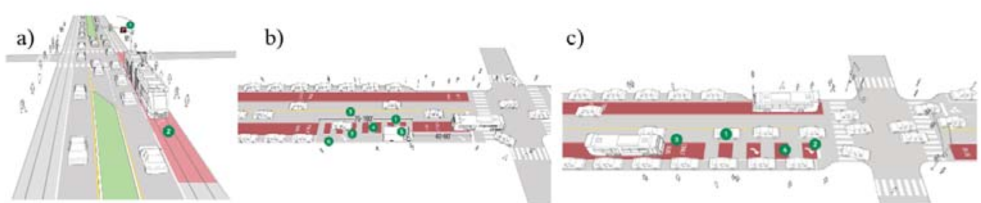


**Figure 2.4 :** A schematic view of (a) Virtual Transit Lane; (b) Right-turn pocket lane; (c) Shared transit/Right-turn lane (NACTO, 2016).

**Bus Queue Jump Lanes concept**

A QJL is a short bus lane at intersections which allows buses to travel in and then move forward from a left or right turning lane depending on left-hand or right-hand driving (see Figure 2.5-a), bypassing traffic queues in adjacent lanes (Danaher, 2010; NACTO, 2012; Farid, Christofa and Collura, 2015). QJLs consist of short, segregated transit facilities with either a leading bus interval or active signal priority that allows buses to enter traffic flow in a priority position. Delicately configurated queue jumping methods can reduce delays considerably, resulting in travel time savings and increased reliability. QJLs implementation requirements may vary according to municipality, but common thresholds include routes with an average headway of 15 min or less; when traffic volumes exceed 500 vehicles/hour in the curb lane during a.m. or p.m. peak hours; when the intersection operates at a level of service D or lower; and when cost and land acquisition are feasible (Townes *et al.*, 1998). To increase TSP effectiveness, this may be combined with spatial priority measures such as segregated BLs and QJLs. Previous studies have investigated the combination of TSP and spatial priority measures, such as TSP with segregated BL (Sakamoto, Abhayantha and Kubota, 2007; Ma, Liu and Han, 2013) or TSP with QJLs (Gan, 2009). Gan aimed to introduce a signal control designs for a QJL employing different simulation scenarios created in VISSIM (PTV, 2017) and evaluate the proposed method performance using results of general actuated mixed-lane TSP. The results of simulation models showed a 3-17% reduction in delay combining queue jump lane and near-side stop with active TSP compared to a far-side stop with TSP with no queue jump (Gan, 2009). In these studies, the combined effects are usually not compared with the individual effects of TSP or RSP measures. Recently, a micro-simulation study using VISSIM has suggested a possible cumulative effect from combining TSP with QJLs (Zlatkovic, Stevanovic and Reza, 2013). It is believed that this can reduce bus travel times by allowing buses to jump the car queues, and also eliminate the possibility for buses to conduct maneuvers that lead to run-ins with cars, leading to reduced car delays, too. The QJL-TSP approach here was located along thirteen locations with actuated-coordinated signalized intersection, except one intersection which was a free-running intersection. As a result, a 13–22% reduction in travel times and a 22% increase in bus speed was recorded in the case study area. In another study, micro-simulation models created in VISSIM were used to demonstrate that transit gains the greatest benefit from a full queue bypass lane approaching a far-side stop. As volume per capacity (V/C) ratio approaches 1.0, queue bypasses (greater than the length of the average traffic queue) with TSP become increasingly effective at reducing transit and general traffic delay (Bugg *et al.*, 2016). Moreover, in terms of the effects of TSP with segregated BL implication or TSP with QJL implication at multiple intersections, Troung et al. (2017a, b) found that a policy implication of both time-based and spatial priority can achieve better benefits for PT.

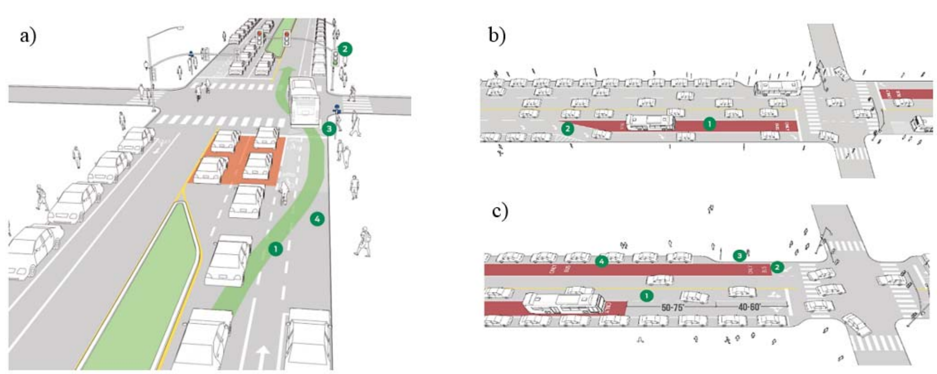


**Figure 2.5 :** A schematic view of (a) Queue jump lane (b) Short transit lane; (c) Dropped transit lane (NACTO, 2016).

**Transit Approach Lane/Short Transit Lane**

Short transit lanes on the approach to major intersections, sometimes paired with active signal priority, allow transit vehicles to bypass long queues that form at major cross streets. This method allows transit vehicles to bypass general vehicle queues and right-turn queues, as well as allowing separate signal phases or other accommodations to be made for right-turning traffic (see Figure 2.5-b).

Transit vehicles proceed into the approach lane without changing lanes, an advantage over combined right-turn/queue lanes – this is especially important for retrofitting existing streetcar lines, and reduces delays for both bus and rail.

**Dropped Transit Lane concept**

On narrow transit streets, mixed traffic is expected to use the transit lane both for right turns, and to occasionally divert around vehicles waiting to turn left. If enforcement is robust and/or automated, dropping the transit lane approaching an intersection can clarify which movements are permitted (see Figure 2.5-c).

The dropped transit lane will have a relatively low impact on transit operations, especially where the elimination of double-parking and curbside loading is more important for transit operations than eliminating intersection delay. Other vehicles may enter the transit lane to circulate around left-turning vehicles, but must re-join mixed-travel lanes after the intersection when segregated transit lanes resume.

#### 2.1.2.2 XBLs along roads

**Bus lanes based on implementation direction**

The first classification of XBLs along road segments is based on their direction with respect to the general flow direction. In this section, we are purposefully focused on the potential advantages and disadvantages provided by setting on bus lane parallel with general traffic direction hereinafter named with-flow and in opposite direction of general flow known contra-flow. Figure 2.6 shows the different types of contra-flow configurations of BLs, as indicated in red.

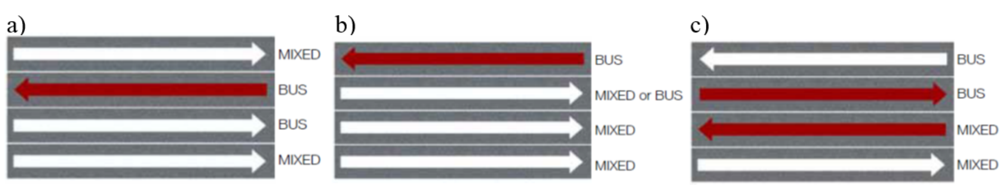


**Figure 2.6 :** (a) Offset contraflow bus system on a one-way street; (b) Curbside contra-flow bus lane; (c) median contraflow on a two-way street (Neves, 2006).

The potential advantages and disadvantages of both sorts of bus lane applications are noted in Table 2.1.

**Table 2.1 :** Advantages and disadvantages of bus lane in with-flow vs. contra-flow implementation.

| BL implementation direction | Potential Advantages | Potential Disadvantages |
|---|---|---|
| With-flow | • Possibility of authorizing other vehicles (e.g. Taxis, Shuttles or Emergency vehicles) to use it specific times,<br>• Travel time reduction,<br>• Gain in reliability,<br>• Energy related and environmental,<br>• Resulting in modal shift, | General traffic travel times increases because road capacity reduced (bus lane).<br>Failure of operating conditions in the surrounding area<br>Safety; interaction with adjacent general traffic or pedestrian flow.<br>Logistical changes; an effective loss in parking provision, loading and unloading that supports the commercial activity and the access provision to properties.<br>Higher level of enforcement (cost); using this lane by unauthorized vehicles or as an (illegal) parking option. |
| Contra-flow | • Travel time reductions; they allow buses to skip lengthily diversions,<br>• Possible reduction in passenger walking time to the bus stop,<br>• Service perception by changing the lane use from general traffic schemes into one-way ones,<br>• Lower level of enforcement; reduction in lane use by unauthorized vehicles or as an (illegal) parking option. | Mainly due to changes in the junctions that may deteriorate the circulating conditions for the traffic running in the opposing direction of the new scheme,<br>Structural (lane conversion, etc.) and operational (retiming and phase changes, permitted turns, etc.) changes at the intersections,<br>Travel time increases result in extra delays for the general traffic,<br>Safety; requiring good knowledge by different road users especially Pedestrian for preventing new conflicts & accidents,<br>Higher setting cost because of being one-way scheme (re-arrangements in junctions, re-signing, channeling works),<br>Loading/Unloading operations; the difficulty of considering a peak hour schedule for this type of lanes, which enables delivery vehicles to operate. |

**Bus lanes based on separation methods**

The second classification of XBLs along road segments is based on their separation methods. Bus priority, in terms of space allocation, generally involves giving the right of way to the bus along its travel route. Various forms of priority treatments fall under this category. In general, XBLs along road segments can be sub-categorized according to segregated BLs (i.e. highly reserved right of way like BRT) and non-segregated BLs (e.g. High-occupancy vehicle/toll lanes, bus shoulder lanes) described in following sections in detail. The most common BLs in developing countries are fully segregated BLs such as BRT systems, while non-segregated BLs are more common in developed countries where space is allocated for bus-use only.

**Segregated bus lane**

In the context of space-based priority schemes, the implementation of segregated BLs is one of the main bus priority measures used in urban areas particularly in developing countries where lane violations by unauthorized vehicles occur frequently, and can improve the efficiency of the transportation system overall by carrying more people with less space. The following are the most-common segregated BLs:

- ✓ Curbside segregated bus lane: At the edge of the road, fully segregated from the main road, completely or partly reserved for buses (e.g. some urban BL),

- ✓ Median segregated bus lane: Fully separated from main road, completely reserved for buses in the middle of the road (e.g. BRT, Light Rail Transit lanes),

By allocating exclusive road spaces to buses, BLs allow buses to continue unimpeded regardless of traffic conditions. However, Levinson (Levinson, 2001; Levinson *et al.*, 2003) found that the application of XBLs has a worsening effect on congestion in other lanes and systems. Moreover, segregated BLs waste road capacity in the event that bus departure frequency is not high. On the other hand, these measures are only appropriate when the total traffic flow is low enough to allow for a reduction of lanes open to general traffic; if it is possible to reroute adjacent traffic; or if it is possible to extend the road with additional lanes. Hensher (Hensher and Waters, 1994; Hensher, 1998) compared LRT and bus priority schemes such as Busway and HOV, and concluded that bus priority methods are capable of serving more passengers at lower cost compared to LRT. A combination of facility, system, and vehicle investments that increase the efficiency of the service for the end user is present in BRT. Appropriate and effective BRT strategies improve system performance, increase transit ridership, and improve air quality (Levinson, Adams and Hoey, 1975; Levinson, 2001; Levinson *et al.*, 2002, 2003). Bus travel speeds on fully segregated lanes have been empirically quantified for specific locations in the USA (Jacques and Levinson, 1997), and also standardized (Kittelson & Assoc Inc., 2013). The latter also quantifies the capacity of bus vehicles in mixed traffic (Kittelson & Assoc Inc., 2013). Bus Lanes/Bus Rapid Transit Systems on sub-urban corridors (e.g. highways) have been examined by Miller (2009), who notes that on-street bus facilities (placement of the curb bus lane or median ones), direction of flow (with-flow or contra-flow), mix of traffic (buses only, buses and taxies, buses and goods delivery vehicles, or mixed traffic flow with automobiles), and traffic controls (turn controls, parking, loading and unloading of commercial motor vehicles, and signalization) all showed widespread applicability due to their relatively low costs, ease of implementation, and opportunities for incremental deployment. Stewart and Wong (2013) proposed a "Guidelines for Planning and Implementation of transit priority measures in Urban Areas of Canada to improve the performance of transit system (transit travel time, travel time reliability, and/or safety). Despite BRT' success in many cities, success is still unproven in the context of small-to-medium-sized cities in developing countries.

A practical experience of BRT planning in Khon Kaen, Thailand shared by (Jaensirisaka, Klungboonkrongb and Udomsri, 2013) including study on the feasibility of the developing of a BRT Prototype in the city in order to alleviate transport related issues; collect necessary information and data required for undertaking the detailed design and construction of the BRT; and assess benefits of the BRT system. Al-Deek (Al-Deek *et al.*, 2017) technically examined the effectiveness of BRT with TSP and stated that BRT, with a conditional TSP three minutes behind, significantly improved travel times, average speed, and average total delay per vehicle for the main through movements compared with no BRT or TSP, with only minor effects recorded in terms of street crossing delays.

**Non-Segregated bus lane**

There are many forms of non-segregated BL applications with various types of configuration conditions used around the world that demonstrate that non-segregated BLs can be utilized in every position inside roads including curbside, offset, and median line. Following are the various types of non-segregated BLs, of which curbside non-segregated BL is common in inter-city roads, while HOV/HOT as median non-segregated BLs are mostly used in sub-urban corridors (i.e. expressways, highways):

- ✓ Curbside non-segregated bus lane: At the edge of road, with or without colored pavement (e.g. urban BL, sub-urban Bus on Shoulder Lane),
- ✓ Offset non-segregated bus lane: One lane away from the curb to allow for curbside parking (e.g. urban BL),
- ✓ Median non-segregated bus lane: Non-segregated bus lane in the middle of the road (e.g. sub-urban HOV/HOT lane)

In (HCM, 2000), it is noted that the passenger car equivalent of a bus traveling without making stops is estimated at about 2 that of passenger cars. However, for Type 2 BLs (partial use of the adjacent lane depending on use of this lane by other traffic), merging, weaving, and diverging movements can raise this equivalency by 3 or 4 or more. Princeton and Cohen (2010) presented a comparison between macroscopic simulation and on-site measurements of the implementation of a segregated lane on the A1 motorway near Paris, France considering the following items; I) Segregated lane's impacts on traffic conditions, II) Subsection capacity along the segregated lane initially, III) Traffic volumes on the segregated lane. The key findings of the study indicate the occurrence of a new bottleneck at the upstream end of the segregated lane shown by both simulation and on-site measurements with the same congestion pattern. Due to drivers' poor compliance with the operation - despite penalties - however, simulated travel times were lower than real ones. Before-After study results demonstrated a 3~10-minute travel time saving for a 200 veh/hr switch from the segregated to the general-purpose lanes. Agrawal et al. (2013) examined policies and strategies governing the operations of BLs in major congested urban centers where the BLs do not completely exclude other users. In general, nearly every city studied allowed all vehicles to use curbside bus priority lanes to make right turns (left turns in the cases of UK and Australia) and to access driveways on a given block. Taxies were universally allowed to use the lanes to pick up and discharge passengers. Several cities authorized bicycles and taxies to drive in bus lanes as well. Others (Burinskienė, Gusarovienė and Gabrulevičiūtė-Skebienė, 2014; Abdelfatah and Abdulwahid, 2017) studied the impact of XBLs configuration on the commercial speed of buses and traffic performance in the inter-city area and found that XBLs are effective at a demand per capacity ratio of 0.8 or more.

BSHL operations, also referred to internationally as bus by-pass shoulder operations, are considered a low-cost strategy permitting buses and/or disabled vehicles under emergency conditions to travel at or near free-flow speeds through congested arterial and freeway routes in order to bypass congestion (Martin, Levinson and Texas Transportation Institute, 2012). There are several examples of the BSHL applications in US cities including SR 52 in San Diego, Falls Church, Virginia, Miami, Florida, Seattle, Washington DC regions, Bothell, Minneapolis-St. Paul, Minnesota (using them since the 1990s and has over 300 shoulder miles) (FHWA, 2006) and other countries like Vancouver (Canada), Paris (France) during morning and evening peak periods (Miller, 2009; Thakuriah, Metaxatos and Mohammadian, 2014; Litman, 2015;

U.S. FWHA, 2017). According to US traffic rules and conditions, buses are authorized to use BSHL lanes when traffic is moving slower than 35 mph (c. 56 km/h). The benefits of implementing BSHL in the Chicago area were recorded immediately: on-time performance, for example, increased from 68% to nearly 95% since it had started in 2011. By mid-2013, the buses had roughly doubled their daily ridership, so Pace added new trips, including off-peak service (Litman, 2015). One of the most effective strategies of Active Traffic Management (ATM) in USA is called Dynamic Shoulder Lanes (DBSHL) by which the use of the shoulder enables as a travel lane(s) based on congestion levels during peak periods and in response to incidents or other conditions as warranted during nonpeak periods (Varaiya and Kurzhanskiy, 2010).

In contrast to a static time-of-day schedule for using a shoulder lane, an Active Traffic and Demand Management (ATDM) approach continuously monitors conditions and uses real-time and anticipated congestion levels to determine the need for using a shoulder lane as a regular or special purpose travel lane (e.g., transit only). For on-ramp locations, dynamic junction control may involve a dynamic lane reduction on the mainline upstream of a high-volume entrance ramp, or might involve extended use of a shoulder lane as an acceleration lane for a two-lane entrance ramp, which culminates in a lane drop.

Several studies have been conducted in order to investigate how non-segregated lanes, especially HOV lanes, impact traffic congestion in real terms. Menendez and Daganzo (Menendez and Daganzo, 2007) showed that HOV lanes may smooth flow through certain bottlenecks by dampening lane changing activity. On the other hand, Kwon et al. (Chen, Varaiya and Kwon, 2005; Kwon and Varaiya, 2008) found that single-HOV lanes suffer a 20% capacity drop and provided less time saving compared to adjacent general purpose lanes. The authors attributed these results, obtained from peak hour traffic data from 700+ loop detector stations installed on California's HOV system, to overtaking restrictions on such facilities.

Bus Shoulder Lane
(The Minneapolis/St. Paul region, USA)

Curbside segregated bus lane
(Istanbul's SBL, Turkey, 1979)

Curbside non-segregated bus lane
(Istanbul's NSBL, Turkey, 2012)

Offset non-segregated bus lane
(Albany, New York, USA)

Median non-segregated bus lane
(Albany, New York, USA)

Median segregated bus lane
(Istanbul's BRT, Turkey, 2007)

**Figure 2.7 :** Examples of different types of bus lane applications along road segments.

**Bus lanes based on operation type**

The last classification of XBLs along road segments is based on their operational condition which can be divided into two sub-classes; static- and dynamic-based operation. In static-based operation (e.g. median-segregated BRT lanes), BLs cannot be used by other vehicles even in low bus frequency condition resulting a non-feasible BP methods implementation while in dynamic-based operation, BLs can be used by other vehicles when buses do not exist along BLs as shown in Fig. 7. Most of spatial BP methods discussed in section 4.2 contain static-based operation conditions. It means, their usage by other vehicles is not allowed based on buses frequencies. This section is comprised of the Dynamic Bus Lane (DBL) concept and related topics. The main goal with DBLs is to utilize the existing infrastructure in order create the same benefits for bus service as with fully segregated BLs but with less impact on adjacent traffic. In other words, the goal is that the travel time and travel time variability of buses should decrease without the travel time and travel time variability for adjacent traffic deteriorating significantly. The method to achieve this is to only dedicate the bus lane for buses when they need it (Viegas and Lu, 1997).

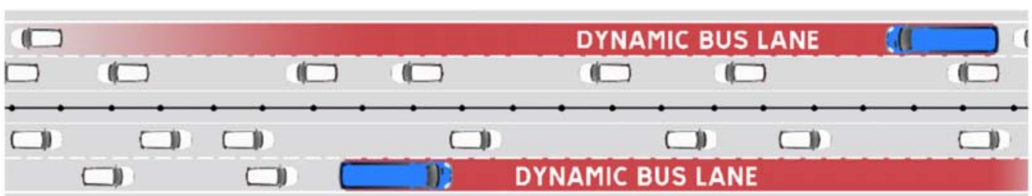


**Figure 2.8 :** An illustration of the dynamic bus lane concept (Olstam, Habibovic and Anund, 2015).

Joskowicz (2012) evaluated the feasibility of implementing a DBL system in Texas, USA to determine the particular conditions when the system could be applied to other arterial streets. Proposed regression models forecasted that the bus travel time would be reduced by 2.7% and 5.6% during morning and afternoon peak hours, respectively.

The HCM (HCM, 2010) methodology was used to assess the impact of the DBL system on other vehicles. Generally, the impact was that the DBL would cause the intersection level of service to drop by one level. However, the total system impact on other vehicles was much greater than the DBL benefits in terms of person-hour delay.

The sensitivity analysis of the intersection saturation levels versus the DBL benefits and impacts showed that the DBL system would perform ideally at or below the 90% saturation level. Also, it was found that because of the high level of traffic saturation on Westheimer road, Houston, US, it would be very difficult for vehicles to change lanes when the DBL system was activated.

The spacing between major intersections should be at least 9/10th of a mile to allow for lane-change maneuvers. The DBL system improved the transit levels of service for the test section by one level for both peak hours.

**Intermittent bus lane concept**

The total person hours of delay in the system can increase when segregated BLs are applied. However, it is possible to improve the system without harming buses by allowing cars to share the space between buses only at bottlenecks. These types of DBL allocations have been previously investigated and proposed by Viegas and Lu (Viegas and Lu, 1997, 2001, 2004; Lu and Viegas, 2003) as IBL. Simulation results for the IBL with transit priority showed that bus travel time would decrease by 30%, while the impact on the other vehicles would result in only a 3% increase in additional travel time. Field experiments in Lisbon, Portugal showed that the strategy can increase bus speeds by as much as 15–25%, compared to the mixing of buses and cars together in traffic (Viegas *et al.*, 2006). Similar experiments in Melbourne, Australia (Currie and Lai, 2008) and in Shizuoka, Japan (Rahman, Sakamoto and Kubota, 2007; Sakamoto, Abhayantha and Kubota, 2007) were similarly successful, but even though travel time improvements to buses were observed in Melbourne as well, the authors (Currie and Lai, 2008) observed that these improvements were not as remarkable as in the case of Lisbon. Using cellular automaton traffic flow model and the concept of PT priority, Zhu (Zhu, 2010) proposed a numerical study of urban traffic flow with segregated bus lane and IBL. He found that IBL is only appropriate for low general traffic flow at the adjacent lane in a two-lane road. Zyryanov and Mironchuk (2012) simulated IBL and the TSP strategy under various volumes of background traffic using AIMSUN for two and three-lane inter-city roads. The simulated case study area was a three-lane one-way street with a length of 1 km, two signalized intersections, max. traffic volume of 2500 veh/hr, and bus frequency of 20~30 buses/hr depending on time of day. Study concluded that there were different speed changes of general traffic and buses at the increase of the traffic volume for standard BLs and IBL.

**Bus lanes with intermittent priority concept**

For the implementation of one variation of this IBL, referred to as bus lanes with intermittent priority (BLIP), cars are required to vacate their present lane in advance of an approaching bus. Eichler and Daganzo (2006) discovered that the application of BLIPs reduces the interaction between buses and cars, and that this can significantly reduce bus delays (Eichler, 2005; Eichler and Daganzo, 2006; Todd *et al.*, 2006). Considering Eichler's finding (Eichler, 2005), the difference between the BLIP and the IBL concept is that the BLIP does not rely on TSP to flush the vehicle queues in front of the bus, as the IBL does. The BLIP modelled as a "moving bottleneck," which creates long-lasting queues that propagate upstream when traffic demand is at capacity.

The effect of the BLIP on long roads and short roads investigated using flow-density diagram in a steady state. They also determined that TSP can enhance the BLIP operation, but be potentially disruptive to autos. Based on their theoretical work, they recommended a qualitative ranking of rough domains of application as follows: Use of segregated BLs with or without TSP when traffic demand is less than 80% or 90% of the capacity of the reduced lane system; Use of BLIP systems with or without transit signal priority when the traffic demand is close to the capacity of the reduced lane system; Use of transit signal priority alone, with queue-jump lanes if possible, when the traffic demand is over 120% of the capacity of the reduced lane system (Eichler and Daganzo, 2006).

Chiabaut et al. (2012) and Xie et al. (2012) theoretically analyzed the capacity of BLIPs while also taking into account capacity drops that might arise due to the merging and acceleration of lane-changing vehicles at the first signalized intersection of an arterial where BLIPs are implemented. The authors concluded that this activation effect can be negated if the signalized arterial on which BLIPs are implemented is long enough (i.e., consists of 6 or more intersections). Beyond this length, travel time benefits to buses can be expected with the implementation of BLIPs.

Taking the connected vehicle (CV) environment into consideration, Wu (Wu *et al.*, 2017) evaluated operational effects of BLIP and concluded that configuration BLIP under the CV environment is applicable considering reasonable bus departure interval, clear distance and traffic.

As a conclusion, Table 2.2 presents minimum requirements in order to implement spatial BP methods each based on their design, planning, and operational conditions. In which, the column entitled “right of way” is referred to the interaction between BLs with adjacent general traffic which is consists of segregated (S) and non-segregated (NS). Safety level of the BP schemes is presented in the next column noted by L, M, H, refer to Low, Medium, and High levels of accident severity.

Two important BL performance measures and decision-making criteria for policy implication include the minimum bus frequency and average bus speed which are mentioned in column 4 and 5. “V/C rate” and “right turn rate” are also two most important factors contributing in successful operation of BLs which are noted in the next two columns labelled.

As found in the existing studies, high V/C and right-turn rates in adjacent mixed traffic lane cause increasing interaction between buses and other vehicles, particularly in non-segregated types of BLs. It might cause a reduction in BL capacity and safety level.

Required ITS equipment such as detectors, signals, variable message signs (VMS), enforcement and cameras (EDS) are determined as well. The last four columns indicate the location and direction of BLs in which the first two are related with the application of BLs in inter-city or suburban corridors and the two former ones are related to direction of bus movements in parallel with general flow or contra-flow.

Developing countries like Turkey have different driving behaviors, road network size and complexity compared to developed countries. Therefore, minimum requirements regarding bus frequency, avg. bus speed, V/C rate, and right-turn rates to implement spatial BP schemes which are unknown could provide the subject of potential research topics for future studies.

Moreover, a summary of pros and cons of temporal and spatial BP methods is presented in Table 2.3. Table 2.4 also summarizes the benefits of bus priority for a range of cities around the world. It shows some variation in the benefit criteria and also some degree of variability in the levels of benefit between different cities. It should be noted that these benefits are often affected by the policy adopted rather than the capability of the system. For example, in London, the policy is to provide bus priority with minimal impact on other traffic. Given the high levels of bus flow and congestion in London, this means that priority has had to be constrained (Gardner *et al.*, 2009).

**Table 2.2 :** Minimum requirements in order to implement spatial BP methods.

| No. | Spatial bus priority methods | Right of Way | Safety | Bus Frequency (Bus/hr.) | Ave. Bus Speed (kph) | V/C rate of adjacent lane | Right-turn rate in adjacent lane | ITS needs | | | | Location & Direction (vs. general flow) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | VMS | Detector | EDS | SP | Non-highway | Highway | With flow | Contra flow |
| 1 | XBLs near to junctions | | | | | | | | | | | | | | |
| 1.1 | Right-turn Lane (Pocket) | NS | L | - | N.A | N.A | H | - | - | - | - | ● | - | ● | - |
| 1.2 | Virtual Transit Lane | NS | H | M | N.A | N.A | Semi-permitted | ● | ● | ● | ● | ● | - | ● | - |
| 1.3 | Shared Transit Lane | NS | M | N.A | N.A | N.A | M | - | - | - | ● | ● | - | ● | ○ |
| 1.4 | Queue Jump Lane | NS | M | < Bus/15’ | N.A | > 500 veh/hr | Protected right-turn | - | - | - | ○ | ● | - | ● | ○ |
| 1.5 | Short transit Lane[1] | NS | H | M | N.A | N.A | H | - | - | - | ○ | ● | - | ● | - |
| 1.6 | Dropped Transit Lane[2] | NS | H | L | N.A | M | M | - | - | - | - | ● | - | ● | - |
| 2 | XBLs along roads | | | | | | | | | | | | | | |
| 2.1 | BRT (Median lane) | S | H | >20-90 | N.A | M | - | - | - | - | ○ | - | ● | ○ | ● |
| 2.2 | HOV & HOT | NS | L | >20 | N.A | M | <200 v/h | ● | - | ● | - | - | ● | ● | - |
| 2.3 | Curbside BL | NS - S(○) | M | >20 | <15 | M | <100 v/h | ● | - | ● | ○ | ● | - | ● | ○ |
| 2.4 | Bus Shoulder Lane | NS | H | N.A | <55 | N.A | L | - | - | ● | - | - | ● | ● | - |
| 3 | Dynamic Bus Lane | | | | | | | | | | | | | | |
| 3.1 | IBL | NS - S(○) | M | <40 | N.A | L, M | N.A | ● | ● | ● | ○ | ● | ○ | ● | - |
| 3.2 | BLIP | NS - S(○) | M | <40 | N.A | L, M | N.A | ● | ● | ● | ○ | ● | ○ | ● | - |

● Essential criteria, ○ Optional criteria, N.A: Information is Not Available.

* V/C ratio; Low: L (V/C ≤ 0.3), Medium: M (0.3 < V/C < 0.8), High: H (V/C ≥ 0.8).

[1] Especially where a right-turn/queue jump with signal priority is not practical such as locations with long right-turn queue.
[2] Especially where the elimination of double-parking and curbside loading is more important for transit operations than eliminating intersection delay.

**Table 2.3 :** Summary of pros and cons of temporal and spatial BP methods.

| No. | Bus priority method | Advantages | Disadvantages |
|---|---|---|---|
| 1 | Time-based methods | | |
| 1.1 | Signal Priority | • Reduces delay,<br>• Improves reliability, | • Risks interrupting coordinated traffic signal operation,<br>• Risks lowering intersection LOS if intersection is close to capacity,<br>• Requires ongoing inter-jurisdiction coordination,<br>• Buses on cross streets may incur added delay greater than the time saved by the favored route, |
| 1.2 | Pre-signal Priority | • Recover the lost time at the intersection due to bounded acceleration,<br>• Separate left-turning vehicles and through-moving vehicles to maximize the discharging capacity of the intersection for both directions,<br>• Minimize negative bus–car interactions at signalized intersections,<br>• Provide priority to buses using the opposite lane, | • In cycles where buses are not present, the car delay will remain the same as in the case of mixed-use lanes, but the number of stops experienced by cars may increase,<br>• Risks losing the main signal capacity,<br>• Applicable only in under-saturated traffic condition and sometimes where the segregated bus lane is available, |

**Table 2.3 (continued) :** Summary of pros and cons of temporal and spatial BP methods.

| No. | Bus priority method | Advantages | Disadvantages |
|---|---|---|---|
| 2 | Spatial methods | | |
| 2.1 | Queue Bypass | • Reduces delay from queues at ramp meters or other locations, | • Bus lane must be available and longer than the back of the queue, |
| 2.2 | Queue Jump | • Reduces delay to queues at signals,<br>• Buses can leapfrog stopped traffic, | • Bus lane must be available and longer<br>• than the back of the queue,<br>• Right-turn or special transit signal required,<br>• Reduces green time available to other intersection traffic,<br>• Bus drivers must be alert for the short period of available green time, |
| 2.3 | Curb Extensions | • Reduces delay due to merging back into traffic,<br>• Increases riding comfort because buses do not need to pull in and out of stops,<br>• Increases on-street parking by eliminating need for taper associated with bus pullouts,<br>• Increases space for bus stop amenities,<br>• Reduces pedestrian street crossing distances, | • Requires at least two travel lanes in bus direction of travel to avoid blocking traffic while passengers board and alight,<br>• Bicycle lanes require special consideration, |
| 2.4 | Boarding Islands | • Increases bus speed by allowing buses to use faster-moving left lane, | • Requires at least two travel lanes in bus direction and significant speed difference between the two lanes,<br>• Requires more right-of-way than other treatments,<br>• Pedestrian and disabled people accessibility, comfort and safety issues must be carefully considered, |

**Table 2.3 (continued) :** Summary of pros and cons of temporal and spatial BP methods.

| No. | Bus priority methods | Advantages | Disadvantages |
|---|---|---|---|
| 2.5 | Parking Restrictions | • Increases bus and auto speeds by removing delays caused by automobile parking maneuvers, | • May significantly impact adjacent land uses (both business and residential),<br>• Requires ongoing enforcement, |
| 2.6 | Bus-Stop Relocation | • Uses existing signal progression to bus advantage, | • May increase walking distance for passengers transferring to a cross street bus, |
| 2.7 | Turn Restriction Exemption | • Increases bus speed by eliminating need for detours to avoid turn restrictions, | • Potentially lowers intersection LOS,<br>• Safety issues must be carefully considered, |
| 2.8 | Exclusive BLs | • Increase bus speed by reducing sources of delay,<br>• Improves reliability,<br>• Increases transit visibility, | • Traffic and parking effects if eliminating a travel or parking lane must be carefully considered,<br>• Requires ongoing enforcement,<br>• Requires additional space for boarding islands once BRT modes implemented, |
| 2.9 | Dynamic Bus Lane | • Applicable when and where the buses need spatial bus priority, and otherwise open for all vehicles to use in order to create the same benefits for buses as with segregated BLs but with less impact on adjacent traffic,<br>• Decreasing travel time and travel time variability of buses without deteriorating significantly the adjacent traffic, | • Only applicable where the V/C rate of adjacent lane is too low otherwise it would be very difficult for vehicles to change lanes when the DBL system is activated,<br>• DBL would cause the intersection level of service to drop one level,<br>• Risks of crashes between bus and general traffic increased because of lane-changing maneuver, |

**Table 2.4 :** BP methods benefits and impacts around the world (Gardner *et al.*, 2009).

| City | Benefits and impacts on bus transport | | | | Impacts on general traffic |
|---|---|---|---|---|---|
| | Delay Saving | Travel Time | Variability | Patronage | |
| Aalborg | 5.8 sec/bus/jun | 4% reduction in average | | | |
| Genoa | | 7-10% reduction | | | |
| Cardiff | | 3-4% reduction | Improved schedule adherence | | 1-2% increase |
| Gothenburg | | 13-15% decrease | | | 5-10% savings |
| Helsinki | | 11% reduction | | 11% increase | |
| Stuttgart | | Speed increased from 9 to 10.1 miles/hr | | 10% increase | |
| London | 9 sec/bus/jun at isolated and 3-5 sec/bus/jun at SCOOT junctions | | | | |
| Auckland | 11 sec/bus/jun | | | | |
| Sydney | | up to 21% reduction | Up to 49% reduction | | |
| King County | 25-34% | reduced by 5.5-8% | Reduced by 35-40% | | Minimal effect |
| Los Angeles | | reduced by 6-8% | | Increased by 1-13% | Typically, 1 sec/veh/jun |

As implementation recommendations, it is worse to say that implementation location (intersection or along a street), existing infrastructure, traffic pattern (i.e. driving behavior) and condition (i.e. V/C ratio), and project budget are the most influenced factors for choosing one specific BP scheme. Thus, urban transport policy makers in developing countries have to carefully evaluate the compatibility of their local conditions with consideration noted in Table 2.2 and 2.3. Although it is not appropriate to recommend one specific BP scheme as the best method for a specific location, some points can be proposed based on the traffic pattern of potential cities for BP implementation. For instance, in developing countries with densely populated cities where illegal vehicle parking and right-turning maneuvers along BL observed frequently, it is strongly recommended to take items 2.5, 2.6, and 2.7 of Table 2.3 into account before implementation of BL project. In these countries, implementation of some BP scheme (i.e. dynamic bus lane) as unsegregated curbside BL cannot be feasible and successful because of their high V/C rate at the adjacent lane. In contrast, implementation of DBL and time-based BP scheme noted in items 1.1, 1.2 can be feasible in developed countries where traffic pattern, driving behavior, the obedience of traffic rules and signs as well as existing ITS infrastructure is better than developing countries.

By taking all above-mentioned arguments into consideration, and conducting an extensive review of transit-preferential treatments used around the world, it appears to be essential for transit policy-makers in developing countries to be aware of possible advantages and disadvantages of each measure as well as their implications requirements before choosing a specific bus priority schemes for their potential area of study. This fact has confirmed the need for a precise evaluation procedure to select the best-matched treatments based on local operational characteristics which would be impossible without making a comparative analysis of various types of bus priority methods. The proposed Tables 2.2 & 2.3 address the limitation of literature in this regard as well as helps the designers and planners to be fully aware of pros, cons and requirements of each bus priority schemes in making decision and planning stages.

## 2.2 Most Influencing Factors in the Failure of Spatial BP Methods

As noted, BP methods have become the most commonly adopted measures to ensure bus transport efficiency. However, in some cases, BP methods' operation faces various challenges. These challenges are clustered into five main groups of factors that must be considered in order to achieve a successful BP project which are discussed below:

- ✓ legal and regulatory aspects,
- ✓ design and technical issues,
- ✓ operational conditions,
- ✓ safety, and
- ✓ user behavior.

In this section, first, these five groups of important factors will be discussed. Then a comprehensive guideline will be proposed in order to bridge the existing gap in the literature.

### 2.2.1 Legal (regulatory) aspects

The success of newly-implemented BL projects, especially in developing countries, strongly depends on legislation that should answer the questions:

- ✓ Who is responsible for planning, who is responsible for implementation, and who for the operation of the BLs?
- ✓ Who is responsible for monitoring/enforcing BLs?
- ✓ Which road users can utilize BLs?

The conditions and areas of responsibility for planning, implementing, operating, monitoring, enforcing and using BLs should be well-defined in law in a nationwide context in order to prevent conflicts of interests occurring between stakeholders. Thus, each entity or organization ought to be aware of their responsibilities as well as the interrelations between one another and external parties in implementing the new policy. For instance, in the existing traffic regulation in Turkey (Turkish Legislation Office, 1997), there is no articles regarding BL settings, operation, enforcement conditions, and penalties for violators. Thus, relatively weak BL enforcement results in an increasing number of violations, leading to deterioration in operational effectiveness and levels of passenger safety.

### 2.2.2 Design, technical and operational issues

A range of design and technical aspects must be considered in order to ensure that BLs are designed for optimal performance. For instance, narrowing the driving lane with the aim of dedicating one lane exclusively for buses decreases the lateral gap between vehicles in adjacent lanes. It should be noted that the number and width of lanes directly influence the behavior of road users in terms of passing/overtaking, and affects the ability to keep the lateral safety distance (Yousif, Nassrullah and Norgate, 2017). BL planners/designers should also bear in mind that pedestrians/cyclists perceive BLs as relatively safer than general traffic lanes to walk/cycle on because of the low frequency of buses. In Istanbul's BL projects, pedestrians or cyclists tried to use the BL to avoid pedestrian/bicycle queues in densely crowded areas; therefore, the separation measures between the BL and sidewalk/bikeway should also be considered carefully during the design stage. The interaction between buses and cyclists moving along the BL is another significant issue. Finally, a larger number of pedestrian crossings decreases the service level and capacity of the BL (Ryus *et al.*, 2016).

The distance between two successive access and exit points along curbside BLs (from/to small streets, alleys, etc.) is another limiting factor impacting the efficiency of curbside BLs, and must be acknowledged at the design stage. Knowledge of the number and location of carparks and goods delivery bays, especially in commercial areas, is also important in order to minimize private car and delivery drivers' violations. The location and capacity of bus stops should also be considered in detail (Kittelson & Assoc Inc., 2013).

Consideration of traffic control measures such as signals, variable message and other signs, and additional ITS infrastructure should also inform BL design. Prioritizing the movement of buses along streets, at junctions, optimizing the no. of bus routes sharing the same BL and stops, and strategies to optimal use of stops (*e.g.* stop skipping) can highly improve the operational speed, travel time, and delays of buses. Giving priority to buses may increase travel time and delay for mixed traffic at adjacent lane along the streets as well as at junctions (Jacques and Levinson, 1997).

BL-related operational policies typically encompass the need to minimize the impact on the surrounding traffic environment, to reduce bus travel time, to improve bus service reliability, to increase passenger safety and bus service visibility, and to reduce the operating costs (Neves, 2006). As most of the recent research summarized by Cesme *et al.* (2018) focus on BL evaluation in the United States, UK, and EU countries, their findings require critical assessment and/or adjustment to account for the differences between developed and developing countries explained at the beginning of the section.

### 2.2.3 Safety

Bus lane safety issues require a cross-sectional analysis covering legal aspects, evaluation of design and technical parameters, operational conditions, and road user behavior. Risk factors for crashes are directly or indirectly associated with one or a combination of these factors.

Traffic accidents generally occur due to design and operation errors (Chimba, Sando and Kwigizile, 2010; Kim *et al.*, 2012; Currie *et al.*, 2014; Tse, Hung and Sumalee, 2014; Ye *et al.*, 2016; Mangones, Fischbeck and Jaramillo, 2017) and/or road user errors or violations (Clabaux, Fournier and Michel, 2014; Duduta *et al.*, 2014; Donoughe and Katz, 2015; Verma *et al.*, 2017).

### 2.2.4 Road user behavior

In this study, we refer to authorized and unauthorized BL user behaviour. Most national legislations authorise buses, emergency vehicles, minibuses, and taxis to use bus lanes, while prohibiting other road users such as private cars, cyclists, and pedestrians, especially during operating hours. As discussed in previous sections, the utilization of BLs by these unauthorized users has adverse effects on authorized BL users in terms of both travel time and safety. Thus, the management and effective monitoring/ enforcement of BLs can play a vital role in their success.

In Istanbul, for instance, despite the operation of automated and human surveillance systems, a large number of unauthorized user violations (e.g. lane-changing manoeuvres, overtaking, right turn movement, parking, and jaywalkers) occurred, resulting in safety issues and accidents as authorized and unauthorized users interacted.

All these factors are grouped and shown in Figure 2.9 must be taken into account in order to have a successful BL.

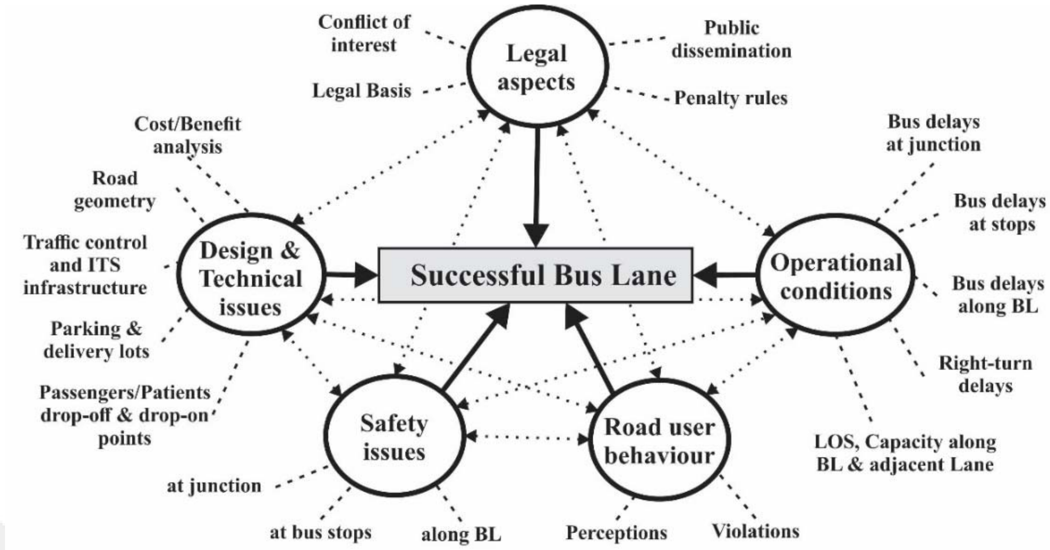


**Figure 2.9 :** Influencing factors in successful BL implementation.

The challenges facing the successful implementation of new PT initiatives in developing countries appears greater when compared to developed countries. These challenges derive from differences between developed and developing nations in terms of the nature and volume of their traffic (*i.e.,* traffic composition), the relative size and complexity of their transport networks and urban populations, their existing infrastructure, governmental and municipal policy frameworks, land value and lane pressure issues mainly in the central business district, and driver behaviors and user perspectives.

In addition, budgetary support for such projects may vary significantly among developed and developing countries. From the design and planning stages to the operation and monitoring stages, the proper implementation of BL projects requires adequate levels of funding from relevant state agencies.

Table 2.5 present a summary of the discussion of challenges in implementing bus lanes, and how these can be addressed. The main factors and corresponding challenges are noted in columns 1 and 2 respectively. Relevant suggestions and best practices for improving the applicability of BLs methods are summarized in the third column. Detailed information related to the suggested solutions can be found in the studies listed in the fourth column.

Because these components interact, they must be examined in advance and should be well managed throughout the implementation of the BP. Within each group of factors, the relevant challenges, suggestions or proposals for the solution are listed together with existing best practices and their supporting references, where further insight can be gained. Taking the above-noted arguments into consideration, decision-makers and urban transit planners can achieve successful BL projects; however, the efficiency of any BL may decrease over time due to increased demand, or lack of maintenance. Existing BLs should thus be systematically and periodically monitored to ensure their long-term success.

It should be noted that some planners and designers in developing countries like Turkey have adopted data/standards/formulas from developed countries, which might not meet local requirements or account for local traffic characteristics. These may result in the unwarranted or unsuccessful BP projects described in sections above. Therefore, I recommend a greater focus on determining the required design, implementation, and operational conditions for BP projects, based on each uniquely-configured national context before using the suggested solutions and best practices.

**Table 2.5 :** Summary of challenges and the best practices associated with bus lanes.

| Factors | Challenge | Solutions | More detailed implementation information can be found: |
|---|---|---|---|
| **Legal (regulatory) aspects** | Conflicts of interest | • Inclusion of BL-related laws in "National Traffic Law" specifying design, implementation, operational, monitoring, and enforcement regulations and the responsibility of each entity in order to prevent conflicts of interest. | ODOT, 2013; Gómez-Lobo and Briones, 2014; Hernández and Mehndiratta, 2015 |
| | Public recognition of and adherence to laws (Penalty Charge) | • Dissemination of the rules and ensuring respect for the rule of law.<br>• Encouraging responsible entities to allocate the budget collected from penalties to improving BL enforcement facilities.<br>• A cumulative penalty system for violators, *i.e.,* establishing separate (higher) penalty/fine amounts for repeat offenders. | Essex County Council, 2017; Liverpool City Council, 2014; Mckibbin, 2014; Roisman and Koudounas, 2017; TfL, 2008; The NZ Transport Agency, 2010 |
| **Design & Technical issues** | Cost/Benefit Analysis | • Conduction of a comprehensive cost/benefit analysis before the implementation of potential BL projects.<br>• Evaluation of effects of curbside BLs on general traffic compared to dedicated BLs and normal mixed lanes. | Ang-Olson and Mahendra, 2011; Litman, 2015; The NZ Transport Agency, 2010 |
| | Design of BL (road geometry and bus stop locations) | • Avoid designing on-street bus stops, and construct separate bus bays.<br>• Analyse optimal no. of stops, the distance between stops, and distance of stops to junctions *e.g.* average stop spacing for local bus services might be 250 - 350 m while in case of BL implementation, it might be 700 - 1 000 m.<br>• Analyse road lane width in relation to lateral distance and safety issues. | Gardner, 1991; TRRL, 1993a; Danaher, 2010; Wang *et al.*, 2013; Cunradi *et al.*, 2016; NACTO, 2016 |
| | Large no. of successive junctions, merging and diverging points | • Avoid implementing BLs along roads with a large number of access and egress points to BL, due to the short distance between successive junctions. Because of short spacing between two successive access/egress, the monitoring of BL by surveillance cameras may result in mistakes in issuing fines for merging/diverging vehicles as they would have recognised as BL violators. This problem is observed in Istanbul's BL in 2012 where the distance between successive access/egress points was on average 100 m. | |
| | High-rate of right-turn, High-rate of buses | • Introduction of right-turn pockets and dropped transit lanes.<br>• Introduction of queue jump lane at junctions. | Dadashzadeh and Ergun, 2018; NACTO, 2016 |
| | Location of carpark and goods delivery bays | • Appropriate estimation of the number & location of parking and goods delivery points in central business districts (can be designed as extra space between BL and sidewalk).<br>• Restriction of on-street car parking and goods delivery during BL operation hours. | DfT, 2015 |
| | Traffic control and ITS infrastructure | • Optimal junction design (signalised/unsignalised) considering BL configuration with or without TSP & pre-signal priority.<br>• Installation of VMS and other required devices in dynamic BL settings.<br>• Enhancing visibility at night by improving street lighting, illuminating road markings, and traffic signage, and maximising the visibility of buses themselves.<br>• Continuous enforcement using cameras on buses and/or fixed enforcement cameras; the rotation of fake enforcement devices may increase enforcement domains without significantly increasing system costs. | Currie and Lai, 2008; Danaher, 2010; Guler and Menendez, 2014; H. J. Kim, 2003; NACTO, 2016 |

**Table 2.5 (continued) :** Summary of challenges and the best practices associated with bus lanes.

| Factors | Challenge | Solutions | More detailed implementation information can be found: |
|---|---|---|---|
| **Operating conditions** | Bus delays at junctions, right/left turning | • Permitting through-movements at some intersections on transit lanes where automated enforcement is tied to the lane design may be appropriate.<br>• Restricting right-turn for general traffic along BL.<br>• Establishment of dropped transit lanes to alleviate mixed-traffic delay and congestion at pinch points by permitting through-moving vehicles to merge right and bypass left-turning vehicles.<br>• Stops should be located far enough from junctions and midblock stops to minimize the effects of right-turning traffic on bus speeds when buses can use the adjacent lane. It is also recommended to relocate bus stops of near-side of the junction to far-side depending on existing queue length in particular in TSP-based junctions in order to decrease the variation of bus's arrival time to the signals.<br>• Using protected left-turn (high demand) signal phase on centre-lane BLs. | Jacques and Levinson, 1997; Weinstein Agrawal, Goldman and Hannaford, 2013; Cesme, Altun and Lane, 2015; NACTO, 2016 |
| | Bus delays at stops | • Reduction of passenger dwell time at bus stops using new fare collection systems, wide multichannel doors, low floor buses, and sufficient main interchange stations to distribute commuter loads.<br>• Reduction of variations in dwell time by separating local and express bus stops where each service may have widely different dwell times, especially during peak hours.<br>• BL speed and travel time enhancement by providing skip-stops services where buses stop only at pre-defined stations not at all stations along BL considering the availability of adjacent lane (possible if the V/C ratio is $<0.8$).<br>• Relocation of bus stops along the main arterials, especially in crowded areas based on the required stop spacing mentioned above. | Gardner, 1991; Gu and Cassidy, 2013; Liu, Yan, Qu, and Zhang, 2013; Nesheli *et al.*, 2015; Peña and Moreno, 2014; TRRL, 1993a |
| | Bus delays* along BL | • Prohibition of illegal car parking and goods delivery along BLs.<br>• Reduction in the number of pedestrian-only crossings and replacing them with footbridges.<br>• Restriction of merging flows from streets and alleys into BLs.<br>• Using trunk-and-feeder operations instead of conventional bus network operations to decrease no. of bus routes along BL. | Gardner, 1991; Liverpool City Council, 2014; TRRL, 1993a; X. Ye and Ma, 2013 |
| | BL & adjacent lane LOS and capacity | • Calculation of LOS, travel time, delay, and capacity both for BL and general adjacent lanes, for several variants. | Jacques and Levinson, 1997; Ryus et al., 2016 |

**Table 2.5 (continued) :** Summary of challenges and the best practices associated with bus lanes.

| Factors | Challenge | Solutions | More detailed implementation information can be found: |
|---|---|---|---|
| **Safety** | Crashes at stops | • Widening and lengthening of bus stop areas for decreasing sideswipe and rear-end crashes between buses and between buses and the station platform.<br>• Design of safe median waiting areas to raise pedestrian safety levels.<br>• Raising bus passengers' awareness of safety rules (boarding, alighting, seatbelts, etc.). | DfT, 2007; Donoughe and Katz, 2015; Duduta et al., 2014; Tse et al., 2014; Z. Ye et al., 2016 |
| | Crashes along BL | • Introduction of physical separation (fully or selected) between the BL and other lanes to prevent interaction between buses and other road users.<br>• Introduction of passing facilities and safe overtaking zones to reduce risky overtaking manoeuvres.<br>• Construction of adequate footbridges, especially in dense central business districts to prevent jaywalking.<br>• Increasing sidewalk width to prevent pedestrians from using curbside BLs to avoid densely-crowded sidewalks<br>• Prohibition of bike riding on BLs.<br>• Avoiding the configuration of contra-flow BLs (in Mexico City this correlated with a 55% increase in vehicle collisions and a 39% increase in pedestrian crashes and Porto Alegre correlated with a 74% increase in vehicle collisions. | |
| | Crashes at junctions | Restriction of right and/or left turning for general traffic along curbside BLs. | |
| **Road User Behaviour** | User perceptions & complaints | • Dissemination of information about new BL projects, changes in legislation<br>• Surveying and monitoring the views of daily users of the relevant road segment (*e.g.* PT drivers & users, emergency vehicle drivers and general vehicle users) before, during and after the implementation of the bus lane. | The NZ Transport Agency 2010 |
| | User violations (disobedience) | • Penalisation of bus drivers for illegal overtaking, overloading, accepting passengers outside designated stops, speeding and using handheld devices while driving.<br>• Penalisation of bus operators for timetabling excessively long driver shifts (more than 12hr with no days off). Obligatory provision of co-drivers to prevent fatigue-related crashes.<br>• Enforcement of penalties for paratransit drivers (*e.g.* taxi, minibus) stopping illegally to alight and board passengers standing in the curbside BL.<br>• Prohibition of pedestrian mid-crossings through BLs, or jaywalking in the curbside BL<br>• Penalisation of itinerant traders using curbside bus lanes to move or sell goods<br>• Fines for unauthorised users traversing BLs illegally *e.g.* lane-changing near junctions), or using the BL for overtaking/queue jumping. | Gavanas et al., 2013; Jayatilleke et al., 2010; Kepaptsoglou et al., 2011; Lim, 2017; Liverpool City Council, 2014; Weinstein Agrawal et al., 2013 |

*During BL operation hours only (morning and evening rush-hours)

# 3. BUS PRIORITY SCHEMES IN ISTANBUL

With a population of 15.67 million, Istanbul is home to around 18.5% of Turkey's population, making it by far the nation's largest city (TUIK, 2018a.). Car ownership in Istanbul is around 228 vehicles/1000 inhabitants and the number of registered vehicles is 3.38 million (TUIK, 2018b.). Istanbul is one of the top ten most congested cities worldwide, one of the three most congested cities in Europe, and the most congested city nationally (INRIX, 2017; TomTom, 2018). Istanbul also ranks 5th among 50 cities measured for levels of noise pollution considering traffic congestion as one of the most influencing factor (World Economic Forum, 2018).

In Istanbul, 38% of road trips are taken by private car, compared to 62% for PT. In the PT sector, road-based systems such as bus (29.2%) and paratransit (48.8%) serve far greater numbers of daily passengers compared to rail-based and sea-based systems, which hold shares of 17.6% and 4.4% respectively (IMM, 2017). Accordingly, bus and paratransit modes have a very important role in the daily trips of inhabitants, indicating the requirement to focus more on buses in order to maximize public transport efficiency.

In Turkey, where urban rail systems (*e.g.* light rail transit and tram) cross junctions, the most widely used measure is TSP. In addition to rail systems and for prioritizing bus movement, spatially-based BP schemes were introduced in some cities and also in Istanbul between 1979 and 2012. Istanbul's spatially-based BP schemes are as follows:

1. The first BLs (known as PT-preferential routes) ran in central Istanbul from 1979-2001.
2. After many years, a median fully-segregated BL, known also as the "Metrobus", was introduced in 2007.
3. The latest BL projects were implemented in 2012 and have not been operational since 2013.

Figure 3.1 illustrates all BP methods implemented in Istanbul since 1979. In Figure 2.3, The green line shows the first BL (1979) while the blue lines depict other BLs (2012) now defunct. The only active bus priority method, Metrobus, is highlighted by red color.


**Figure 3.1 :** BP priority schemes in metropolitan Istanbul (1979-present).

### 3.1 Segregated Two-Way Curbside Bus Lane, 1979

Operational from 1979, the first BL project served an important tourist and commercial hub in Istanbul and was used in 80 bus routes. It was a curbside, segregated, two-way road with a lane width of 3 m (Gardner, 1991). Some researches (Gardner, 1991; TRRL, 1993b.) evaluated the performance of BLs in developing cities, including BL projects in Istanbul. These studies indicated that buses were delayed by:

- ✓ increasing passenger numbers and buses in each direction, which made bus stops inadequate for handling bus and passenger volume;
- ✓ the high demand relative to the number of buses, plus out-of-date ticketing and cash payment at the front door of buses, which led to increased passenger boarding times at stops;
- ✓ the inability to overtake buses at bus stops;
- ✓ overuse of the BL by different bus routes sharing the same stops;
- ✓ inadequate green times at junctions.

As a result of bus delays:

- ✓ general traffic at intersections was blocked and delayed due to queues at the bus stops;
- ✓ level of passenger satisfaction declined.

### 3.2 Segregated Two-Way Median Bus Lane (Metrobus), 2007-Present

Istanbul's Metrobus (kind of BRT system) was first opened in 2007 and has since been extended in to cover a length of c. 52 km with a capacity to transit 600 000 passenger per day (Yazıcı *et al.*, 2013). The studies on its ridership and passenger capacity showed that Istanbul Metrobus has one the of the highest commuter levels amongst BRT systems in the world (Alpkokin and Ergun, 2012). In 2018 (EMBARQ, 2018), it is noted that the ridership of Istanbul's Metrobus had risen to around 750 000 passengers per day.

In Figure 3.2, Metrobus location in a congested segment of O-1 highway and a crowded Metrobus stop are shown.

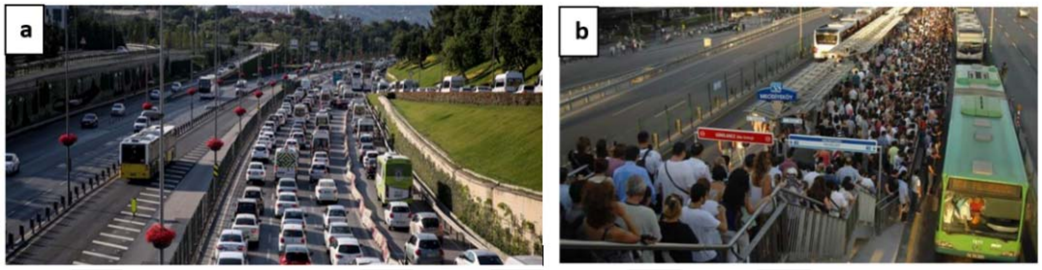


**Figure 3.2 :** (a) A view of the Metrobus and adjacent general traffic; (b) An example of rush-hour Metrobus stop in Istanbul.

This project has been attracted the researchers attention globally as stop design and safety issues evaluated by (Duduta *et al.*, 2014). One of the main Challenges of Istanbul Metrobus system is:

- ✓ Merging to O-1 (E5) highway's mixed traffic to cross over Bosphorus bridge which affects driving behavior characteristics resulting in worsening congestion and delays for BUS and Car accordingly.

That is why this study aims to concentrate on the design and operational condition of Metrobus in the merging segments of O-1 highway in Istanbul in order to provide priority to Metrobus movement in bottleneck area.

### 3.3 Non-Segregated One-Way Curbside Bus Lane, 2012

Istanbul's latest BL was implemented along Millet Road between Topkapi and Aksaray (3.3 Km), and between the Şirinevler and Mahmutbey districts (5 km) as an exclusive lane for buses, shuttles (schools and employee service) and taxis. It was a non-segregated curbside lane located on a road consisting of three-lane carriageways in each direction divided by a median two-way tramway with a lane width of 3 m (see Figure 3.3).

The BL served 47 bus routes carrying passengers to some of the city's central districts and was operated only during morning and evening rush hours, between 7 a.m. and 10 a.m., and 4 p.m. and 8 p.m. (Kantoğlu, 2013). There was also another pilot area for implementing TSP for buses along Kennedy street between Ataturk Airport and Sirkeci district cross through Yenikapi. (12.2 km). Millet road consists of 3 lanes in each direction divided by a median two-way Tram line with lane width of 3m/lane.

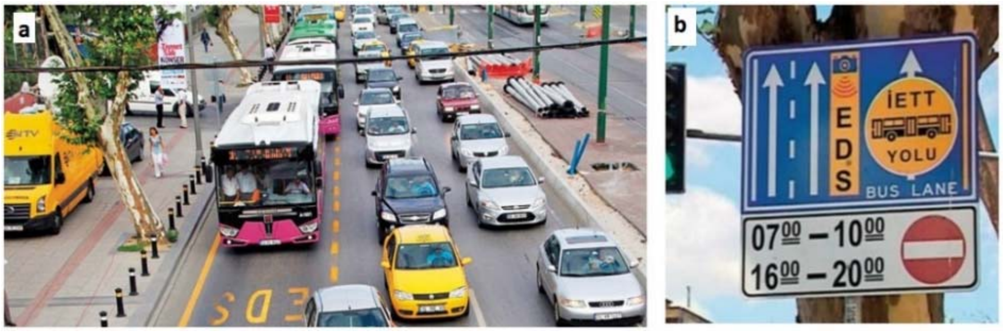


**Figure 3.3 :** (a) view of curbside BL on Millet Rd.; (b) traffic enforcement area's sign during curbside BL.

This project faced with several challenges caused the unsuccessful operation of BL in Istanbul in 2012 which are:

- ✓ Taxis and minibuses' illegal use of the BL.
- ✓ Illegal parking along the BL, especially in business districts.
- ✓ Illegal loading and unloading of commercial goods on the BL
- ✓ Lack of monitoring and enforcement systems, and the erroneous penalization of general lane drivers, especially those right-turning. Right-hand traffic (driving) is used in Turkey.
- ✓ Overuse of the BL for a large number of bus routes with the same destination.
- ✓ Use of the BL by emergency vehicles picking up/dropping off patients or those with mobility issues in front of medical centers along the BL.
- ✓ Illegal utilization of the BL for queue-jumping (illegal lane-changing or overtaking).

During the operation of this BL, traffic police issued warnings to many lane violators who made illegal lane-changing or insisted on driving along the BL. Thus, Istanbul Metropolitan Municipality (IMM) transport officials canceled the operation of the BL project due to the large number of violations which occurred in terms of driver obedience, lane-changing behavior, and illegal car parking by unauthorized users.

# 4. RESEARCH METHODOLOGY

The research methodology of the thesis is divided into two main parts based on thesis objective. First, the development of a fully-automatic and hybrid calibration procedure to determine well-tuned driving behavior parameters of traffic simulation models according to real driving conditions is presented. Then, by explaining various highway bottleneck control models, it proposes a new combined ramp metering and variable speed limit control model in the presence of high bus volume so called VSL+ALINEA/B.

## 4.1 Fully-Automatic Calibration Procedure of Driving Behavior Parameters

In recent years, advances in computing hardware technology and new traffic engineering applications have led to traffic simulations being more utilized in the analysis of complex interactions between various traffic components (Barcel *et al.*, 2005). Microscopic traffic models are those based on the principle of motion of each individual vehicle or pedestrian included in the traffic , taking account of actions and decisions such as acceleration, deceleration, and lane/trajectory changes in response to surrounding conditions (Barcelo, Fellendorf and Vortisch, 2010).

Several traffic microscopic simulation tools are either commercially or freely available on the market. Some examples of this microsimulation software include VISSIM, AIMSUN, CORSIM, PARAMICS, MITSimLab, FRESIM, DRACULA, and SUMO.

In this study, I selected VISSIM (PTV, 2017) as well-known microscopic simulation software. Although a wealth of microscopic traffic simulation software is available, traffic simulation studies still lack a unified perspective in terms of mimicking real-world conditions. Having a fine-tuned and best-matched simulation model which represents the real-life behavior of drivers is of pivotal importance to traffic engineers.

Thus, before any analysis can take place, models need to be calibrated to be able to represent real-life conditions. The calibration process has the objective of finding the statistically significant values of model parameters based on data collected from the field (Dowling, Skabardonis and Alexiadis, 2004). From these samples, the performance of a traffic model can be determined by employing statistical analysis with respect to various measures (Hourdakis, Michalopoulos and Kottommannil, 2003; Ma, Dong and Zhang, 2007; Ciuffo, Punzo and Torrieri, 2008; Paz, Molano and Gaviria, 2012).

There exist two types of methods for Driving Behavior Parameters (DBP) calibration; (i) calibration of DBP using trajectory data (lane-changing, acceleration, deceleration, etc.) extracted from video files using image-processing techniques (Kovvali *et al.*, 2007; Ossen and Hoogendoorn, 2011; Abbas and Chong, 2013; Kanagaraj *et al.*, 2015;

Lu *et al.*, 2016), (ii) calibration of DBP using traffic flow measurement data (volume, speed, etc.) collected by detectors (Menneni, Sun and Vortisch, 2008a.; Lu *et al.*, 2014; Chiappone *et al.*, 2016; Durrani, Lee and Maoh, 2016; Yu and (David) Fan, 2017; Markou, Papathanasopoulou and Antoniou, 2018). As I don't possess capabilities for automatic image processing, I used the second approach. It means that I am not aiming to calculate actual (local) driving behavior parameters value which can be measured by driving simulator, however, I will obtain the well-tuned parameter values based on field traffic data such as speed, volume, and density.

### 4.1.1 Driving behavior parameters

In this section, VISSIM driver behavior models including car-following, lane-change, their parameters' description, and optimization methods are discussed. Many studies opt to use default car-following and lane changing parameters. However, the traffic composition, network geometry, vehicle ages, engine size, and (most of all) driver behavior varies significantly in different parts of the world. Thus, the default parameters of the simulation software should be carefully examined in order to obtain reliable results. As an example, it has been noted that lane-changing is a highly strong characteristic of Istanbul traffic and drivers are frequent and aggressive in cutting and overtaking, taking every opportunity to change lanes at the slightest opening (Kesten, Ergün and Yai, 2013). As explained in (PTV, 2017), the two models of driving behavior parameters are Wiedemann 74 (W74) and Wiedemann 99 (W99). The W74 model, generally, has been used for urban arterials and merging areas. The W99 has been utilized in modeling freeways and diverging areas. Tables 4.1 to 4.4 outline the general parameters, lane-changing, W74, and W99 models' parameters respectively. The first column contains the ID of each parameter used by VISSIM during COM interface, along with the parameter description, their range, and default values in other columns.

**Table 4.1 :** General Car Following Parameters.

| IDrivingBehavior | Parameter description | Range | Default |
|---|---|---|---|
| LookBackDistMax | Max. look back distance (m) | 50 ~ 200 | 150 |
| LookAheadDistMax | Max. look ahead distance (m) | 100 ~ 300 | 250 |
| ObsrvdVehs | No. of observed preceding vehicles (veh) | 1.00 ~ 5.00 | 2.00 |
| StandDist | Standstill distance in front of static obstacles (m) | 0.00 ~ 3.00 | 0.50 |

**Table 4.2 :** Wiedemann 74 car-following model parameters.

| IDrivingBehavior | Parameter description | Range | Default |
|---|---|---|---|
| W74ax | Average standstill distance | 0.50 ~ 2.50 | 2.00 |
| W74bxAdd | Additive factor for security distance | 0.70 ~ 4.70 | 2.00 |
| W74bxMult | Multiplicative factor for security distance | 1.00 ~ 8.00 | 3.00 |

**Table 4.3 :** Lane-changing model parameters.

| IDrivingBehavior | Parameter description | Range | Default |
|---|---|---|---|
| DecelRedDistOwn | Reduction rate for leading (own) vehicle (m) | 100 ~ 200 | 200 |
| AccDecelOwn | Accepted deceleration for leading (own) vehicle ($m/s^2$) | -3.00 ~ 0.50 | -1.00 |
| MinHdwy | Min. Spacing (headway) (m) | 0.50 ~ 3.50 | 0.50 |
| SafDistFactLnChg | Safety distance reduction factor | 0.10 ~ 0.60 | 0.60 |
| CoopDecel | Max. deceleration for cooperative lane-change/braking ($m/s^2$) | -6.00 ~ 3.00 | -3.00 |
| CoopLnChgSpeedDiff | Max. speed difference for cooperative lane-change/braking (m/s) | 5.00 ~ 20.00 | 10.80 |
| MaxDecelOwn | Max. deceleration for leading (own) vehicle ($m/s^2$) | N.A | -4.00 |
| MaxDecelTrail | Max. deceleration for following (trailing) vehicle ($m/s^2$) | N.A | -3.00 |
| DecelRedDistTrail | Reduction rate for following (trailing) vehicle (m) | N.A | 200 |
| AccDecelTrail | Accepted deceleration for following (trailing) vehicle ($m/s^2$) | N.A | -0.50 |

**Table 4.4 :** Wiedemann 99 car-following model's parameters.

| IDrivingBehavior | Parameter description | Range | Default |
|---|---|---|---|
| W99CC0 | Desired distance between lead and following vehicle (m) | 0.60 ~ 3.05 | 1.50 |
| W99CC1DISTR | Headway Time (s)<br>Desired time between lead and following vehicle | 0.50 ~ 1.50 | 0.90 |
| W99CC2 | Following Variation (m)<br>Additional distance over safety distance that a vehicle requires | 1.52 ~ 6.10 | 4.00 |
| W99CC3 | Threshold for Entering 'Following' State (s)<br>Time in seconds before a vehicle starts to decelerate to reach safety distance (negative) | -15.00 ~ -4.00 | -8.00 |
| W99CC4 | Negative "Following Threshold" (m/s)<br>Specifies variation in speed between lead and following vehicle | -0.61 ~ 0.03 | -0.35 |
| W99CC5 | Positive "Following Threshold" (m/s)<br>Specifies variation in speed between lead and following vehicle | 0.03 ~ 0.61 | 0.35 |
| W99CC6 | Speed dependency of oscillation (1/m.s) | 7.00 ~ 15.00 | 11.44 |
| W99CC7 | Oscillation Acceleration: Acceleration during the oscillation process ($m/s^2$) | 0.15 ~ 0.46 | 0.25 |
| W99CC8 | Standstill Acceleration ($m/s^2$) | 2.50 ~ 5.00 | 3.50 |
| W99CC9 | Acceleration with 80 km/h ($m/s^2$) | 0.50 ~ 2.50 | 1.50 |

### 4.1.2 Calibration and optimization techniques

Various optimization methods have been employed to minimize the difference between the measured and simulated data. These include Genetic Algorithm (GA) (Cheu *et al.*, 1998; Ma and Abdulhai, 2002; Kim, Kim and Rilett, 2005; Menneni, Sun and Vortisch, 2008b.; Strnad and Žura, 2011; Chiappone *et al.*, 2016), Simultaneous Perturbation Stochastic Approximation (SPSA) (Balakrishna *et al.*, 2007; Lee and Ozbay, 2009; Paz, Molano and Gaviria, 2012; Hale *et al.*, 2015; Paz *et al.*, 2015), Particle Swarm Optimization (PSO) (Aghabayk *et al.*, 2013; Boittin *et al.*, 2015), OptQuest/Multistart algorithm (OQMS) (Ciuffo, Punzo and Torrieri, 2008), and a combination/comparison of various of these (Ma, Dong and Zhang, 2007; Kh Abdalhaq and Abu Baker, 2014; Yu and (David) Fan, 2017).

### 4.1.3 Genetic algorithm

The GA (Schaffer and Grefenstette, 1989) is one of the best-known population-based (biological) example among EAs. It has been used for both binary and continuous forms in single and multi-objective optimization processes. It can also solve mixed integer programming problems with parameters restricted to having integer values (Fonseca and Fleming, 1993; Bingul, Sekmen and Zein-Sabatto, 2000).

All GA forms generally possess common rules including selection, crossover, and mutation, at each step creating new chromosomes (generation) from existing ones. At each stage, GA selects initial population (generation) randomly, select parents from among the current population, and combines selected parents to produce offspring (children) for the next generation during the crossover process using various methods such as single, double-point crossover, or uniform crossover.

There are several tuning elements which are involved in the GA, including the number of the initial population, max. iteration number, crossover percentage, mutation percentage, mutation rate, etc. Detailed information concerning how a sensitivity analysis of tuning elements influences the GA is described in chapter 5 of (Haupt and Haupt, 2006). I use uniform random selection for initial population, an arithmetic crossover (a kind of uniform crossover), create and add noise (random number) using Normal Distribution (with mean=0 and variance=sigma) for improving selected offspring during the mutation stage, and following settings for the GA elements given in Table 4.5.

**Table 4.5 :** GA operator settings for the current proposed methodology.

| | |
|---|---|
| MaxIt=40; | Maximum Number of Generation (stopping criteria) |
| nPop=10; | Population Size |
| pCrossover=0.8; | Crossover Percentage |
| nCrossover=round(pCrossover*nPop/2)*2; | Number of Parents (Offspring) |
| pMutation=0.3; | Mutation Percentage |
| nMutation=round(pMutation*nPop); | Number of Mutants |
| Mu=0.1; | Mutation rate |

The studies (Cheu *et al.*, 1998; Ma and Abdulhai, 2002; Kim, Kim and Rilett, 2005; Menneni, Sun and Vortisch, 2008b.; Strnad and Žura, 2011; Chiappone *et al.*, 2016) show that GA is the optimization method most favored by researchers because of its ease-of-implementation. However, no information exchange is taking place between individuals during the GA process. For instance, in the selection stage, members of the initial population have no direct competition to being selected and neither do parents in the crossover stage experience any information exchange with each other or that of the offspring created by them. On the other hand, when a mutation occurs, this mutant lacks the right direction. These are the reasons for lower performance of GA compared to other techniques.

### 4.1.4 Particle swarm intelligence optimization

The PSO, firstly introduced by (Kennedy and Eberhart, 1995), is also a population-based algorithm but uses particle swarms of intelligence ability, for instance, the behavior of fish when they are confronted with a shark.

PSO is an algorithm for continuous variables, but with some modification can be used in discontinuous optimization problems too (Erik, Pedersen and Pedersen, 2010; Mezura-Montes and Coello Coello, 2011).

PSO begins with a determination of the position and velocity of each individual (particle) and proceeds with a calculation of the objective function based on that particle's location. Then, the objective function values are to be compared with global objective function values, with the better one assigned as a global objective value. The new velocity and position of the particles are calculated based on the best particle information.

The main advantages of PSO is that an information flow exists between all particles at each moment. This means that all particles use other information to find the best solutions. This capacity of PSO is used for solving GA limitation issues, particularly during the selection, crossover, and mutation stages. PSO elements assumption are noted in Table 4.6.

**Table 4.6 :** PSO operator settings for the current proposed methodology.

| | |
|---|---|
| MaxIt=40; | Maximum Number of Iterations |
| nPop=10; | Swarm (Population) Size |
| phi1=2.05; | Definition of Constriction Coefficients |
| phi2=2.05; | |
| phi=phi1+phi2; | |
| chi=2/(phi-2+sqrt(phi^2-4*phi)); | |
| w=chi; | Inertia Weight |
| c1=chi*phi1; | Personal Learning Coefficient |
| c2=chi*phi2 | Global Learning Coefficient |

### 4.1.5 Objective (cost) function definition

Selection of appropriate objective function and stopping criteria are two common steps of all optimization algorithms. There are many single and multi-objective functions used to minimize the error of simulated and observed data. The Root Mean Square Error (RMSE) (Hourdakis, Michalopoulos and Kottommannil, 2003; Ma, Dong and Zhang, 2007; Lu et al., 2014) and the Mean Absolute Normalized Error (MANE) (Ciuffo, Punzo and Torrieri, 2008; Hollander and Liu, 2008; Lee and Ozbay, 2009; Yu and (David) Fan, 2017) fall among several multi-objective functions used in previous studies for the calibration of VISSIM simulation model parameters and are widely used around the world.

In this study, I tried to minimize the error between simulated and observed data utilizing MANE and RMSE objective functions formula:

$$Minimize\ \ Z\ (MANE) = \frac{1}{N}\sum_{j=1}^{N}(\frac{\left|V_{obs_j} - V_{sim_j}\right|}{V_{obs_j}} + \frac{\left|S_{obs_j} - S_{sim_j}\right|}{S_{obs_j}}) \tag{4.1}$$

$$Minimize\ \ Z\ (RMSE) = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(S_{obs_j} - S_{sim_j})^2} \tag{4.2}$$

w.r.t the constraints: $Lb_{Xi} \leq Xi \leq Ub_{Xi}$

Where:

**Z:** General form of objective function (here: speed and traffic volume),

**Xi**: The vector of continuous parameters (e.g. W74 or W99 Car following models + Lane-change model parameters),

**$Lb_{Xi}$, $Ub_{Xi}$:** Lower and upper value of parameter Xi (e.g. CC1: $Lbcc_1$= 0.5 and $Ubcc_1$=1.5 s),

**$Vtarget_j$, $Starget_j$:** Target (observed) traffic volume and speed collected by detectors,

**$Vsim_j$, $Ssim_j$:** Traffic volume and speed simulated by VISSIM,

**N**: Total number of data collection intervals (e.g. for one-hour observation (3600 sec) with two minutes intervals (120 sec), N = 3600/120 = 30).

The developed code, here, can perform the optimization process based on both single (e.g. speed-only, volume-only, and occupancy rate) and multi-objective functions. For decreasing the effect of speed differences among lanes of a main road, weighted average speed is used in the MANE formula both for target (observed) and simulated speed data. Let's assume that there three lanes on main road. The weighted average speed is calculated based on the exiting traffic volume of each lane:

$$V_{w.avg.} = (v_1*q_1+v_2*q_2+v_3*q_3)/(q_1+q_2+q_3) \tag{4.3}$$

Where:

**$V_{w.avg}$**: Weighted average speed for n lanes,

**$v_i$:** Speed of ith lane of main road, i = (1, 2, …, n),

**$q_i$:** Traffic volume of ith lane of main road,

**n:** number of lanes of main road (here n=3).

This study outlines an automatic calibration process for driving behavior models' parameters using metaheuristic algorithms. The GA, PSO, and a combination of the GA and PSO (i.e. hybrid GA and hybrid PSO) were utilized for optimization purposes. The main contribution the proposed methodology provides is a hybrid method for overcoming the limitation of single optimization algorithms in order to yield better results in a fully automatic way. Although hybrid PSO and hybrid GA are used previously (Garg, 2016; Katiyar, 2013; Nik, Nejad, & Zakeri, 2016; Q. Zhang, Ogren, & Kong, 2016), this study is the first that implemented a combination for the calibration of traffic microsimulation parameters.

There are several possible combinations of GA and PSO for the hybrid method (Abd-El-Wahed, Mousa and El-Shorbagy, 2011; Sharma, Gaur and Mittal, 2014; Garg, 2016; Nik, Nejad and Zakeri, 2016; Barroso, Parente and Cartaxo de Melo, 2017; Liang, Ouyang and Yang, 2018). All try to use the advantages of local search capability of GA and social thinking ability of PSO as both algorithms have strengths and weaknesses. They concluded that the combination of standard PSO and standard GA results in better performance compared to use of single algorithms. Some of them used only one or more operators of GA such as using crossover and mutation operators in the PSO for improving and balancing PSO's exploration and exploitation ability (Garg, 2016). Others are using the ability of PSO in saving and updating the personal and global best in the GA (Sheikhalishahi *et al.*, 2013).

The order of the operation of the GA operator and the PSO operator is related to the hybrid type used for the calibration. In hybrid GAPSO, initial position and velocity of particles (here driving behavior parameters) are determined randomly over search space. In the proposed methodology, as seen in the optimization process flow of Figure 4.1, the initial population of PSO is created and assigned by the GA operator (hybrid GAPSO). The total numbers of iterations are equally shared by GA and PSO, if maximum sub-iteration number of GA (MaxSubItGA) and MaxSubItPSO are set to 1. In other words, in every iteration, the code runs one GA and one PSO operator. A user can also modify the share of using the GA and PSO operators in every iteration by increasing or decreasing the number of MaxSubItGA and MaxSubItPSO.

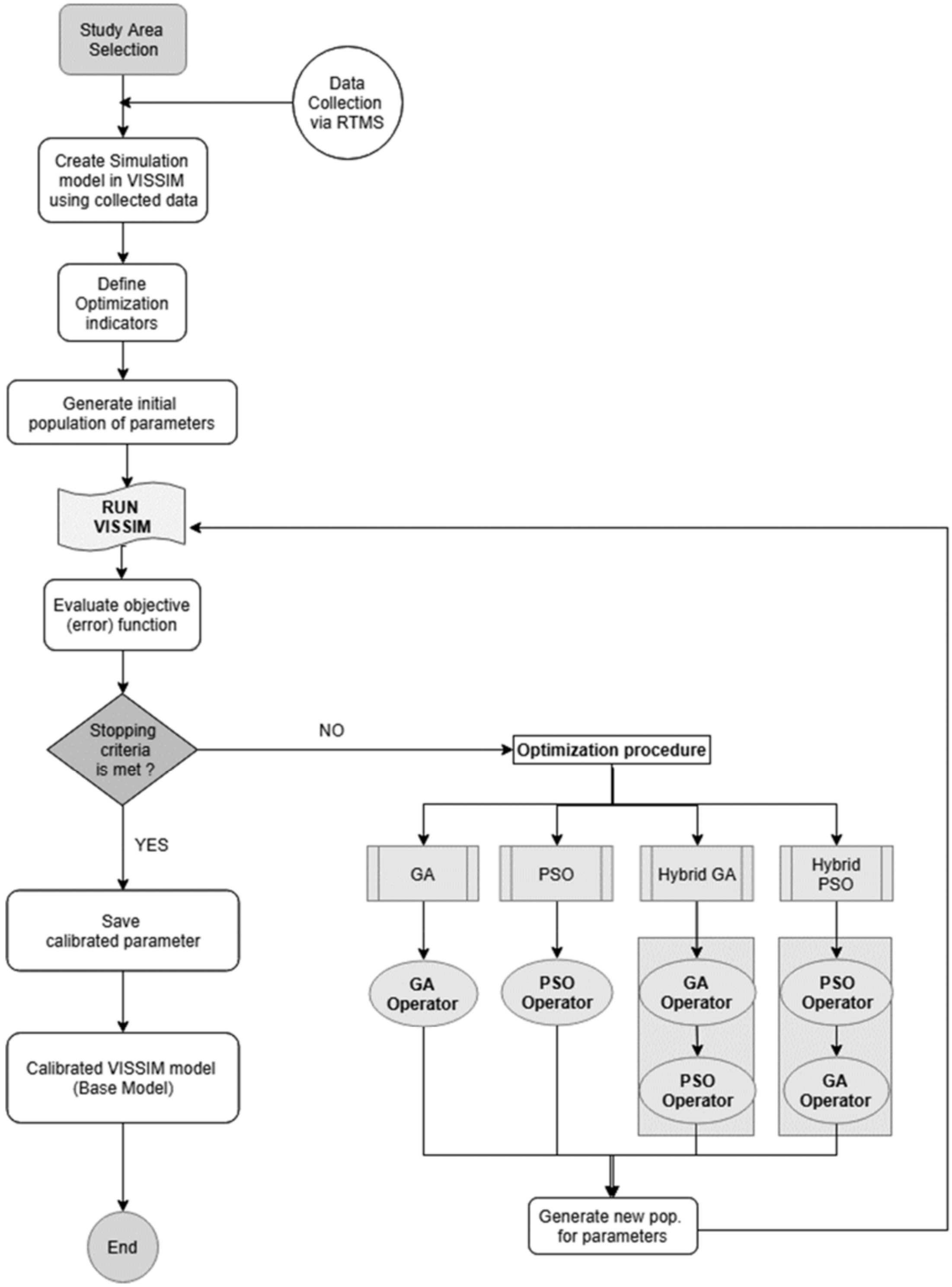


**Figure 4.1 :** Flowchart of the proposed methodology.

Then, crossover and mutation operators of the GA is applied for each particle in swarm separately to improve the diversity of the population and find better sets of parameters.

The information (position, velocity) of the particles each were calculated and compared with its previous information and also with the global best. If the new information is better than the previous personal best and global bests both of them were updated based on new information.

The solutions obtained by the GA operator are given as an initial population of the PSO, PSO operator starts to search within search space around the best particle by introducing swarm intelligence as explained in previous chapter. It attracts the particles toward the actual best position while maintaining the parameters diversity to gain the new best in every iteration compared to the previous iteration.

Implementation of the iteration step of the proposed flowchart in Figure 4.1 needs to be programmed using the aforementioned required information on GA and PSO algorithms. Four optimization algorithms – namely the GA, PSO, GAPSO, and PSOGA – were coded in MATLAB and the results compared in order to find the most suitable to be used in the VISSIM calibration process. The algorithm structure for GA, PSO, and hybrid were coded without utilizing the optimization toolbox of MATLAB. This increased the flexibility of the proposed methodology and gave us the opportunity to extend/improve the code for further studies noted in the conclusion part. There are also several stopping criteria for optimization algorithms, including Max Stall Iterations, Function Tolerance, Max Iterations, Objective Limit, and Max Stall Time. Here, I have purposefully used only Max Number of Iteration (MaxIt) as stopping criteria for the proposed method in order to allow all the methods to perform a similar number of function evaluations (NFE). To this end, MaxIt value for single algorithm (GA or PSO) and hybrid algorithms (GAPSO or PSOGA) are set to 40 and 20 respectively. Due to the algorithms' structure, in both conditions NFE will be around 430.

Problem definition is the common component between all four-optimization methods noted above, while the initial condition and the main structure is different for each of them. The following, Table 4.7, are the assumptions used during the optimization procedure:

**Table 4.7 :** Problem definition for the current proposed methodology.

| | |
|---|---|
| model = CreateVISSIMmodel(); | % Start VISSIM and set new values of parameters |
| ObjectiveFunction=@Nima_Calib; | % Objective (ERROR) Function |
| nVar = model.numberOfparameters; | % Number of parameters to be calibrated |
| VarSize = [1 nVar]; | % Size of Matrix |
| VarMin = model.lb; | % Lower Bound of Selected Variables |
| VarMax = model.ub; | % Upper Bound of Selected Variables |
| VarRange = [VarMin VarMax]; | % Variation Range of Variables |
| VelMax=(VarMax-VarMin)/10; | % Maximum Velocity to be used in PSO |
| VelMin=-VelMax; | % Minimum Velocity to be used in PSO |

### 4.1.6 Improving calibration time using Parallel Computing Technique

Generally, all Evolutionary Algorithms (EAs) such as GA and PSO consists of a number of common steps, including initialization, variables/parameters definition, objective function definition, iteration steps, stopping criteria. When applying EA to traffic simulation models calibration problem, EA has to run a simulation and calculate its corresponding objective function value *i.e.* the error between simulated and observed data once for each set of parameters, causing a time-consuming step. Although the developed hybrid calibration procedure (GAPSO and PSOGA) showed successful computational performance, one might consider using parallel computing Parallel Computing Technique (PCT) to decrease the computation time of the proposed calibration procedure. PCT and known multithreading technique have been introduced in the field of modeling and calibration when most of the modelers were suffering from weak performance of sequential (serial) computing methods in terms of its long computational time.

The basic idea behind this technique is to divide a large problem into smaller tasks solved simultaneously on multiple processors in a process called parallel execution or parallelization. There are two different kinds of PCT:

- Sharing computation work among available cores of one computer, called PCT in this study.
- Distributing computational work among a cluster of several computers.

Sequential use of GA (Stevanovic, Martin and Stevanovic, 2007; Zhou, Gan and Shen, 2007; Stevanovic *et al.*, 2008; Lin, Ph and Wang, 2014; Espejel-Garcia *et al.*, 2017; Siam *et al.*, 2018), PSO (Gopalakrishnan, 2010; Babazadeh, Poorzahedy and Nikoosokhan, 2011; Boittin *et al.*, 2015; Dabiri and Abbas, 2016), hybrid GAPSO, and PSOGA have been studied thoroughly; however, in the existing literature there is no study regarding implementation of PCT on hybrid GAPSO and hybrid PSOGA models. Another contribution of this study has been to develop a quick calibration procedure for the driving behavior parameters using EA and PCT.

#### 4.1.6.1 Sequential GA vs. Parallel GA

In this study, a real coded standard GA having an initialization, evaluation, fitness scaling, crossover, and mutation steps are programmed in MATLAB. An arithmetic crossover operator using uniform distribution with the rate of 0.80 is employed. A gaussian mutation operator using normal distribution is also used to restore genetic diversity lost during the application of reproduction and crossover.

The mutation rate is set to 0.3, meaning in each stage 30% of population will be selected as mutants. The other randomly controlled parameters for the proposed approach are taken as delta=0.01 for a crossover operator, and gamma=0.01 for a mutation operator (Hassani and Treijs, 2009). In the application of GA, objective function evaluation for each selected set of VISSIM parameters' values is the main time-consuming step in calibration problems. GA has to run a simulation and calculate its corresponding objective function value once for each set of parameters. However, using PCT, GA is able to run several separate VISSIM instances simultaneously and calculate several objective function values in parallel. Here is the proposed Pseudo code of the parallel GA algorithm for VISSIM calibration. The only difference between serial and parallel implementation of the GA algorithm in such a problem is the parallelization of the objective function evaluation as shown in Pseudo code below. This parallelization technique is used in initialization, crossover, and mutation steps where the relevant objective function of positions should be evaluated.

**Parallel GA Initialization Loop**

***Parfor idx = 1: nPop***

Initialize position randomly

Evaluate cost function (run simulations in parallel)

***End***

Sort population based on their cost

Update best solution ever found

Parallel GA Main Loop

***For i=1: MaxIt***

% Crossover operator (Popc)

***Parfor idx = 1: nCrossover***

Select parents randomly

Create offspring (position) using parents

Evaluate cost function (run simulations in parallel)

***End***

% Mutation operator (Popm)

***Parfor idx = 1: nMutation***

Select parents randomly

Create offspring (position) using parents

Evaluate cost function (run simulations in parallel)

***End***

Merging the Population (Pop, Popc, Popm)

Sorting the Population

Delete Extra Population (Truncation)

Generate new population

Update Best Solution

***End***

In PCT implementation, the time saved depends on the number of available cores on CPU (c), and the number of parallel tasks to be allocated to them (p). It is recommended that the number of tasks is a multiple of the number of cores, as some cores would not be used at all times otherwise. If I assume, I have ten tasks (p=10) and four cores (c=4) available on CPU, then k=p/c means that two of ten tasks would have to wait in queue and start after the cores finished the previous tasks. Thus, total number of steps in which tasks are allocated to cores should be an integer coefficient (k=1, 2, 3, …, n) of the number of existing cores, in order to increase the efficiency of the using PCT (can save more computational time).

#### 4.1.6.2 Sequential PSO vs. Parallel PSO

PSO is one of the best-known heuristics and population-based algorithms. It was developed while observing social behaviours of a swarm of birds and fish while the swarm was looking for food collectively (Kennedy and Eberhart, 1995).

The most appropriate PSO parameter values used in these experiments are as follows: both personal learning coefficient ($C_1$) and population(global) learning coefficient ($C_2$) are set to 1.5, and inertia weight (w) = 0.73 ($w_{min}$ = 0.7 and $w_{max}$=0.9).

Selected driving behavior parameters of VISSIM have been assumed as a swarm ($X_i$) which contains n particles, in which the position and velocity vectors of $i^{th}$ particle are updated using the following formulas:

$$X_i = (x_{i1}, x_{i2}, \dots, x_{id}), X_{Lb} \le X_{ij} \le X_{Ub} \quad (4.4)$$

$$V_i = (V_{i1}, V_{i2}, \dots, V_{id}), \qquad -V_{max} \le V_{ij} \le V_{max} \quad (4.5)$$

$$V_{ij}^{k+1} = w \times V_{ij}^{k} + c_1 r_1 \left(pop.best_{ij} - x_{ij}\right) + c_2 r_2 \left(global.best - x_{ij}\right) \quad (4.6)$$

$$X_{ij}^{k+1} = X_{ij}^{k} + V_{ij}^{k+1} \quad (4.7)$$

Where:

**i** = 1, 2, …, n, j =1, 2, …, d,

**k:** iteration number,

**$r_1$, $r_2$:** random number between 0 and 1.

The differences between serial and parallel implementation of PSO algorithm are:

- ✓ Cost function evaluation for each particle, and
- ✓ Updating the global best value. The proposed Pseudo code of a parallel PSO algorithm for VISSIM calibration is presented below. As can be seen, the allocation of the parallel cost function evaluation to workers is as same as the explanation of parallel GA.

In contrast to serial PSO, in parallel PSO "*parfor loop*" (MATLAB syntax) is used during the initialization and updating stages of the particles' position and velocity. However, in updating the global best value, "*for loop*" (MATLAB syntax) is used instead of "*parfor loop*" because the nature of parallelization makes it impossible to simultaneously update the global best value based on each particle's best value.

**Parallel PSO Initialization Loop**

```
 Parfor idx = 1: nPop
   Initialize position and velocity of particles randomly using (equation 4.4, 4.5)
   Calculate cost of particles (run simulations in parallel)
   Update Best Personal (position, cost)
        if pop(idx).Cost<pop(idx).Best.Cost
             pop(idx).Best.Position=pop(idx).Position;
             pop(idx).Best.Cost=pop(idx).Cost;
        End
 End
 Update Best_Global
 For k = 1: nPop
     If pBest(k) < gbest
        gBest= pBest(k)
     End
 End
```

**Parallel PSO Main Loop**

```
 For j=1: MaxIt        % Stopping criteria
      Parfor idx = 1: nPop
         Update particles velocity using (equition 4.6)
         Apply Velocity Bounds
         Velocity Reflection
         Apply Position Bounds
       Function (Cost) Evaluation (run simulations in parallel)
         Update Best_Personal using (equition 4.7)
             if pop(j).Cost<pop(i j).Best.Cost
                pop(j).Best.Position=pop(j).Position;
                pop(j).Best.Cost=pop(j).Cost;
             End
       End
      Update Best_Global
      For j = 1: nPop
```

***If*** pop(j).Best < gBest

gBest= pop(j).Best

***End***

***End***

***End***

### 4.1.6.3 Sequential Hybrid GAPSO vs. Parallel Hybrid GAPSO

The application of hybrid GAPSO and hybrid PSOGA on the calibration of traffic microsimulation models is introduced in previous sections. The initial population of parameters is created by PSO operator (initialization loop) in both hybrid GAPSO and hybrid PSOGA. Then, in the main loop of hybrid model (e.g. GAPSO), the solutions obtained by the GA operator are used as an initial population of the PSO, as shown in the optimization process flow of Figure 4.2.

Implementation of the iteration steps of the flowchart proposed in Figure 4.2 needs to be programmed using the aforementioned required information on GA and PSO algorithms. MATLAB PCT toolbox was employed to implement a parallelization procedure on the workers (cores).

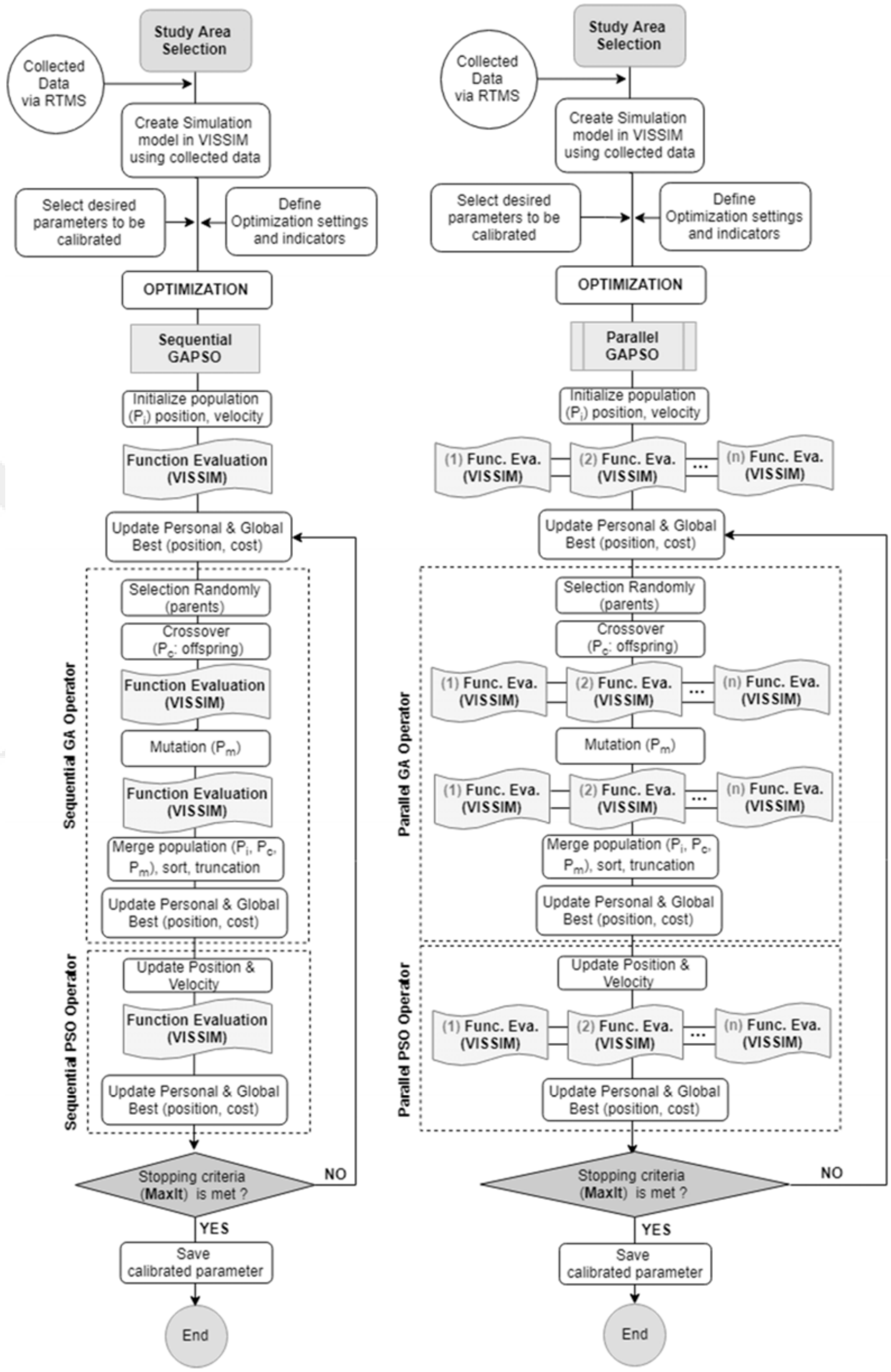


**Figure 4.2 :** Flowchart of the proposed model: left) Serial Hybrid GAPSO, right) Parallel Hybrid GAPSO.

In parallel hybrid models called ParGAPSO and ParPSOGA, MaxSubItGA and MaxSubItPSO are two important parameters which determine the share of GA and PSO operators inside hybrid models, as shown in the Pseudo code. In this study I set both of them to one. Thus, the total numbers of iterations (generation) are equally shared by GA and PSO operators. In every iteration, the code runs one GA and one PSO operator. The order in which the GA operator and PSO operator operate is related to the hybrid type used for the calibration. In the given example, MANE value, total computational time, and function evaluation time of GAPSO and PSOGA models have little to no statistical difference in both serial and parallel, because of their structure. Accordingly, different values for MaxSubItGA and MaxSubItPSO will result in different outputs.

```
Parallel GAPSO Initialization Loop
  Parfor idx = 1: nPop
    …
  End
  Update Global Best
Parallel GAPSO Main Loop
 For i=1: MaxIt
   % Parallel GA operator
   For GAit =1: MaxSubItGA
     % Crossover (Pop_c)
     Parfor idx = 1: nCrossover
       …
     End
     % Mutation operator (Pop_m)
     Parfor idx = 1: nMutation
       …
     End
     Merging the Population (Pop_i, Pop_c, Pop_m)
     Sorting the Population
     Delete Extra Individuals (Truncation)
     Generate new population
     Information exchange between offspring and parents (cost, velocity).
     Update Global Best
   End
   % Parallel PSO operator
   For PSOit =1: MaxSubItPSO
     Parfor idx = 1: nPop
       …
     End
     Information exchange between offspring and parents (cost, velocity).
     Update Global Best
   End
 End
```

### Adjustment of "User-Preferred Settings" using GUI

In order to prevent confusion over the content of the code and desired calibration settings, it is necessary to create a graphical user interface (GUI) page (see Figure 4.3) which helps the user perform the calibration process with greater ease.

For the proposed calibration procedure used in the flowchart shown in Figure 4.2, I have provided an easy-to-use GUI page in which users can quickly select their desired models and parameters, optimization measures, and optimization algorithm.

Inside the "Instruction" section, the required information is prepared to help users benefit from the GUI. "Parameters Description" contains information concerning the models and parameters.

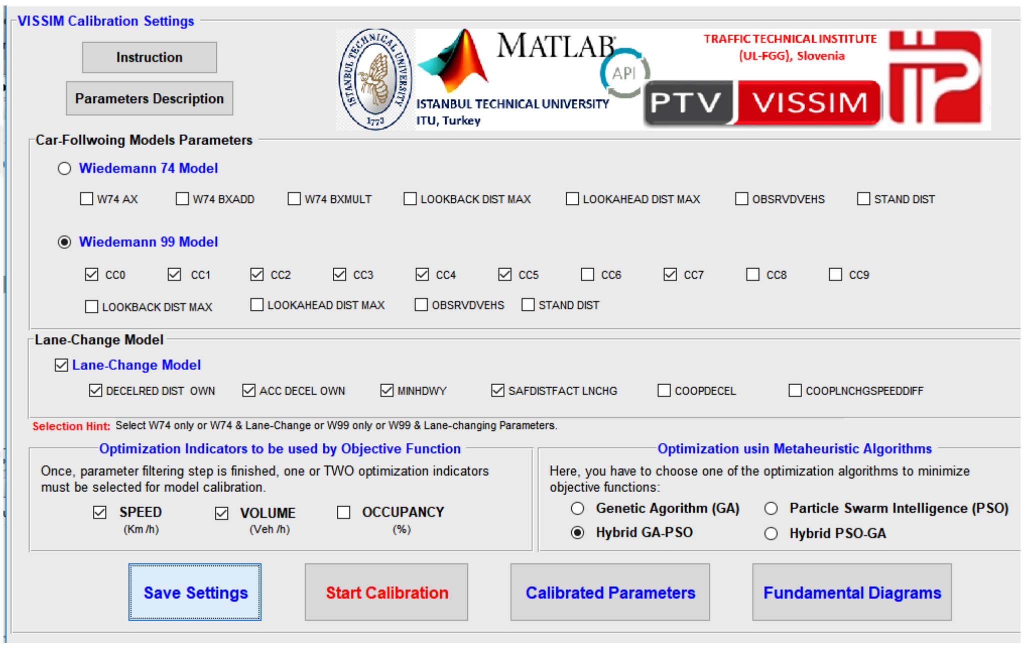


**Figure 4.3 :** User-friendly GUI of proposed calibration procedure developed using MATLAB.

## 4.2 Development of a Novel Merging Control Method in the Presence of High Bus Demand

Once the best-matched sets of VISSIM's driving behaviour parameters for the study area have been obtained through the proposed calibration procedure, it is time to develop different scenarios.

This section first explains merging congestion control such as TSP, VSL, and RM methods exist globally. Then, it proposes a new combination of VSL+RM model considering a high rate bus volume in the on-ramp area.

### 4.2.1 Transit signal priority on ramp

As mentioned, in TSP method, buses are provided priority with green extention and recall (early green) together on ramp area depending on bus detection time. TSP system consists of the following required equipment:

- A priority request sensor on bus
- A receiver sensor on signal, and
- A signal controller for making priority decision

In VISSIM, general, detecors are used instead of sensors mentioned above. These required detectors can be classified into three main groups:

i) Demand,

ii) Queue, and

iii) Exit detectors.

The first one is used as bus demand (call) sensor which gives the information to signal controller whether the bus is approaching or not while car demand detector gives the information of the presence of cars in the vicinity of signals.

Queue detectors are mostly used for detecting the spillback phenomena of queue on ramp area. The third group of detectors are installed after signal head in order to give required cancelation information to the signal controller whether the approaching bus has already left signal or not.

Detectors' location is on the most effective parameters in the accuracy of TSP systems must be tested and analyzed for each specific case (Ahmed, 2016).

Different detectors' location and their effects on the TSP performance have been tested in this study. Figure 4.4 illustrates the required detectors and their optimum location in TSP system.

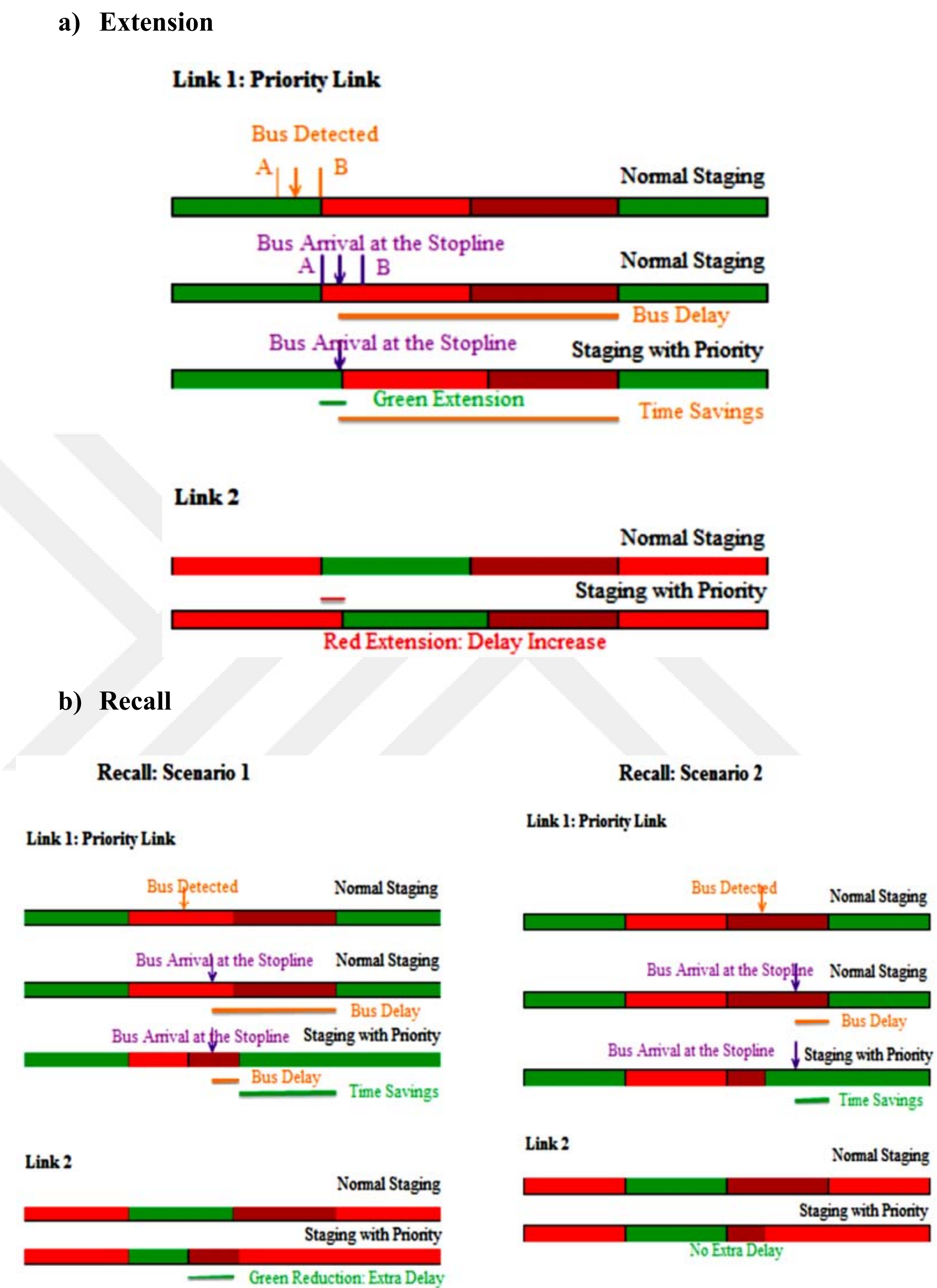


**Figure 4.4 :** Signal phase diagram in TSP: a) green extension, b) recall (early green).

It shows different manners of bus approaching to the signal and its priority request. Link 1 is referred to link which include buses and link 2 refers to another traffic flow.

In this study and in order to implement TSP, as can be seen in Figure 4.5, three bus demand detectors with length of 5 m are located in the upstream of signal head with the distance of 3 m, 50 m and 80 m respectively.

The first one is sending the information of the existing bus close to the signal while the second one is sending priority request of the bus to the signal controller to get green extension or recall priority.

Third one is dedicating the following bus (if any) in order to prevent any probable stop in the signal after passing the leading bus of signal. Exit detector is located in the downstream of signal head with a very close distance of 0.2 m in order to give bus passing information to signal controller to cancel priority phase and to active green phase for cars.

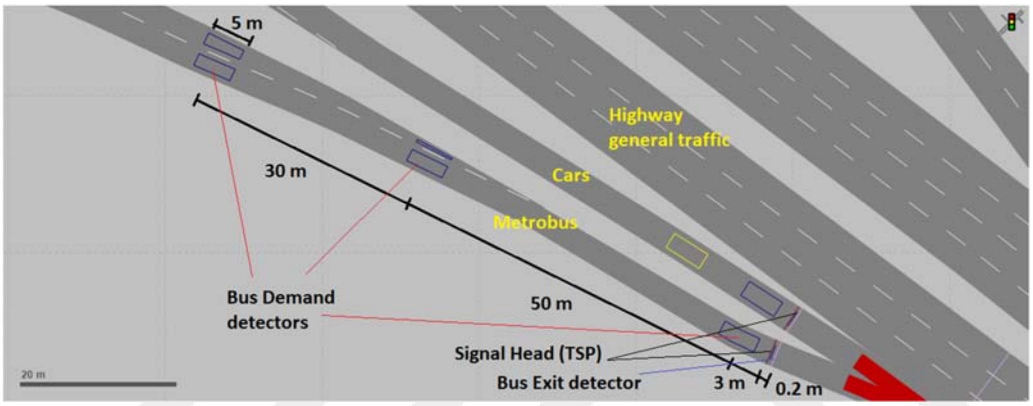


**Figure 4.5 :** Required detectors and their optimum location for TSP

To implement green extension and recall based TSP system, the extension and cancellation conditions should be determined to be used the flowchart.

**Green Extension conditions:**

- ✓ Condition 1: Maximum extension not reached.
- ✓ Condition 2: Bus is not detected at the exit detector

Priority (green extension) time can be calculated as sum of the estimated bus travel time from detector to signal head (sec) + extra time due to variation of travel time (e.g. 30%).

**Priority Cancellation conditions:**

- ✓ Condition 1: Previous recall ended.
- ✓ Condition 2: Minimum priority green for recall provided.
- ✓ Condition 3: Bus detected at the exit detector.

Figure 4.6 shows how TSP model works by providing priority with extension and recall together. The developed TSP code by VisVAP can be found in Appendix A.

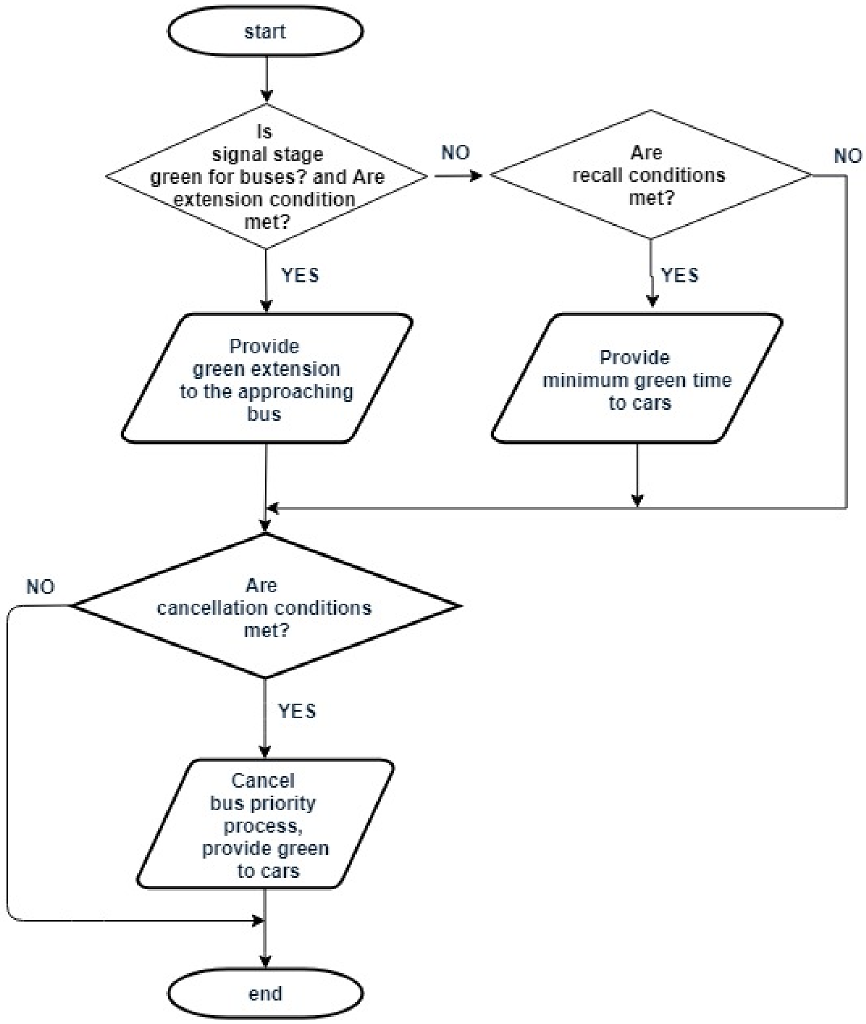


**Figure 4.6 :** Flowchart of the TSP algorithm.

As shown in the flowchart, the algorithm first checks the active stage in the signal, if it is green for car, the minimum green time for cars should be checked, then the bus demand detector value should be checked. If there is a bus priority request from a demand detector, the stage must be green for the bus immediately, otherwise, the green for cars can be continued. If the active stage is green for bus flow, and a bus is detected by demand detectors, depending on estimated bus travel time from the detector to signal head, the required green extension time will be calculated by the signal controller and transfer to signal head. In case of bus detection during signal stage change interval (green to red for buses), the recall condition is met and the signal controller will provide early green for buses once minimum green time for cars is reached.

### 4.2.2 Ramp metering control strategy

RM is one of the widely used and effective congestion control strategies especially for merging congestion of highways often only operate in rush hour periods (Shaaban, Khan and Hamila, 2016). Basically, ramp meters consist of a signal head per lane, check-in and check-out sensors, queue override detector on the slip road, and upstream and downstream detectors on the main road. One-car or two- cars-in-green-stage RM control are two commonly used methods over the world (Chaudhary *et al.*, 2004). RM systems have two main groups called local RM and coordinated (cooperative, competitive, and integral) RM. In the first category, the metering rates are decided considering local traffic conditions only while the latter is using both local and system-wide traffic information for arranging metering rate (Zhang *et al.*, 2001). There are also a few cases in which RM controllers have to provide preferential treatment for high occupancy vehicles (HOV) being tested in U.S. cities or buses bypass lane implemented in Utrecht, Netherlands (Kotsialos, Kosmatopoulos and Papageorgiou, 2004). RM controller operates as off-line or open-loop e.g. fixed time ramp meters, reactive or closed-loop control e.g. real-time ramp meters, and proactive or predictive control that utilizes both offline and online traffic information. In this study, a closed-loop local ramp metering strategy so-called ALINEA (Papageorgiou, Hadj-Salem and Blosseville, 1991), a well-studied and successful RM control algorithm has been selected to be used in scenario analysis. Metering rate in ALINEA can be determine by:

$$r(k) = r(k-1) + K_R[O_{des} - O_{out}(k-1)] \tag{4.7}$$

Where:

k: discrete time index (1, 2, …);

r(k): ALINEA metering rate at time step k;

$O_{out}$ (k-1): measured occupancy (%) of downstream in the last time interval;

$O_{des}$: desired occupancy (%) in downstream;

$K_R$: regulator parameter used for adjusting the constant disturbances of the feedback control (veh/h/%).

Figure 4.7 presents a Schematic of local ramp metering strategy, ALINEA.

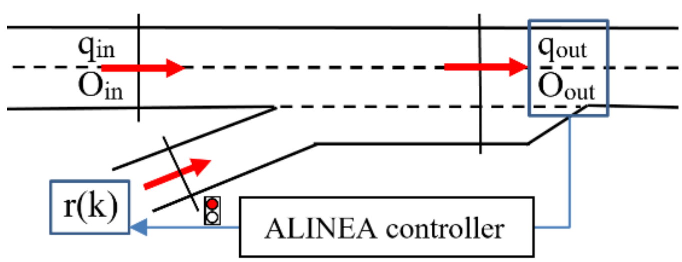


**Figure 4.7 :** Schematic of local ramp metering strategy: ALINEA.

According to (Papageorgiou *et al.*, 2008; Papamichail and Papageorgiou, 2008), the calculated metering rate (r) should be the range ($r_{min}$=200-400 veh/h, $r_{max}$=1800 veh/hr) in order to avoid the ramp closure and mainline congestion. $K_R$ also should be a range ($K_{Rmin}$=50, $K_{Rmax}$=150) which after several test the results showed that the optimum value of $K_R$ can be selected 70 veh/h/% for different condition. They also suggested that the optimum downstream location for detectors is the beginning point of congestion (usually 40 to 500 m), in this study, it is located in 150 m of downstream from the ramp nose. Desired occupancy rate is another important parameter to have accurate ALINEA control model. In this study, ALINEA performance has been tested with different desired occupancy rate range (18% to 30%). $O_{desired}$=22% has been selected as desired occupancy rate which is slightly close to the critical (capacity) occupancy in the study area. In addition, to model and implement the ALINEA control model in microsimulation software like VISSIM (i.e. VisVAP), it requires to convert metering rate (r) to green time of signal head through the following formula:

$$g = (r(k)/r_{sat}).C \quad (4.8)$$

Where

$r_{sat}$: ramp's saturation flow;

c: cycle time;

g: green-phase duration (to avoid ramp closure gmin> 0, gmax ≤ c).

Figure 4.8 illustrates the ALINEA algorithm which has been coded in VisVAP. As shown in the flowchart, the algorithm first checks the number of existing lanes in the mainline (highways) then it starts to calculate the metering rate based on the average of observed (measured) occupancy rate through downstream detectors.

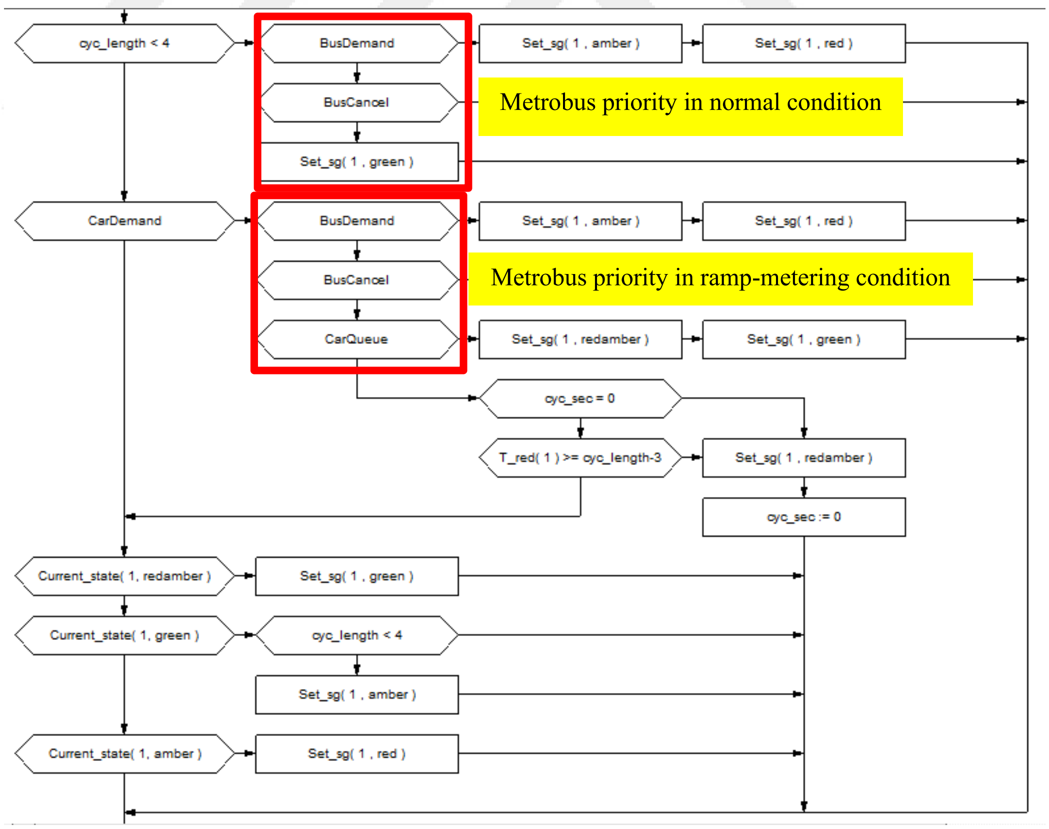


**Figure 4.8 :** Flowchart of ALINEA model developed in VisVAP.

### 4.2.3 Variable speed limit control

VSL control is another effective congestion management method. All VSL control systems aimed to balance traffic speed and homogenize the traffic flow according to the current traffic (congestion, incidents) and weather conditions by utilizing variable speed message (Khondaker and Kattan, 2015). The logic in behind of VSL control is that it keeps merging bottleneck throughput close to the bottleneck capacity means $q_b <= q_{capacity}$ by creating a congestion discharge segment in the upstream of the merging area. To this end, VSL system checks the upstream volume in mainline and on-ramp and compares with bottleneck critical volume (see Table 4.8).

**Table 4.8 :** Assumed parameters' value and critical volume for VSL design.

| Parameters | Value |
|---|---|
| PCU | 2 (Dolmus), 3 (Bus), 3.6 (Metrobus) |
| Data Collection Time Interval | 1 minute |
| Detector smoothing factor | 0.5 |
| Desired speed | 120 km/hr ( < 3 600 veh/hr) |
| **q-On-100 km/hr** | **4 200 veh/hr ( 1400 veh/hr/lane )** |
| q-Off-100 km/hr | 3 600 veh/hr ( 1200 veh/hr/lane ) |
| **q-On-85 km/hr** | **5 000 veh/hr ( 1660 veh/hr/lane )** |
| q-Off-85 km/hr | 4 500 veh/hr ( 1500 veh/hr/lane ) |
| **q-On-70 km/hr** | **5 700 veh/hr ( 1900 veh/hr/lane )** |
| q-Off-70 km/hr | 5 100 veh/hr ( 1700 veh/hr/lane ) |

If the sum of these volumes was more than bottleneck capacity, it tries to decrease the speed of approaching vehicles in the upstream of discharge area (see Figure 4.9). It is suggested that the length of this discharge area should be a range of 500 – 700 m beginning from merging nose (Hegyi, De Schutter and Hellendoorn, 2005; Chen, Ahn and Hegyi, 2014).

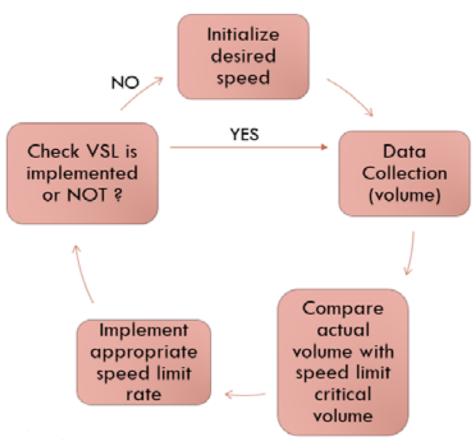


**Figure 4.9 :** Determination of speed limits based on bottleneck volume.

Required volume and occupancy values can be measured using traffic simulation software like VISSIM through programming the VSL algorithm in VisVAP OR can be predicted based on historical data and mathematical models so-called Model Predictive Control. In Model Predictive Control, the future condition is predicted based on historical data and using mathematical formula (Khondaker and Kattan, 2015).

In this study, VISSIM and VisVAP has been used in order to model traffic condition and to measure volume and occupancy rate as well as to design VSL control algorithm. In VISSIM, one detector per lane per vehicle class (car, heavy vehicle, bus) must be defined.

The location of Variable Message Sign (VMS) in the upstream of the discharge area is another important component of VSL system – in this study 850 m. due to give the appropriate reaction time to the driver to adjust their speed based on the desired speed calculated by VSL algorithm.

### 4.2.4 A novel VSL+ALINEA/B model vs. existing VSL+ALINEA model

As mentioned, RM e.g. ALINEA and VSL are two widely used and effective congestion management strategies especially for "merging congestion" of highways. According to literature review conducted, the implementation of RM and VSL control strategies have been used both separately (Kušić *et al.*, 2016; Strnad, Kramar Fijavž and Žura, 2016; Conran, 2017; Zhang, Bie and Qiu, 2017) and in a combined manner (Carlson *et al.*, 2012; Carlson, Papamichail and Papageorgiou, 2014; Greguric, Ivanjko and Mandzuka, 2014; Sun, Tang and Zhang, 2014).

Generally, if the mainline upstream flow is too much, VSL is used in order to harmonized upstream flow based on bottleneck capacity or if the on-ramp flow is too much, RM control methods is employed. Sometimes, like this thesis study area, there are heavy demand from both mainline and on-ramp that the well-implemented solution in this is the combined VSL and RM. There are three general forms of VSL and RM combinations:

1. Determination of metering rate before calculation of VSL values,
2. Metering rate and VSL values determined simultaneously,
3. Determination of VSL values before metering rate calculation (see Appendix B).

The important factors to select one of the aforementioned combinations of VSL and RM are safety, drivers' reaction and feedback (obey or disobedience), and model complexity. The programming and code development of the first and third combination models is supposed to be simple while the second combination requires very complex programming to calculate the metering rate and VSL values at the same time.

Among the first and third model, the third model has been selected to use in this study. Frequent speed changes based on pre-determined metering rate might confuse/bother drivers (first combination model) result in disobedience or safety level reduction in mainline while calculation of suitable metering rate based on pre-determined critical VSL can be more feasible to implement.

Having looked at the increase in using spatial bus priority schemes in recent years (Dadashzadeh and Ergun, 2018), giving priority to buses in highways on-ramp area has become a potential issue should be evaluated. As mentioned in chapter two, bus lanes can be effective if implemented successfully both along roads and at junctions.

For instance, implementation of TSP can be a simple solution to decrease the interaction of buses with on-ramp vehicles as well as buses delays reduction. However, in one hand, it will directly affect the on-ramp vehicles delays which are forced to give movement priority to buses and on the other hand, it cannot control the interaction of buses with highway mixed traffic.

Moreover, the implementation of VSL-only, ALINEA-only control benefits transport officials to improve the mainline (highway). In the YILDIZ merging area in which there are several conflicts among three kinds of flows namely mainline (highway), on-ramp, and buses, it is necessary to have an integrated model which is able to control all interactions.

Based on the study area observation, numerous numbers of the buses (and their very long length in Istanbul Metrobus case) directly affects driving behavior in the mainline as well as on-ramp flow. The more lane changing especially in merging points of urban highways, the more the capacity drop in these areas of highways. Moreover, from the extensive literature review conducted in previous chapters, it is found that there is no detailed study regarding the combination of these systems considering high bus demand issue.

Therefore, last but not least, the ultimate goal of this study is to address the gap in the literature by developing and proposing a combined VSL and RM strategies in presence of high bus volume (e.g. Metrobus vehicles in YILDIZ merging segment).

To this end, first, the third model of integrated VSL+RM i.e. algorithm start with calculation and determination of VSL then it calculates the metering rate. The demand detectors are located in the dedicated bus lane in order to record bus priority request and to send it to ALINEA controller. ALINEA controller calculates a suitable metering rate for on-ramp vehicles considering:

- ✓ the measured occupancy in mainline (which is improved by VSL),
- ✓ desired occupancy rate (defined by user), and
- ✓ priority request calling by approaching buses from bus lane.

Figure 4.10 shows the procedure of integrated VSL+ALINEA model modified for the high bus volume. Integrated VSL and ALINEA model considering high bus volume (called VSL+ALINEA/B) have been coded and will be applied to the calibrated model through the VisVAP (see Appendix C).

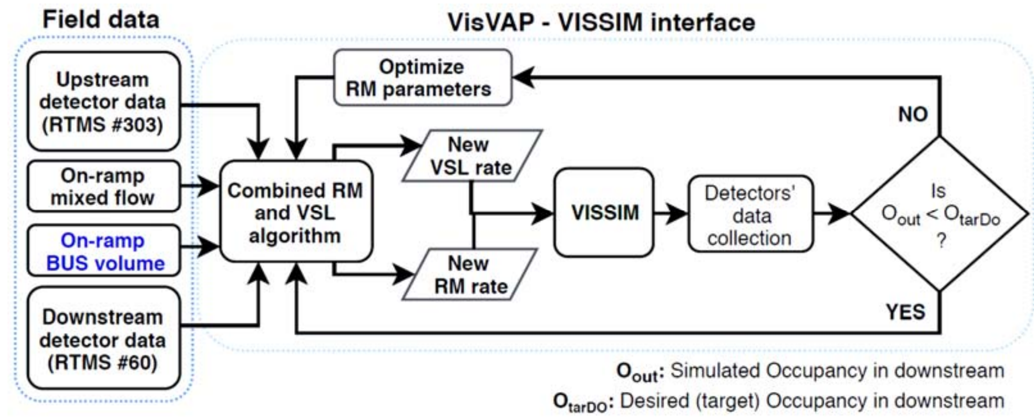


**Figure 4.10 :** Flowchart of the proposed model (integrated VSL and B-ALINEA).

In the following chapters, various scenarios namely i) no control, ii) with control (TSP, ALINEA, VSL, VSL+ALINEA/B) will be tested on calibrated model of study area in order to evaluate the proposed model's efficiency.

# 5. APPLICATION AND DATA COLLECTION

In order to test the proposed calibration method as well as highways' merging section control methods in presence of high bus volume, one segment of the O-1 Highway in Istanbul, Turkey - specifically the YILDIZ junction, as shown in Figure 5.1 – has been selected. A bottleneck area forms at Yıldız junction, where one mixed traffic lane and a spatial bus priority lane merge into three lane main road flow (see Figure 5.1b). This study only considered the flow of traffic from the European to the Asian side. The driving and lane-changing behavior at this specific section is observably peculiar due to its distinct geometry and traffic composition, in particular the high volume of buses on the on ramp.

a

b

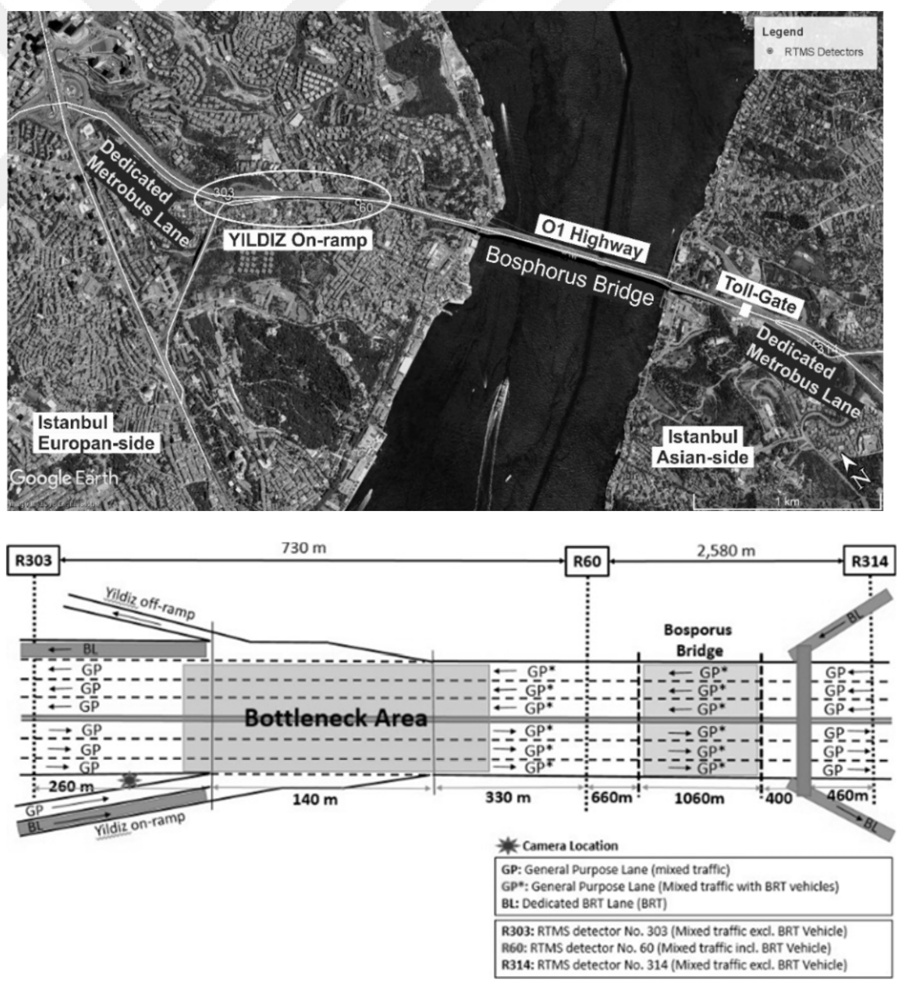


**Figure 5.1 :** Istanbul Yıldız on-ramp: a) bird view (Google Earth), b) layout of studied area (note: not to scale).

## 5.1 Data Collection

As shown in Figure 5.1b, the Yıldız merging area of the O-1 highway consists of three lanes with mixed traffic flow per direction. Due to the distribution of residential and business districts in Istanbul, the majority of Bosphorus crossings go from the Asian side to the European side in the morning hours, with the opposite flow appearing in the evening hours (Kesten, Ergün and Yai, 2013; Kesten, Goksu and Akbas, 2013) . This study just considered the flows of European to Asian-side direction.

There are two Remote Traffic Microwave Sensor (RTMS) devices installed in the upstream (no. 303) and downstream (no. 60) of the on-ramp area. RTMS devices measure volume, occupancy, and speed for each two-minute time interval. The 24/7 data (13.08.18 – 17.08.18) of RTMS detectors provided by IMM-TCC has been analyzed in order to select the start and end point of the merging congestion phenomena during the evening peak hours.

## 5.2 Existing Traffic Flow Characteristics

Before creating a microsimulation model, traffic modelers need to know the traffic flow characteristics of the case study area. Speed-Flow, Speed-Density, and Flow-Density as Macroscopic Fundamental Diagrams (MFD) represent an accurate schematic of existing traffic flow conditions, saturated and unsaturated conditions. These diagrams are also used for examining traffic flow measurements such as free flow speed, capacity, jam density and so on. Figure 5.2 shows MFD for the general flow in Yıldız merging area.

It can be seen that free flow speed, max. volume, and max. density values could be set to around 100 km/hr, 50 veh per 2-minutes time-interval, and 60 veh/km respectively. At the crossings from European side to Asia side, the recurrent traffic congestion starts around 15.30 at the afternoon and remains congested until 22.00 at night which result in a significant speed and capacity drop at study area. The capacity flow is observed around 1400 veh/hr/lane for both directions. There was recorded neither a reversible lane implementation on the bridge, nor a road re-construction, maintenance project to possibly affect data.

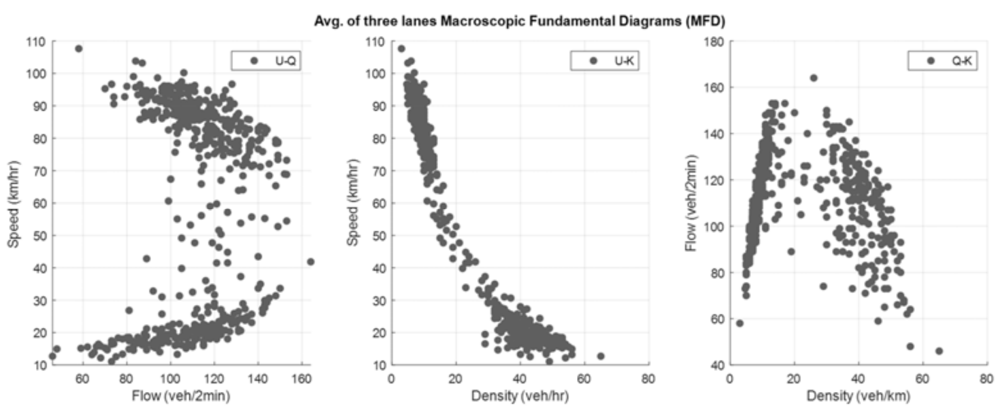


**Figure 5.2 :** Macroscopic Fundamental Diagrams using RTMS No. 303 data in Yıldız merging area.

Daily traffic speed pattern for all the lanes of the study area in given at Figure 4.3 Speed-changes diagram is obtained from detector (No. 303) data located before the merging section. In this study, an uncongested-transition-congested flow conditions between 14:30-15:30 pm (see Figure 5.3) have been modeled by VISSIM microsimulation software.

The interaction between each element creates great complexity in microsimulation traffic models. The driving behavior and lane change model parameters have a major effect on the representativeness of the model. Based on the observation from video files, speed reduction in peak hours has various reasons namely abnormal and aggressive lane-changing behavior of main road drivers facing two merging flows, the shockwave resulting from entrance of Bosphorus bridge and toll gate after bridge. Like many of highways around the world, travel time and delay estimation for this segment of is too complex (Pirc, Turk and Žura, 2015, 2016).

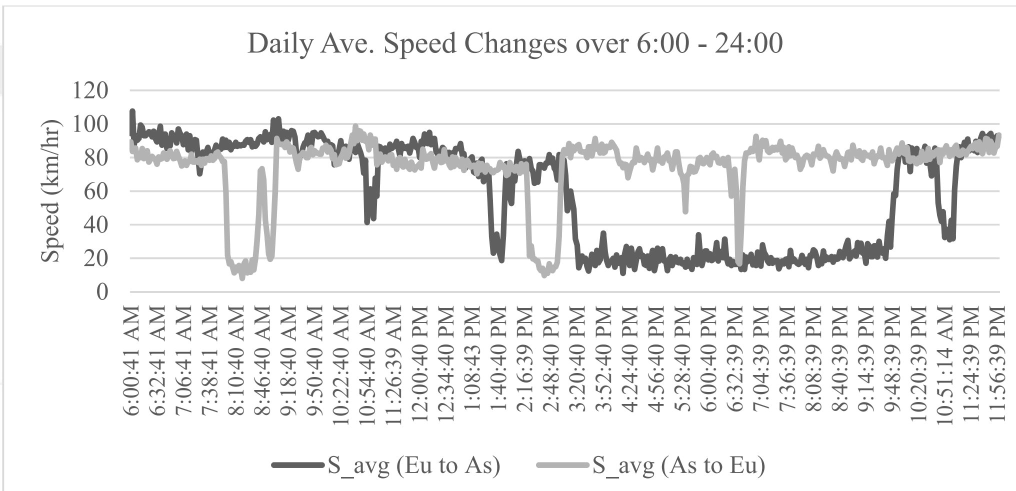


**Figure 5.3 :** Daily average speed changes during RTMS No. 303 data in Yildiz merging area.

## 5.3 Study Area Modeling in VISSIM

The well-known microsimulation software, VISSIM version 10 (PTV, 2017) was used to create a microscopic model of the Yıldız merging area. In the base model, I use the default values of parameters for driving behavior models. After simulation, I compared simulated traffic volumes and speeds at detectors for every two minutes interval with measured values.

Formulating a calibrated model based on actual traffic condition before making a scenario analysis is needed. The results of the optimization process and driving behavior models' parameters using the proposed calibration method are discussed in detail in chapter 6. Figure 5.4 shows the modeled study area by VISSIM (left) vs. Bird’s eye view of study area (right).

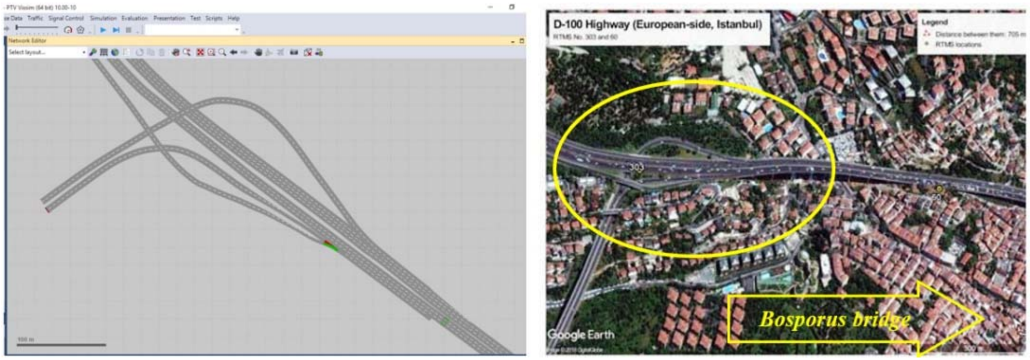


**Figure 5.4 :** Modeled study area by VISSIM (left) vs. Bird's eye view of study area (right, source: Google Earth).

### 5.4 Simulation and Evaluation Settings

I set the following values for the simulation and evaluation attributes. As noted below, the total simulation time (period time) was calculated as 900 + 3,600 + 300 = 4,800 sec. I assumed 900 seconds as a warm-up at the beginning and 300 seconds as warm-down time at the end of the simulation period. Data-collection is done for just 60 minutes simulation period with a two-minute time interval (120 sec) excluding warm-up periods.

In order to decrease the simulation time as well, I activated 'QuickMode' and 'UseMaxSimSpeed' attributes. In order to eliminate stochastic discrepancy, in each scenario, five independent runs with the same initial condition and different seeds were made and average of the total time were recorded. To this end, simulation setting used in VISSIM are as follows:

- ✓ initial random seed = 40,
- ✓ seed increment = 3 (for each run, random seed will increase by 3 means let's say for 5 runs; the random seed will be 40, 43, 46, 49, 52),
- ✓ number of runs = 5,
- ✓ step time (resolution) = 5,
- ✓ Simulation time = 4 800 seconds with max speed for Simulation ('UseMaxSimSpeed', true and 'QuickMode', 1).

# 6. RESULTS AND DISCUSSION

## 6.1 Fully-Automatic Calibration Method's Performance

In this study, 11 parameters have been selected to be optimized using the proposed methodology. They were selected from general parameters ("LookBackDistMax"," LookAheadDistMax"," StandDist", "ObsrvdVehs"), W74, and lane-change models' parameters (see parameters definition and their default value in section 4.1.1).

Table 6.1 presents obtained MANE and RMSE values. As noted in Table 6.1, the simulation with default values of the driving behavior and lane change parameters gave us worse MANE and RMSE values compared to simulations with calibrated parameters using any of metaheuristic methods examined.

It also can be seen that GAPSO, PSOGA algorithms have the best MANE values of 0.353 and 0.366 as well as the best RMSE values of 9.080 and 9.466 respectively.

**Table 6.1 :** Summary of different objective function values for the optimization problem .

| Method | Default | GA | PSO | GAPSO | PSOGA |
|---|---|---|---|---|---|
| **MANE** | 1.280 | 0.436 | 0.433 | 0.353 | 0.366 |
| **RMSE** | 34.508 | 11.611 | 11.721 | 9.080 | 9.466 |

Default and calibrated value of selected parameters which is obtained using GA, hybrid GAPSO, PSO, hybrid PSOGA, and default parameters is presented in Table 6.2.

For example, the value of "DecelRedDistOwn" and "AccDecelOwn" which is calibrated by the GAPSO is 137 m. and -1.62 m/s2, in comparison default values of 200 m and – 1.00 m/s2 respectively.

**Table 6.2 :** Selected driving behavior parameters' values before and after calibration.

| Parameters | Range | Default | GA | PSO | GAPSO | PSOGA |
|---|---|---|---|---|---|---|
| **W74ax** | 0.50 ~ 2.50 | 2.00 | 1.03 | 0.98 | 1.83 | 1.25 |
| **W74bxAdd** | 0.70 ~ 4.70 | 2.00 | 2.88 | 2.42 | 3.18 | 3.03 |
| **W74bxMult** | 1.00 ~ 8.00 | 3.00 | 4.55 | 5.89 | 3.90 | 4.52 |
| **LookBackDistMax** | 50 ~ 200 | 150 | 112 | 128 | 135 | 127 |
| **LookAheadDistMax** | 100 ~ 300 | 250 | 262 | 191 | 195 | 170 |
| **StandDist** | 0.00 ~ 3.00 | 0.50 | 1.50 | 1.93 | 0.76 | 1.08 |
| **ObsrvdVehs** | 1.00 ~ 5.00 | 2.00 | 2.88 | 3.03 | 2.75 | 3.40 |
| **DecelRedDistOwn** | 100 ~ 200 | 200 | 175 | 156 | 137 | 152 |
| **AccDecelOwn** | -3.00 ~ 0.50 | -1.00 | -1.60 | -2.03 | -1.62 | -2.27 |
| **MinHdwy** | 0.50 ~ 3.50 | 0.50 | 2.37 | 2.47 | 2.01 | 1.92 |
| **SafDistFactLnChg** | 0.10 ~ 0.60 | 0.60 | 0.32 | 0.38 | 0.40 | 0.33 |

Figure 6.1 shows the best MANE values obtained by GA, hybrid GA, PSO, and hybrid PSO algorithms with respect to the Number of Function Evaluations (NFE). The value of objective function MANE calculated using equation (4.1). The x-axis denotes the number of function evaluations and the y-axis represents the minimum objective function (MANE) value up to every NFE.

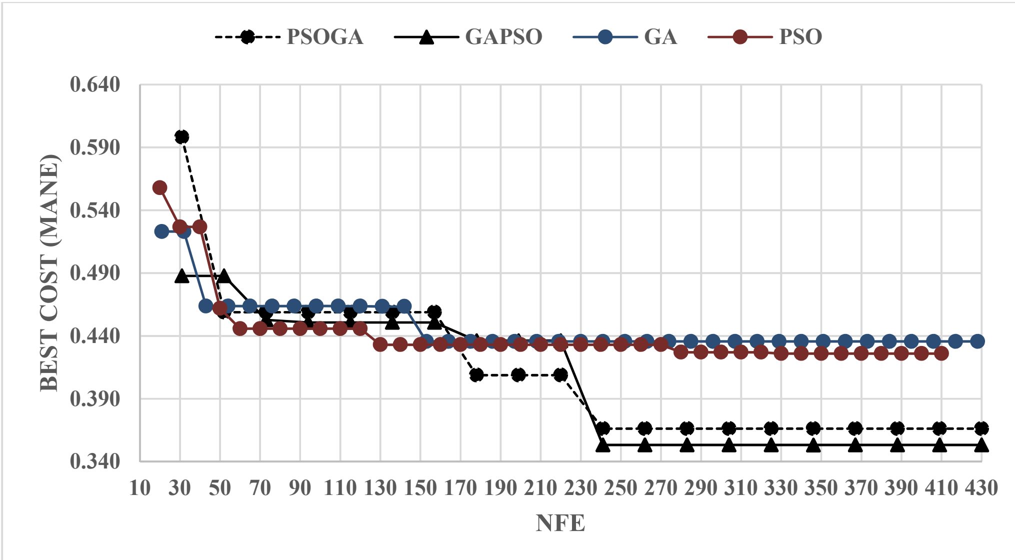


**Figure 6.1 :** The best MANE value obtained by hybrid and single optimization algorithms.

Figure 6.2 shows the best RMSE values obtained by GA, hybrid GA, PSO, and hybrid PSO algorithms with respect to the NFE. The value of objective function RMSE calculated using equation (4.2). The x-axis denotes the number of function evaluations and the y-axis represents the minimum objective function (RMSE) value up to every NFE.

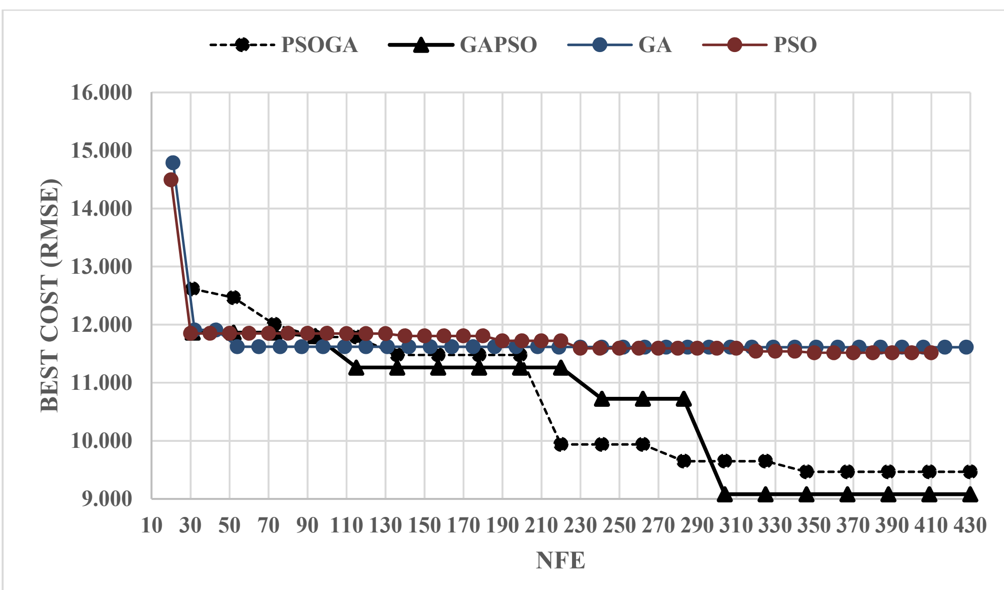


**Figure 6.2 :** The best RMSE value obtained by hybrid and single optimization algorithms.

One can clearly see that hybrid algorithms outperform single algorithms and that the lowest value of both MANE and RMSE are achieved with the hybrid GA algorithm. It is possible to compare the performance of the four algorithms with respect to the percent change from the initial MANE and RMSE scores (are 1.28 and 34.50) calculated using default values for selected parameters. Initially, PSO and PSOGA start with higher MANE values – just above 0.55, whereas GAPSO registers a better value. After around 240 NFE, I can notice good improvement of MANE values at PSOGA and PSO algorithms. Finally, at the end of optimization iterations, hybrid and single algorithms manages to decrease the MANE and RMSE values by 72%, and 66% respectively when compared with the initial values.

Figure 6.3 present speed profile over selected time period including uncongested flow condition (14:30-15:00), transition condition (15:00-15:20), and congested flow condition (> 15:20). As shown, simulated data with calibrated parameters' value are in an acceptable fit status while simulated data with default parameters' value has big difference with observed data in particular in transition and congested traffic conditions. As conclusion for this case study, in uncongested flow condition, simulated models with VISSIM's default parameters outputs acceptable results and can be reliable; however, calibrated parameters provide a better and well-fit result with observed data for transition and congested flow condition.

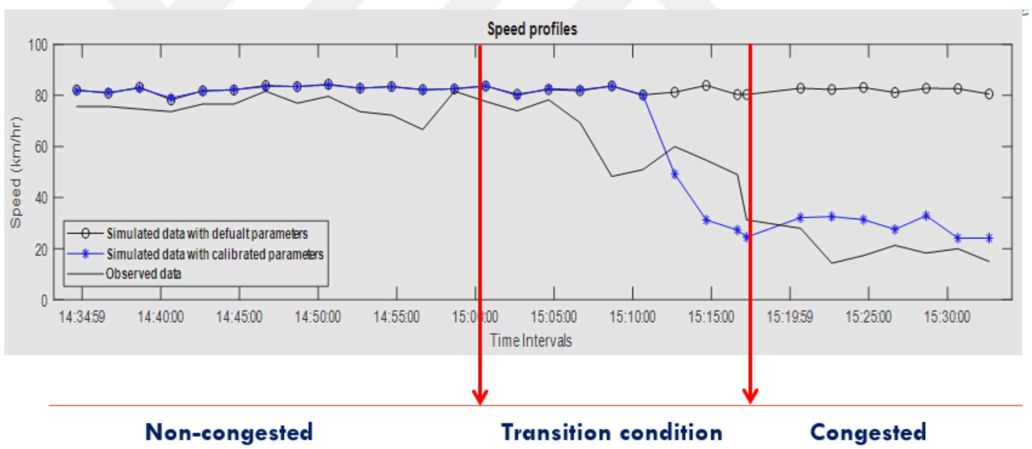


**Figure 6.3 :** Speed profiles using default and calibrated parameters' value.

Modeling and calibration processes were done by a personal laptop with following configuration; CPU: Intel Core™ i5 - 8500@3.00 GHz, RAM: 16 GB, Operation system: Microsoft windows ver. 10 64-bit. This computer needed around 44 hours to complete optimization for each of the methods.

As previously mentioned, this study has aimed to develop a quick calibration procedure for the parameters of driving behavior models using optimization algorithms and PCT. To integrate PCT with the proposed methodology and its performance evaluation, one must determine how many VISSIM instances is appropriate for a specific computer. This also relies on the VISSIM license restriction on the number of simultaneous instances one can start (generally the max. number of instances is 4). In this study, an unlimited thesis-based VISSIM license is used. Therefore, I assume there is no limitation on the number of instances running simultaneously and try to find an appropriate number of parallel VISSIM instances based on the available number of cores on CPU. In order to test the performance of developed methodology (i.e. VISSIM calibration using PCT) the program has been run on an Intel Core™ i7 - 2670QM @2.20 GHz processor with 4 cores (8 multithreading capacity) and 8 GB of Random-Access Memory (RAM). It is able to run eight VISSIM instances in parallel, meaning each core will be used by two VISSIM instances. For instance, I have examined the initialization stage of GA in both serial and parallel modes, where 20 cost functions were evaluated. Table 6.3 summarizes the computation time of different numbers of VISSIM instances in parallel mode.

**Table 6.3 :** Summary of computational time of running several VISSIM instances.

| Time (sec) | Serial Mode | Parallel Mode | | | |
|---|---|---|---|---|---|
| | 1 VISSIM instance | 2 VISSIM instances | 4 VISSIM instances | 6 VISSIM instances | 8 VISSIM instances |
| Overhead time for starting VISSIM | 37.80 | 115.90 | 160.12 | 249.15 | 342.79 |
| Simulation & evaluation of cost function | 1,448.16 | 1,012.10 | 583.36 | 561.35 | 495.03 |
| Total computational time | 1,485.96 | 1,128.00 | 743.48 | 810.50 | 949.51 |

As seen in table above, the time required for opening several VISSIM instances in parallel mode, named overhead time, is almost four times that of the same process in serial mode; however, note that more iterations result in less total computational time in parallel mode compared to serial mode, because there is less “simulation and cost function evaluation” time. Figure 6.4 also illustrates computational time changes for both serial and parallel running of VISSIM instances.

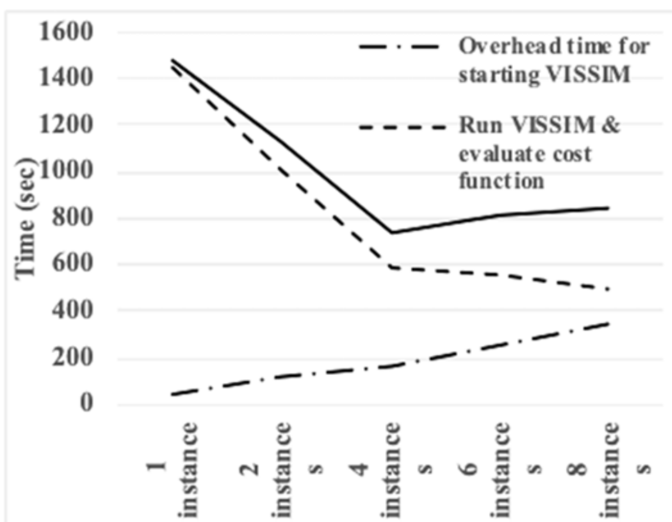


**Figure 6.4 :** Serial vs. Parallel simulation Time by VISSIM.

In studying Figure 6.4, it can be seen that simulation and evaluation time of several VISSIM instances indicated by the dashed line declines sharply until the number of instances is equal to number of available cores (583.3 sec for four instances). A number of VISSIM instances greater than available cores creates a steadily increasing trend in computation time. Therefore, it can be concluded that using an equal number of

VISSIM instances and available cores, in this case, running four VISSIM instances using four cores (each core, one VISSIM), creates the optimum total computational time (743.48 sec) compared to other parallelization modes (2, 6, or 8 instances).

After determining the optimum number of VISSIM instances in parallel mode, two scenarios of the developed methodology (with/without PCT) have been analyzed for the calibration procedure of VISSIM's driving behavior parameters. As mentioned in section 2, a maximum number of generations/iterations (40 for single algorithm and 20 for hybrid mode) has been used as a stopping criterion for all scenarios. Population/swarm size has been set to 10 and a combination of 11 driving parameters including a lane-change and W74 car following models' parameters have been selected to use during the calibration process.

Table 6.4 presents the MANE values and corresponding computational time obtained for different scenarios. To decrease stochastic discrepancy, in each scenario five independent runs with the same initial condition and different seeds have been made, and an average of the total time has been recorded.

**Table 6.4 :** Summary of implemetation of serial and parallel calibration procedure on VISSIM simulation models.

| Algorithm | NFE | Best Cost (MANE) | MANE Decrease (%) | Function Evaluation (Sec/NFE) | Total time (hr) | Time Decrease (%) |
|---|---|---|---|---|---|---|
| Default | - | 0.202 | - | - | - | - |
| GA | 450 | 0.161 | 20.2% | 48.6 | 6.07 | |
| Parallel GA | 450 | 0.161 | 20.2% | 27.9 | 3.65 | 42.6% |
| PSO | 410 | 0.162 | 19.8% | 51.6 | 5.87 | |
| Parallel PSO | 410 | 0.162 | 19.8% | 25.4 | 3.03 | 50.7% |
| GAPSO | 430 | 0.153 | 24.2% | 40.7 | 4.86 | |
| Parallel GAPSO | 430 | 0.153 | 24.2% | 21.8 | 2.75 | 46.5% |
| PSOGA | 430 | 0.155 | 23.3% | 41.1 | 4.91 | |
| Parallel PSOGA | 430 | 0.155 | 23.3% | 22.1 | 2.83 | 46.3% |

As shown in Table 6.4, in the YILDIZ case study, the hybrid metaheuristic algorithm (GAPSO, PSOGA) outperformed the single metaheuristic algorithm (GA, PSO) in terms of MANE value. Hybrid models are able to minimize the error between simulated and observed (real) data by around 23-24% while the single algorithm improved error value by only 19-20%, approximately.

There is no big difference among single-use algorithms containing GA, ParGA, PSO, ParPSO, in terms of MANE value. This can be found among hybrid models, namely GAPSO, ParGAPSO, PSOGA, ParPSOGA, as well.

However, total computation time of the calibration process using PCT, including ParGA, ParPSO, ParGAPSO, ParPSOGA, shows remarkable improvement (i.e. around 50%) compared to scenarios where PCT is not used, such as GA, PSO, GAPSO, PSOGA. The figure below shows total computational time (hour) and MANE function evaluation time for different optimization models (Figure 6.5).

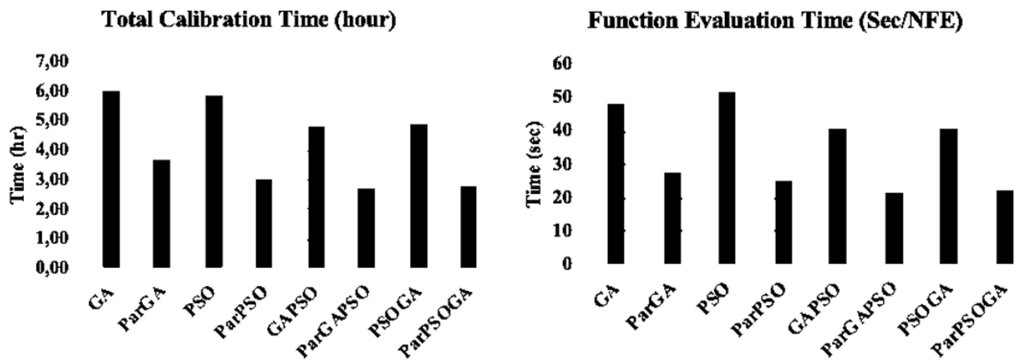


**Figure 6.5 :** Computational time comparison for different optimization models.

The evaluation of four cost functions in parallel mode instead of one cost function evaluation in serial mode, does not mean that calibration time will simply be ¼ of the original time (i.e. decreased by 75%).

Parallelization overhead must be considered, as well as the fact that VISSIM could use more cores for simulation if allowed. Nevertheless, the improvement in total calibration time using PCT would be around 50% compared to original calibration time without PCT.

## 6.2 Scenario Analysis Results

This section discusses different scenario analysis' results of merging congestion control in the presence of bus volumes in observed bus amount and different bus frequency. First, it describes the VSL+ALINEA/B model features implemented on YILDIZ merging area.

Then, it examines the effectiveness of the proposed VSL+ALINEA/B model compared to existing merging congestion control methods such as TSP, VSL-only, ALINEA-only as well as VSL+ALINEA. Lastly, it explores the capability of the proposed VSL+ALINEA/B model under different bus frequency conditions.

Figure 6.6 depicts the schematic of VSL+ALINEA/B model designed for YILDIZ merging area in O-1 highway, Istanbul and has been modelled in VISSIM. As shown, it consists of all required equipment for implementing VSL and ALINEA control models, as well as to detect buses approaching to merging area from Metrobus dedicated lane.

VSL detectors are located in the upstream of bottleneck with a distance of 700 m from ramp nose in order to balance speeds of upstream flow in mainline considering bottleneck condition. There is also VSL signs located in the downstream of bottleneck with a distance of 200 m from merging segment in order to assign the desired speed values to all vehicles.

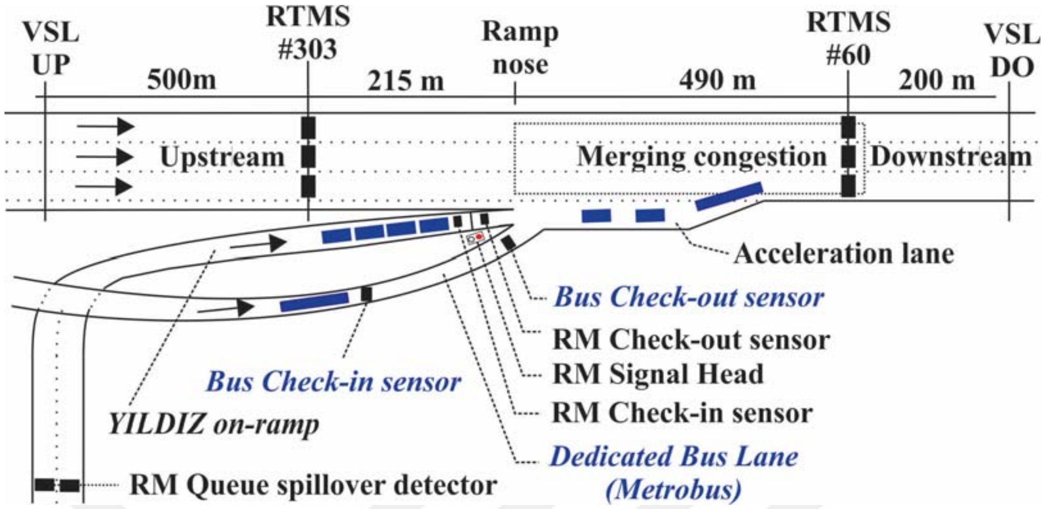


**Figure 6.6 :** Layout of VSL+ALINEA/B model designed for YILDIZ merging area in O-1 highway, Istanbul (note: not to scale).

Three detectors are located in dedicated Metrobus lane in order to detect approaching and leaving buses noted as bus check-in sensor and check-out sensor. To detect and control mixed traffic coming from BESIKTAS, ALINEA's detectors namely queue spillover detector, car check-in and check-out detector are located along YILDIZ on-ramp.

### 6.2.1 Effectiveness of the new VSL+ALINEA/B for current traffic condition

Several performance measures have been used in order to make a precise comparison among existing merging congestion control models and the proposed VSL+ALINEA/B model. These performance measures include total travel time (sec), total travelled distance, average delay, average speed, occupancy rate changes, bottleneck throughput (capacity), fuel consumption, and emissions. All results are the average of five VISSIM runs with different random seeds in order to decrease stochastic effects.

**Total Travel Time**

Total travel time (TRAVTMTOT) in second is total travel time of vehicles traveling within the network or that have already left the network which can be obtained through "Network Performance" menu of VISSIM. In general, for whole network, the proposed VSL+ALINEA/B model is able to decrease total travel time by 44.2% and 6.4% compared to NoControl scenario and the existing VSL+ALINEA model respectively. The bar chart in Figure 6.7 illustrates the total travel time changes of cars due to different scenarios.

It can be seen that the NoControl scenario has the highest value with big difference, while the results of other scenarios are quite similar. For cars, the proposed VSL+ALINEA/B model is able to decrease total travel time by 44.5% and 6.6% compared to NoControl scenario and the existing VSL+ALINEA model respectively.

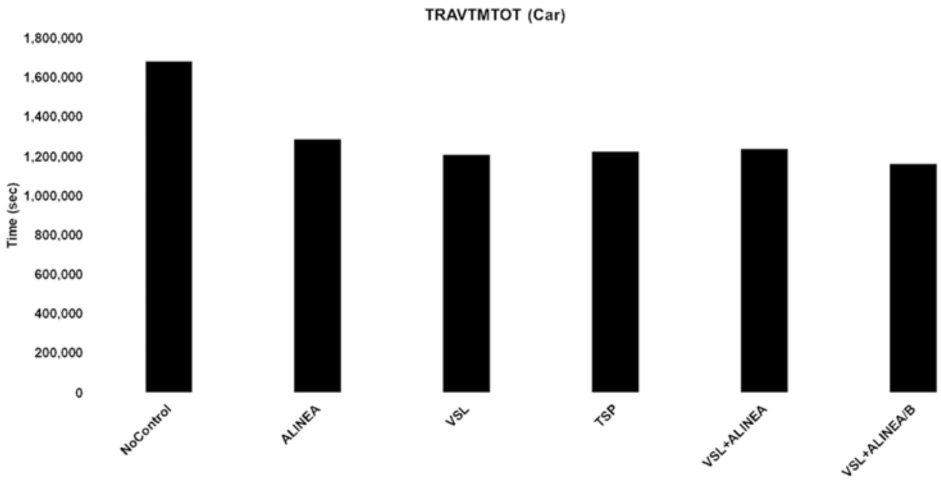


**Figure 6.7 :** Total travel time changes of cars among different scenarios.

For buses as shown in Figure 6.8, the proposed VSL+ALINEA/B model is able to decrease total travel time by 34.9% and 2.5% compared to NoControl scenario and the existing VSL+ALINEA model respectively. As it's clear, the NoControl scenario and ALINEA have the highest values with quite big differences.

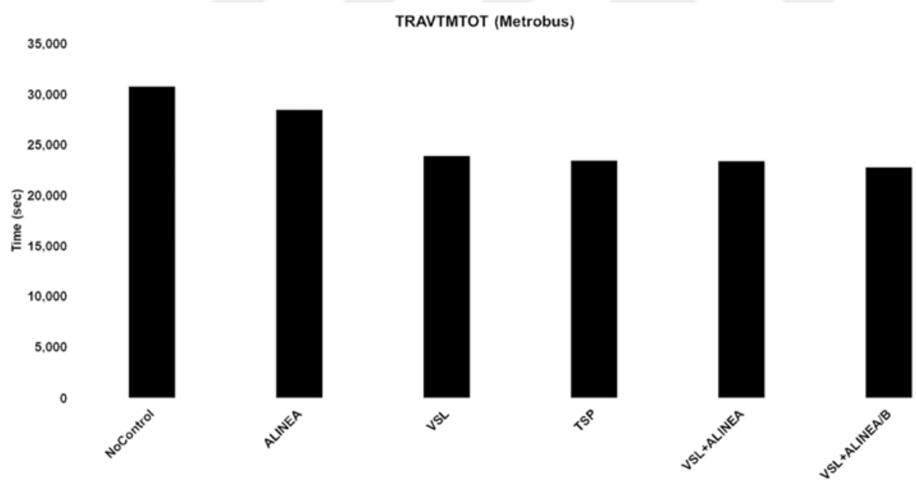


**Figure 6.8 :** Total travel time changes of Metrobus vehicles among different scenarios.

**Total Travelled Distance**

Travelled distance (DISTTOT) refers to average distance traveled [m] by vehicles between the start section and destination section of travel time measurement which can be obtained through "Network Performance" menu of VISSIM. If there is only one path leading from the start section to the destination section, its value corresponds to attribute Distance value of travel time measurement.

In general, for the whole network, the proposed VSL+ALINEA/B model is able to increase total travelled distance by 5.3% and 1.6% compared to NoControl scenario and the existing VSL+ALINEA model respectively. In Figures 6.9 and 6.10, the bar chart shows the total travelled distance changes of the cars and buses among different scenarios. For both of them, NoControl scenario has the lowest travelled distance value, while the other scenarios have quiet similar results. As it is clear, the proposed scenario VSL+ALINEA/B has a better result than VSL+ALINEA which no bus included. However, it has not remarkable improvement for buses' travelled distance compared to VSL+ALINEA.

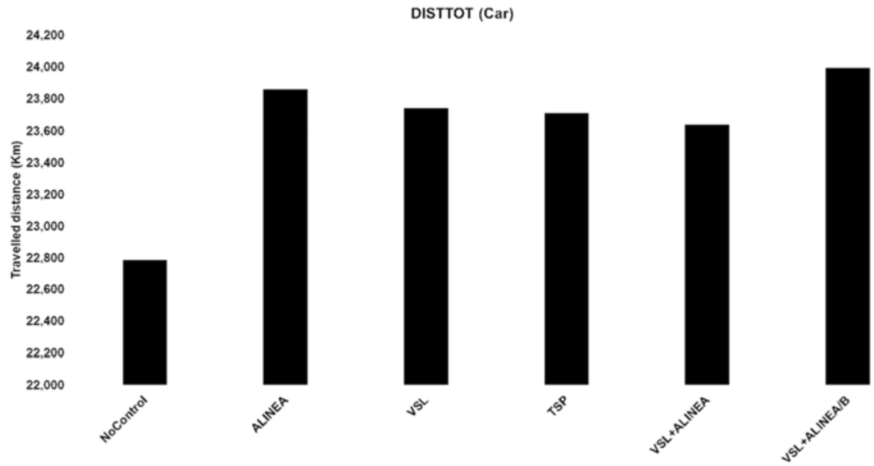


**Figure 6.9 :** Total traveled distance changes of cars among different scenarios.

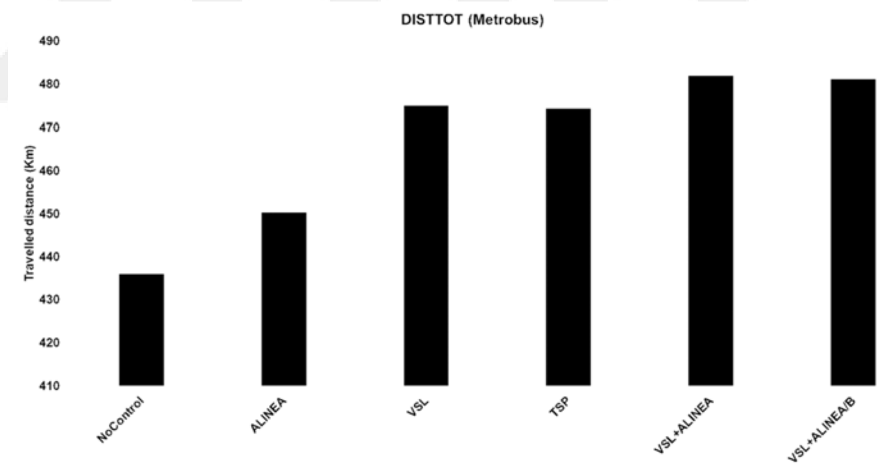


**Figure 6.10 :** Total traveled distance changes of Metrobus vehicles among different scenarios.

**Average Delay**

Average delay per vehicle in second is Total delay / (Number of veh in the network + number of veh that have arrived) which can be obtained through "Network Performance" menu of VISSIM. Table 6.5 summarize the average delays and number of stops in the network for different scenarios. Number of stops represents the number of stop-and-go movement of vehicles. The proposed VSL+ALINEA/B model is able to decrease average vehicle delays and total number of stops compared to NoControl scenario by 177.2% and 145.9% respectively. Compared to the existing VSL+ALINEA model, it improves average delays and no. of stops by 28.6% and 69.9% respectively by decreasing the interaction among car and buses.

Table 6.5 : Average delays (sec) and number of stops among scenarios.

| Scenario | Delay Avg (All) | Delay Avg (Car) | Delay Avg (Bus) | Stops (Car) | Stops (Bus) |
|---|---|---|---|---|---|
| **NoControl** | 142 | 144 | 92 | 22,032 | 102 |
| **ALINEA** | 77 | 78 | 66 | 13,759 | 67 |
| **Changes (%)** | -85.8% | -85.1% | -39.2% | -60.1% | -52.2% |
| **VSL** | 61 | 63 | 21 | 9,366 | 44 |
| **Changes (%)** | -131.7% | -129.2% | -337.2% | -135.2% | -131.8% |
| **TSP** | 60 | 61 | 18 | 8,102 | 15 |
| **Changes (%)** | -139.1% | -136.4% | -417.4% | -171.9% | -580.0% |
| **VSL+ALINEA** | 66 | 68 | 14 | 14,804 | 34 |
| **Changes (%)** | -115.6% | -112.5% | -546.9% | -48.8% | -200.0% |
| **VSL+ALINEA/B** | 51 | 53 | 10 | 8,729 | 13 |
| **Changes (%) vs. No Control** | -177.2% | -172.2% | -860.7% | -152.4% | -684.6% |
| **Changes (%) vs. VSL+ALINEA** | -28.6% | -28.1% | -48.5% | -69.6% | -161.5% |

Number of stops can be an appropriate performance measures representing the stop-and-go shockwaves in the network. As seen in Table above, the number of stops for both cars and buses have been significantly decreased by 69.6% and 161.5% respectively means that the network performance has been improved in terms of stop-and-go shockwaves as well. Not only does VSL+ALINEA improves average delays and stops for buses, but also its benefits cars by reducing their interaction with buses in particular in YILDIZ ramp area i.e. conflicts between Metrobus and BESIKTAS flow.

Figure 6.11 compares the average delay of cars and Metrobus according to the different scenarios. NoControl scenario for cars has the highest value with big difference than other scenarios, while for Metrobus average delays are almost similar to ALINEA scenario.

As it is clear, the proposed VSL+ALINEA/B model has the lowest average delays in both cases Cars and Metrobus than VSL+ALINEA which no bus considered.

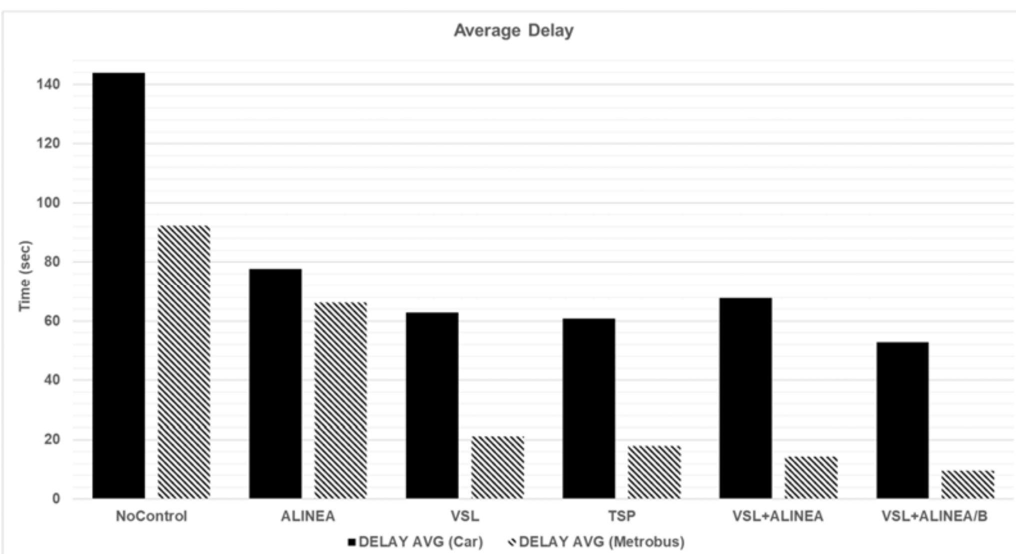


**Figure 6.11 :** Average delays changes of cars and Metrobus vehicles among different scenarios.

**Average Speed**

The average speed of the entire network is another important measure must be considered. Average speed [km/h] or [mph] is calculated from Total distance / Total travel time which can be obtained through "Network Performance" menu of VISSIM. The bar chart below, Figure 6.12, depicts the average speed changes of cars and Metrobus, according to the different scenarios. The NoControl scenario for both cars and Metrobus has the lowest average speed value in whole network by 49 and 52 km/hr respectively with clear difference than other scenarios.

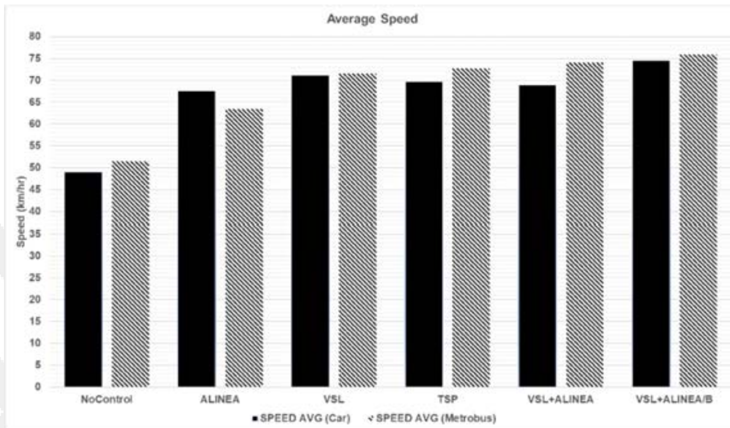


**Figure 6.12 :** Average speed changes of cars and Metrobus vehicles among different scenarios.

The proposed VSL+ALINEA/B model has the highest average speed in both cases; cars (75 km/hr) and Metrobus (76 km/hr) than VSL+ALINEA, it means a better result for the proposed model.

Concerning average speed changes, Figure 6.13 also illustrates the speed heatmap of the entire network for all vehicles in which Y-axes represents the study area divided into four segments namely upstream, merging, bottleneck, and downstream segments and different scenarios. The x-axis represents simulation time (minutes) of the study area in VISSIM.

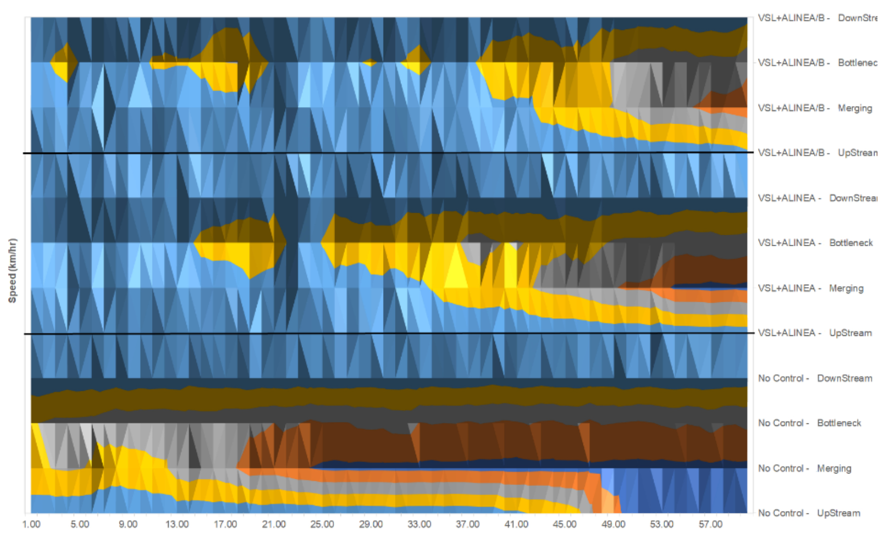


**Figure 6.13 :** Speed heatmap of the entire network for all vehicles.

As clearly seen below, the proposed VSL+ALINEA/B model outperformed NoControl and the existing VSL+ALINEA model by providing the highest average speed both in all four segments of the study area in particular in merging and bottleneck areas and simulation time.

**Occupancy rate changes**

The occupancy rate of the entire network as the calculation basis of ALINEA control model is another important measure must be considered. To this end, Figure 6.14 proposes the occupancy heatmap of the entire network for all vehicles in which X-axes represents the study area divided into four segments namely upstream, merging, bottleneck, and downstream segments and different scenarios. The Y-axis represents simulation time (minutes) of the study area in VISSIM. The Z-axis represents occupancy rate measured by VISSIM.

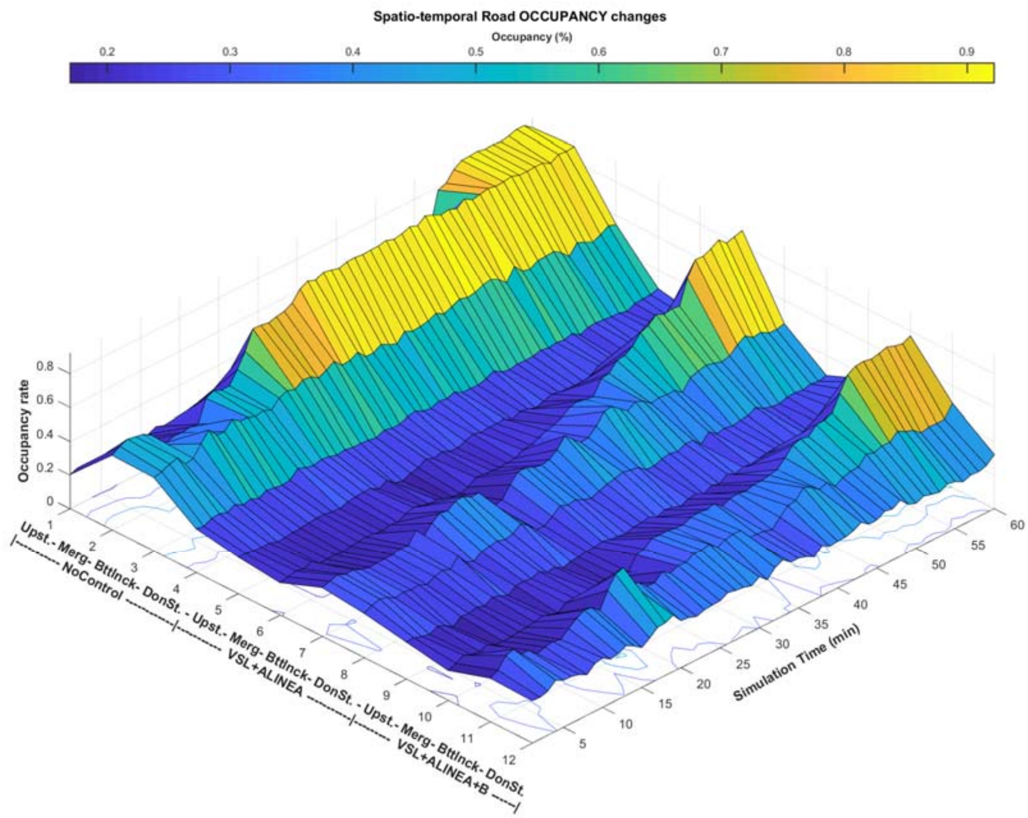


**Figure 6.14 :** Road occupancy heatmap of the entire network for all vehicles.

The main goal of the proposed VSL+ALINEA/B model is to decrease the occupancy rate both in value and time intervals as well as to shift potential merging congestion to the upstream of mainline. It benefits the bottleneck area to have the highest volume close to capacity. The heatmap above demonstrates that the proposed VSL+ALINEA/B model outperformed NoControl and the existing VSL+ALINEA model by providing the lowest occupancy rate during time intervals (SimTime) over all four segments of the study area in particular in merging and bottleneck areas.

**Bottleneck throughput (capacity)**

In general, for the entire network, the proposed VSL+ALINEA/B model is able to increase bottleneck throughput by 6.2% and 2.5% compared to NoControl scenario and the existing VSL+ALINEA model respectively. Figure 6.15 – 6.16 show the bottleneck throughput (VEHicle ARRived) of cars and buses due to different scenarios.

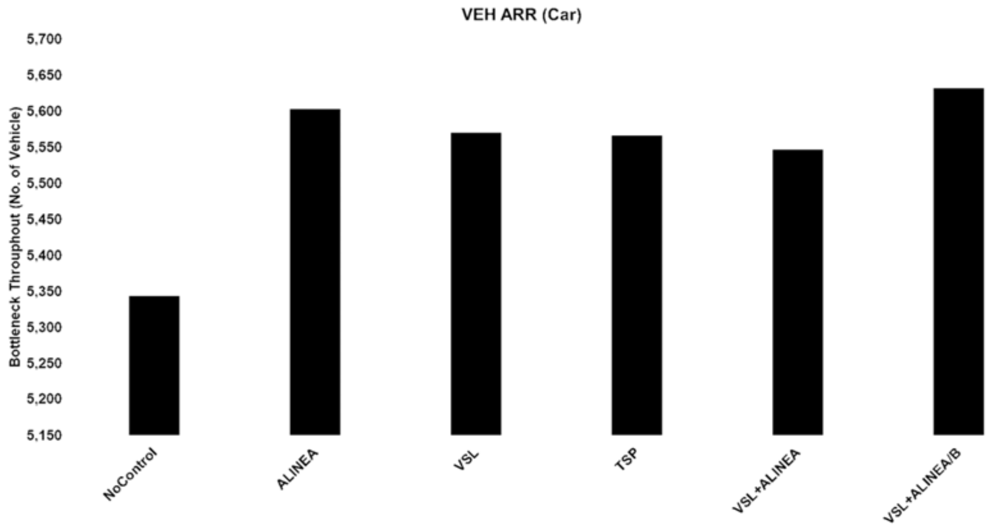


**Figure 6.15 :** Total car throughput changes among different scenarios.

NoControl scenario has the lowest car (5348 veh/hr) and bus (100 bus/hr) throughput with big difference than other scenarios while the proposed VSL+ALINEA/B model has the highest car (5682 veh/hr) and bus (116 bus/hr) throughput by 5.9% and 13.8% respectively. Existing models such as TSP, VSL, ALINEA or even VSL+ALINEA are able to improve bottleneck throughput for only one transport mode; cars (e.g. ALINEA in Figure 6.15) or buses (e.g. VSL in Figure 6.16).

However, the comparison of the proposed VSL+ALINEA/B model and the existing VSL+ALINEA model confirms that the proposed VSL+ALINEA/B model outperformed the existing models not only by increasing the number of bus throughputs from bottleneck but also it increased the number of cars throughput which is the limitation of existing models.

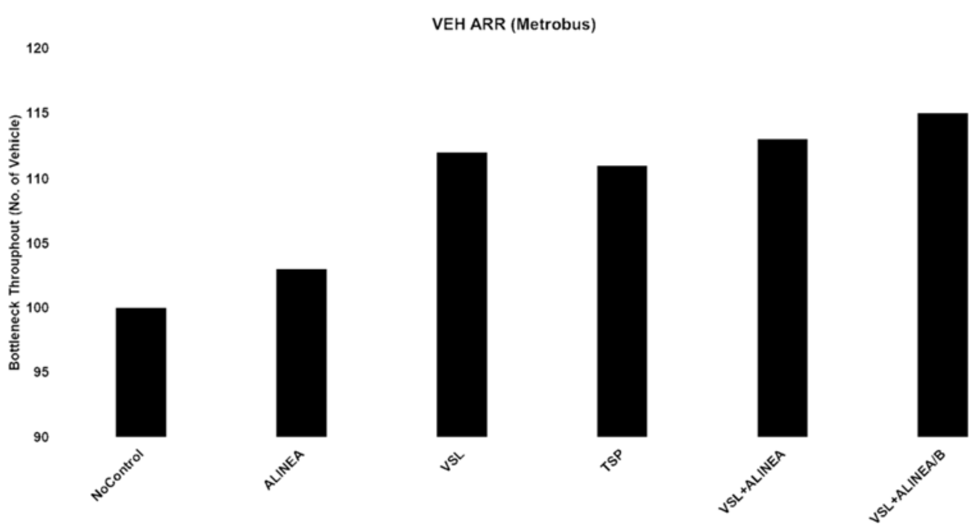


**Figure 6.16 :** Total Metrobus vehicles changes among different scenarios.

**Fuel consumption and emissions**

From *sustainable and energy efficient transport* point of views, fuel consumption and air-pollution relevant emission created by different scenarios are another important performance measure must be discussed. In VISSIM, fuel consumption and emissions can be obtained from "node performance results" section. According to VISSIM manual, these measures are calculated by a speed-based formula which is not released by the Company. Table 6.6 summarize the results of fuel consumption (in Liter) and emissions (in grams) namely Carbon Monoxide (CO), Nitrogen Oxides (NOx), and Volatile Organic Compounds (VOC) produces by different scenarios. As seen in the Table below, the proposed model is able to reduce fuel consumption and emission by 75.4% compared to NoControl scenario and by 8.4% compared to the existing VSL+ALINEA model.

**Table 6.6 :** Fuel consumption (L) and Emissions (gr) summary.

| BEST of scenarios | LOS (ALL) | VEHS (ALL) | FUEL CONS. | CO | $NO_X$ | VOC |
|---|---|---|---|---|---|---|
| **No Control** | LOS F | 5,585.00 | 2551.7 | 47,118.92 | 9,167.63 | 10,920.27 |
| **ALINEA** | LOS D | 5,853.00 | 1778.6 | 32,842.34 | 6,389.93 | 7,611.53 |
| **Changes (%)** | | **4.6%** | **-43.5%** | **-43.5%** | **-43.5%** | **-43.5%** |
| **VSL** | LOS C | 5`,831.00 | 1467.7 | 27,101.53 | 5,272.97 | 6,281.04 |
| **Changes (%)** | | **4.2%** | **-73.9%** | **-73.9%** | **-73.9%** | **-73.9%** |
| **TSP** | LOS C | 5,814.00 | 1280.1 | 23,638.55 | 4,599.20 | 5,478.46 |
| **Changes (%)** | | **3.9%** | **-99.3%** | **-99.3%** | **-99.3%** | **-99.3%** |
| **VSL+ ALINEA** | LOS C | 5,802.00 | 1577.5 | 29,129.73 | 5,667.59 | 6,751.10 |
| **Changes (%)** | | **3.7%** | **-61.8%** | **-61.8%** | **-61.8%** | **-61.8%** |
| **VSL+ ALINEA/B** | LOS B | 5,953.20 | 1455.1 | 26,868.35 | 5,227.61 | 6,227.00 |
| **Changes (%) vs. No Control** | | **6.2%** | **-75.4%** | **-75.4%** | **-75.4%** | **-75.4%** |
| **Changes (%) vs. VSL+ALINEA** | | **2.5%** | **-8.4%** | **-8.4%** | **-8.4%** | **-8.4%** |

Moreover, it gives the level of service (LOS) values obtained by different scenarios. NoControl scenario has the worst LOS (F) while the proposed scenario, VSL+ALINEA/B provides the highest LOS (B) compared to other scenarios namely ALINEA (LOS D), VSL (LOS C), TSP (LOS C) and even VSL+ALINEA scenario with LOS C which confirms the better performance of the proposed model.

As a conclusion, the proposed VSL+ALINEA/B model has a better and acceptable result compared to all the existing models like VSL+ALINEA in terms of current traffic condition as approved by performance measures.

### 6.2.2 Effectiveness of the new VSL+ALINEA/B for different bus frequency

As mentioned, the proposed VSL+ALINEA/B model outperformed the existing VSL+ALINEA model as well as TSP, VSL-only, and ALINEA-only models in the presence of current bus volume *i.e.* 125 bus/hr. However, it is necessary to test the VSL+ALINEA/B model performance with different bus volumes in order to analyze its effectiveness in different possible conditions. To this end, three kind of control scenarios including i) no control, ii) combined VSL and ALINEA, and iii) VSL+ALINEA/B with different Metrobus frequency (25, 75, 125, 175 bus/hr) has been modelled using VISSIM. Figures 6.17 – 6.22 demonstrate the performance measures of different bus volumes scenarios namely total travel time, avg. delay, avg. speed, bottleneck throughput (car, bus) and road occupancy rate changes.

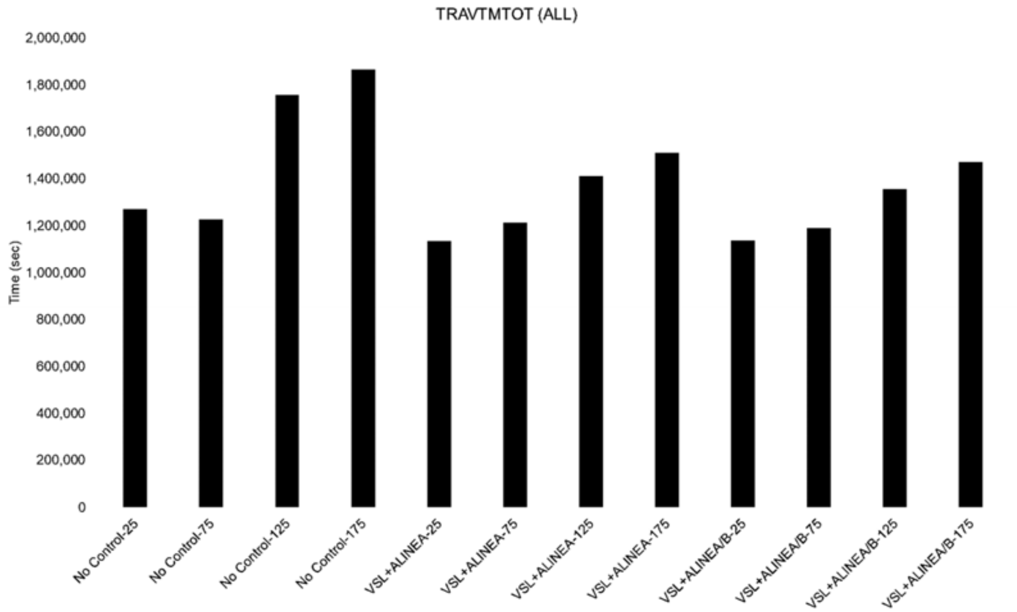


**Figure 6.17 :** Total travel time comparison for different bus volumes.

In general, for the whole network, the proposed VSL+ALINEA/B model is able to improve total travel time for bus frequency of 75, 125, and 175 bus/hr by 2.0%, 4.2%, and 4.5% compared to the existing VSL+ALINEA model respectively. The bar chart in Figure 6.18 illustrates the total travel time changes of buses due to different bus frequency.

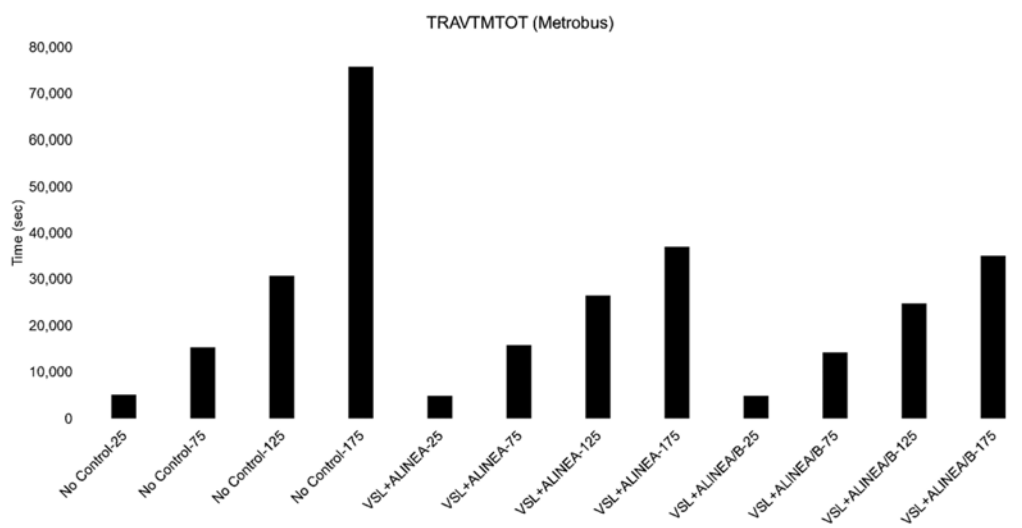


**Figure 6.18 :** Total travel time (bus) comparison for different bus volumes.

In the low bus frequency (25 bus/hr), the proposed model has not any achievement compared to the existing VSL+ALINEA model. However, it can be seen that the increase in the number of buses approaching the merging area resulting in the increasing of the effectiveness of the proposed model. For instance, total travel time improved by the proposed model for the highest bus frequency (175 bus/hr) is 16.3% while the total travel time improvement for the lowest bus frequency (25 bus/hr) is around 4%.

Average delays in the network for different scenarios are shown in Figure 6.19. It is obvious that the proposed VSL+ALINEA/B model is able to decrease average vehicle delays for bus frequency of 75, 125, and 175 bus/hr by 11.6%, 12.3%, and 9.9% respectively compared to the existing VSL+ALINEA model.

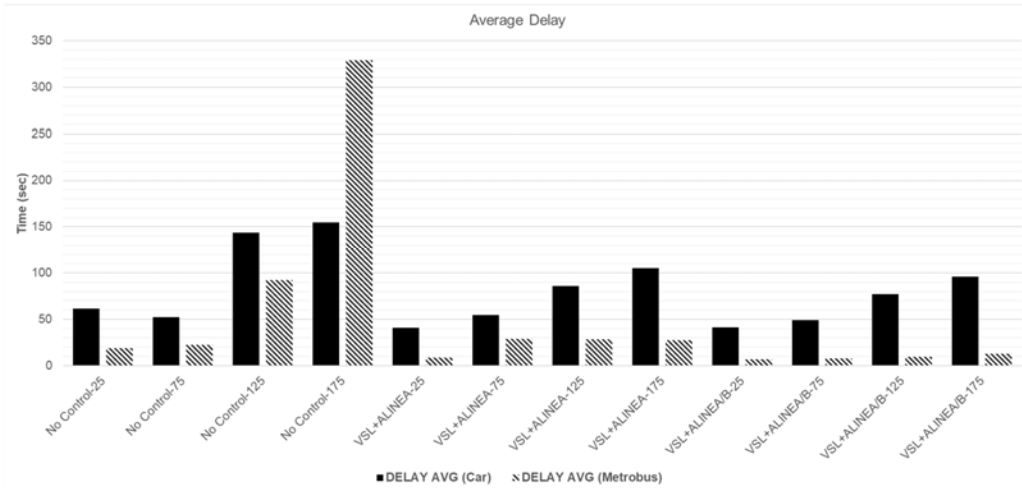


**Figure 6.19 :** Average delay comparison for different bus volumes.

The average speed cars and buses for different scenarios and bus frequency is shown in the bar chart below. It can clearly be seen in Figure 6.20 that the proposed VSL+ALINEA/B model is able to improve average speed in the network with a bus frequency of 75, 125, and 175 bus/hr by 2.4%, 5.5%, and 5.6% respectively compared to the existing VSL+ALINEA model.

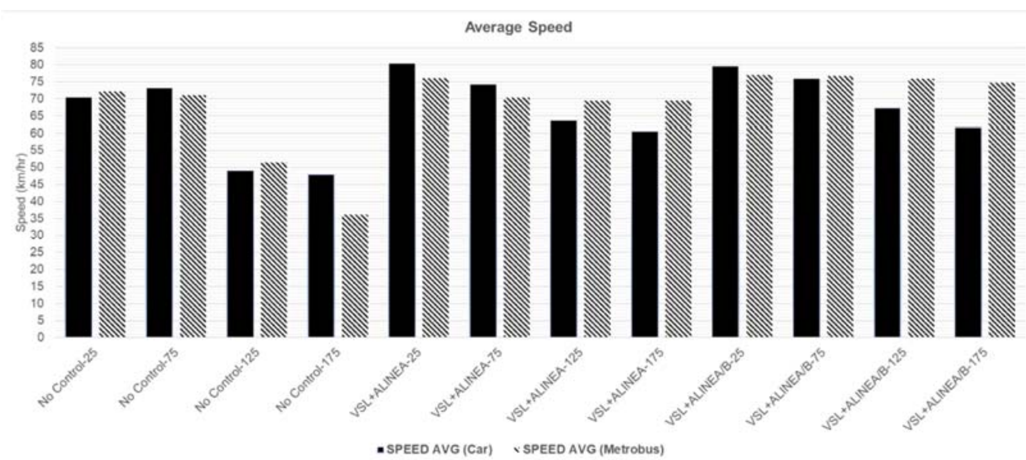


**Figure 6.20 :** Average speed comparison for different bus volumes.

To better understanding of the road occupancy changes in time and space, Figure 6.21 presents the Heatmap of road occupancy changes of the entire network for all vehicles and selected scenarios. In this graph, X-axis represents simulation time (minutes) of the study area in VISSIM while Y-axes represents the study area divided into four segments namely upstream, merging, bottleneck, and downstream segments and different bus frequency.

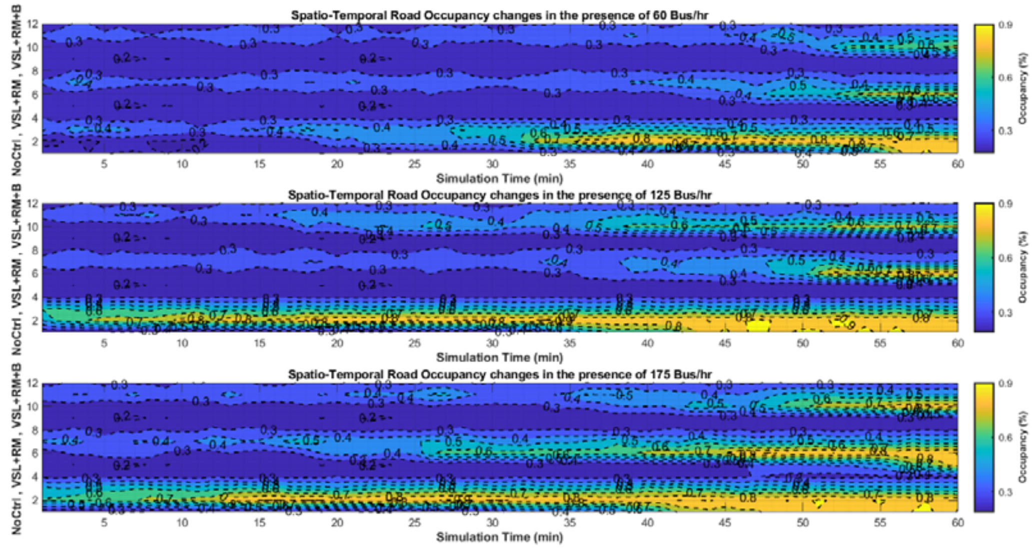


**Figure 6.21 :** Heatmap of road occupancy changes due to different bus frequency.

The Heatmap above demonstrates that the proposed VSL+ALINEA/B model outperformed NoControl and the existing VSL+ALINEA model by providing the lowest occupancy rate during time intervals (SimTime) over all four segments of the study area in particular in merging and bottleneck areas.

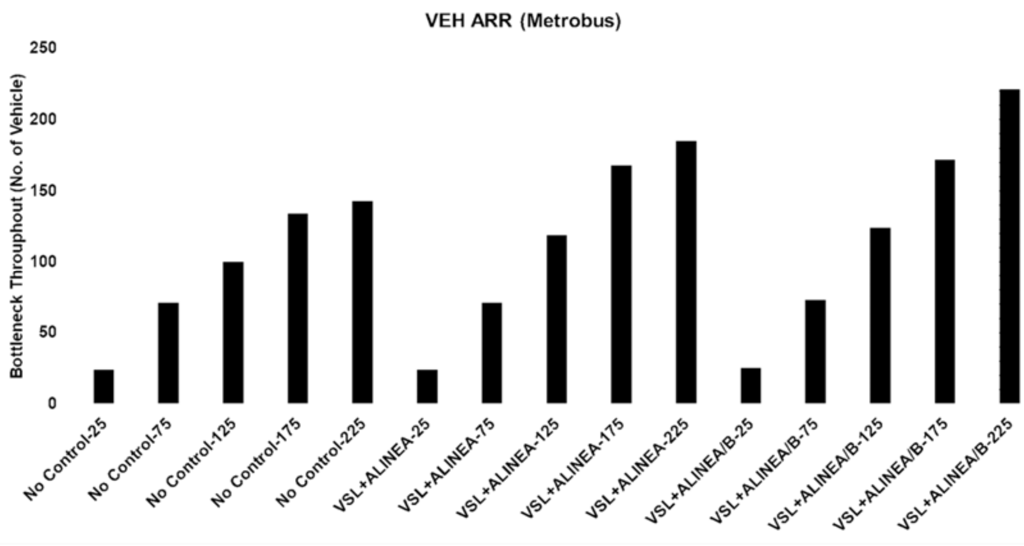


**Figure 6.22 :** Bottleneck BUS throughput comparison for different bus volumes.

The bar chart in Figure 6.22 depicts the total no. of buses passed bottleneck area. In the low bus frequency (25 bus/hr), the proposed model has quiet similar results compared to the existing VSL+ALINEA model. However, it can be seen that the increase in the number of buses approaching the merging area resulting in the increasing of the effectiveness of the proposed model.

For instance, the no. of buses crossed bottleneck area improved by the proposed model for the highest bus frequency (175 bus/hr) is 172 bus/hr (3.5% improved compared to

VSL+ALINEA) while the bottleneck bus throughput for the lowest bus frequency (75 bus/hr) is around 72 bus/hr (1.4% improved compared to VSL+ALINEA).

Briefly, the proposed VSL+ALINEA/B model has a better and acceptable result compared to all the existing models like VSL+ALINEA under different bus frequency i.e. 75, 125, and 175 while it has not a significant achievement in low bus frequency (25 bus/hr) as approved by performance measures. Thus, it can be concluded that the increase in the number of buses approaching the merging area resulting in the increasing of the effectiveness of the proposed VSL+ALINEA/B model.

# 7. CONCLUSIONS

## 7.1 New Automatic Calibration Process using Parallel Computing Technique

Driving behavior and lane change models' parameters has been widely used in order to calibrate and achieve reliable microsimulation models. In this study, metaheuristic optimization methods, namely GA, hybrid GA, PSO, and hybrid PSO, have been developed and applied to calibrate traffic simulation models. The VISSIM as microsimulation software and MATLAB as programming software are employed for the implementation of the proposed optimization methods.

The proposed calibration procedure has been implemented and tested on a segment of the O-1 Highway in Istanbul, Turkey as study area. The calibration is coded as a minimization problem in which the objective function values are set to MANE and RMSE. Results show that, hybrid GAPSO, and hybrid PSOGA methods outperform GA-only and PSO-only methods. Among all the algorithms tested, hybrid GAPSO generated the lowest MANE and RMSE values.

The most time-consuming step in calibrating problems the application of optimization algorithms is generally the objective function evaluation step, where EA has to simulate and calculate a corresponding objective function value for each set of parameters.

Although the proposed hybrid GAPSO showed a successful computational performance, one might consider using PCT to decrease the computation time of the proposed calibration procedure. Another contribution of this study has also been to develop a quick calibration and auto-tuning procedure for the parameters of driving behavior models using EA and PCT. It is able to save a significant amount of time during the optimization process by sharing the total computational time among all cores. Two scenarios with/without PCT were analyzed using the methodology developed. The results of the scenario analysis suggest that using an integrated calibration and PCT are capable of significantly reducing the computational time of the optimization process and improving the optimization algorithm performance in these traffic simulation models – in this study 45-66%. This method is useful for overcoming the limitations of computational time in existing calibration methods.

## 7.2 Effects of Bus Priority Methods on Adjacent Mixed Traffic

Last but not least, to address the gap in the literature, a combined VSL and ALINEA model in the presence of high bus volume (e.g. Metrobus vehicles in YILDIZ merging segment) has been developed. This integrated VSL and ALINEA model considering high bus volume so-called VSL+ALINEA/B has been coded and applied to the calibrated model through the VisVAP. Various scenarios namely i) no control, ii) with control (TSP, ALINEA, VSL, VSL+ALINEA/B) have been tested on the calibrated YILDIZ merging simulation model. The results of scenario analysis showed that, the proposed VSL+ALINEA/B is able to improve network performance compared to the existing VSL+ALINEA model which are as follows:

- Total travel time by 6.6%, (compared to NoControl 44.2%)
- Average delays of mixed traffic and buses by 28.1% and 48.5% respectively,
- Average speed by 7.4%,
- Bottleneck throughput (capacity) by 2.5% (compared to No-Control 6.2%),
- Level of service value achieved by VSL+ALINEA/B for bottleneck area: LOS B, while, by No-Control: LOS F, and by VSL+ALINEA: LOS C.
- Fuel consumption, CO, NOx, VOC emissions by 8.4% on average (compared to No-Control 75.4%).

As can be seen above, the proposed VSL+ALINEA/B model outperformed the existing VSL+ALINEA model as well as TSP, VSL-only, and ALINEA-only models in the presence of current bus volume *i.e.* 125 bus/hr. However, it is necessary to test the VSL+ALINEA/B model performance with different bus frequency in order to analyze its effectiveness in different possible conditions. To this end, three kind of control scenarios including i) no control, ii) VSL+ALINEA, and iii) VSL+ALINEA/B with different Metrobus frequency (25, 75, 125, 175 bus/hr) has been modelled using VISSIM.

It is found that the proposed VSL+ALINEA/B model has a better and acceptable result compared to all the existing models like VSL+ALINEA under different bus frequency i.e. 75, 125, and 175 while it has not a significant achievement in low bus frequency (25 bus/hr) as approved by performance measures. Thus, it can be concluded that the increase in the number of buses approaching the merging area resulting in the increasing of the effectiveness of the proposed VSL+ALINEA/B model.

### 7.3 Further Research

Further research should address the following issues:

- Since the behavior of violators greatly affects the performance of non-segregated bus lanes, the motives for such behaviors, especially in developing countries, should be analyzed. Furthermore, the insufficiency of data regarding the design, implementation, operation, enforcement and fining systems underpinning BL projects currently limits the possibility of conducting longitudinal research into Istanbul's BL projects.
- The application of proposed fully-automatic methodology could be extended to larger freeway networks or signalized roadways. Improving optimization and calibration performance of proposed methodology by developing an auto-tuning process for hybrid GAPSO, and hybrid PSOGA and also using a different combination of GA and PSO operators inside hybrid technique remains an interesting area for investigation.
- Regarding the use of PCT for VISSIM calibration, the question of whether to use more cores for individual simulation or divide cores for multiple parallel simulations is a potential research topic for further study.

- In the development of the proposed VSL+ALINEA/B model, the best set of parameters has been tested and used for VSL and ALINEA algorithm which have been obtained manually. Using an optimization process in order to find the well-matched sets of parameters for VSL and ALINEA can be a potential extension of the proposed model.
- The proposed VSL+ALINEA/B model has been tested as local on-ramp control method which can be extended and tested for large network with several merging points.

## REFERENCES


**Abbas, M. M. and Chong, L.** (2013). 'Car-Following Trajectory Modeling with Machine Learning- A Showcase for the Merits of Artificial Intelligence', *92nd Annual Meeting of the Transportation Research Board*.

**Abd-El-Wahed, W. F., Mousa, A. A. and El-Shorbagy, M. A.** (2011). 'Integrating particle swarm optimization with genetic algorithms for solving nonlinear optimization problems', *Journal of Computational and Applied Mathematics*. Elsevier B.V., *235*(5), pp. 1446–1453. doi: 10.1016/j.cam.2010.08.030.

**Abdelfatah, A. and Abdulwahid, A. R.** (2017). 'Impact of Exclusive Bus Lanes on Traffic Performance in Urban Areas', in *Proceedings of the 2nd World Congress on Civil, Structural, and Environmental Engineering (CSEE'17)*. Barcelona, Spain, pp. 1–10. doi: 10.11159/icte17.125.

**Aghabayk, K. *et al.*** (2013). 'A Novel Methodology for Evolutionary Calibration of Vissim By Multi-Threading', *Australasian Transport Research Forum*, (October), pp. 1–15. Available at: http://www.patrec.org/atrf.aspx.

**Ahmed, B.** (2016). *Exploring New Bus Priority Strategies at Isolated Vehicle Actuated Junctions*, *Thesis*. University of Southampton. Available at: https://eprints.soton.ac.uk/413950/.

**Ahmed, K. I.** (1999). 'Modeling Drivers ' Acceleration and Lane Changing Behavior', *Transportation*, *Ph.D*, p. 189. Available at: http://web.mit.edu/its/papers/DRIVIN.PDF.

**Al-Deek, H. *et al.*** (2017). 'A technical note on evaluating the effectiveness of bus rapid transit with transit signal priority', *Journal of Intelligent Transportation Systems*. Taylor & Francis, *21*(3), pp. 227–238. doi: 10.1080/15472450.2017.1286987.

**Alpkokin, P. and Ergun, M.** (2012). 'Istanbul Metrobus: first intercontinental bus rapid transit', *Journal of Transport Geography*. Elsevier Ltd, *24*, pp. 58–66. doi: 10.1016/j.jtrangeo.2012.05.009.

**Ang-Olson, J. and Mahendra, A.** (2011). 'Cost / Benefit Analysis of Converting a Lane for Bus Rapid Transit — Phase Ii Evaluation and Methodology', *Transportation Research Board*, *Research R*(April), p. 29. doi: 10.17226/14518.

**APTA** (2008). *Public Transportation Fact Book*. 59th Editi. Edited by J. Neff. Washington, DC: American Public Transportation Association. Available at: http://www.apta.com/resources/statistics/Documents/FactBook/APTA_2008_Fact_Book.pdf.

**Babazadeh, A., Poorzahedy, H. and Nikoosokhan, S.** (2011). 'Application of particle swarm optimization to transportation network design problem', *Journal of King Saud University - Science*. King Saud University, *23*(3), pp. 293–300. doi: 10.1016/j.jksus.2011.03.001.

**Balakrishna, R. *et al.*** (2007). 'Calibration of Microscopic Traffic Simulation Models: Methods and Application', *Transportation Research Record: Journal of the Transportation Research Board*, *1999*, pp. 198–207. doi: 10.3141/1999-21.

**Banks, J. H.** (1991). 'The two-capacity phenomenon: some theoretical issues', *Transportation Research Record*, (1320), pp. 234–241.

**Barcel, J. *et al.*** (2005). 'Microscopic traffic simulation: A tool for the design, analysis and evaluation of intelligent transport systems', *Journal of Intelligent and Robotic Systems*, *41*(2–3), pp. 173–203. doi: 10.1007/s10846-005-3808-2.

**Barcelo, J., Fellendorf, M. and Vortisch, P.** (2010). *Fundamentals of Traffic Simulation*. Springer. doi: 10.1007/978-1-4614-1900-6.

**Barroso, E. S., Parente, E. and Cartaxo de Melo, A. M.** (2017). 'A hybrid PSO-GA algorithm for optimization of laminated composites', *Structural and Multidisciplinary Optimization*, *55*(6), pp. 2111–2130. doi: 10.1007/s00158-016-1631-y.

**Beirão, G. and Sarsfield Cabral, J. A.** (2007). 'Understanding attitudes towards public transport and private car: A qualitative study', *Transport Policy*, *14*(6), pp. 478–489. doi: 10.1016/j.tranpol.2007.04.009.

**Bingul, Z., Sekmen, A. and Zein-Sabatto, S.** (2000). 'Genetic Algorithms Applied to Real Time Multi-Objective Optimization Problems', *Proceedings of the 2000 IEEE SouteastCon Conference (SoutheastCON'2000)*, pp. 95–103.

**Boittin, C. *et al.*** (2015). 'Particle swarm for calibration of land-use and transport integrated models', *CUPUM 2015 - 14th International Conference on Computers in Urban Planning and Urban Management*.

**Bugg, Z. *et al.*** (2016). 'Effect of Transit Preferential Treatments on Vehicle Travel Time', *Transportation Research Board 95th Annual Meeting*. Washington, DC: Transportation Research Board, pp. 1–17. Available at: http://docs.trb.org/prp/16-1724.pdf.

**Burinskienė, M., Gusarovienė, M. and Gabrulevičiūtė-Skebienė, K.** (2014). 'The Impact of Public Transport Lanes on the Operating Speed of Buses', in *The 9th International Conference 'Environmental Engineering 2014'*. Vilnius, Lithuania: Vilnius Gediminas Technical University Press "Technika" 2014. doi: 10.3846/enviro.2014.112.

**Carlson, R. C. *et al.*** (2012). 'Integrated ramp metering and mainstream traffic flow control on freeways using variable speed limits', *IFAC Proceedings Volumes (IFAC-PapersOnline)*, *45*(24), pp. 110–115. doi: 10.3182/20120912-3-BG-2031.00021.

**Carlson, R. C., Papamichail, I. and Papageorgiou, M.** (2014). 'Integrated feedback ramp metering and mainstream traffic flow control on motorways using variable speed limits', *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, *46*, pp. 209–221. doi: 10.1016/j.trc.2014.05.017.

**Carry, W. *et al.*** (2014). 'Red Bus Lane Treatment Evaluation', *Transportation Research Board 93rd Annual Meeting. January 12-16, Washington, D.C.*, pp. 1–31.

**Cassidy, M. J., Anani, S. B. and Haigwood, J. M.** (2002). 'Study of freeway traffic near an off-ramp', *Transportation Research Part A: Policy and Practice*, *36*(6), pp. 563–572. doi: 10.1016/S0965-8564(01)00016-7.

**Cassidy, M. J. and Bertini, R. L.** (1999). 'Some traffic features at freeway bottlenecks', *Transportation Research Part B: Methodological*, *33*(1), pp. 25–42. doi: 10.1016/S0191-2615(98)00023-X.

**Cassidy, M. J. and Rudjanakanoknad, J.** (2005). 'Increasing the capacity of an isolated merge by metering its on-ramp', *Transportation Research Part B: Methodological*, *39*(10), pp. 896–913. doi: 10.1016/j.trb.2004.12.001.

**Cesme, B. *et al.*** (2018). 'Strategies and Barriers in Effective Bus Lane Implementation and Management : Best Practices for Use in the Greater Washington, D.C. Region', in *Transportation Research Board 97th Annual Meeting*. Washington, D.C.: Transportation Research Board. Available at: https://trid.trb.org/view/1495604.

**Cesme, B., Altun, S. Z. and Lane, B.** (2015). 'Queue Jump Lane, Transit Signal Priority, and Stop Location Evaluation of Transit Preferential Treatments Using Microsimulation', *Transportation Research Record: Journal of the Transportation Research Board*, *2533*, pp. 39–49. doi: 10.3141/2533-05.

**Chaudhary, N. A. *et al.*** (2004). 'Ramp Metering Algorithms and Approaches for Texas', *7*(2).

**Chen, C., Varaiya, P. and Kwon, J.** (2005). 'An Empirical Assessment Of Traffic Operations', in *Proceedings of the 16th International Symposium on Transportation and Traffic Theory*. College Park, MD: Elsevier, pp. 105–124. Available at: https://people.eecs.berkeley.edu/~varaiya/papers_ps.dir/isttt_trb_expanded.pdf.

**Chen, D., Ahn, S. and Hegyi, A.** (2014). 'Variable speed limit control for steady and oscillatory queues at fixed freeway bottlenecks', *Transportation Research Part B: Methodological*. Elsevier Ltd, *70*, pp. 340–358. doi: 10.1016/j.trb.2014.08.006.

**Chen, X. M. *et al.*** (2015). 'Investigations of interactions between bus rapid transit and general traffic flows', *Journal of Advanced Transportation*, *49*(3), pp. 326–340. doi: 10.1002/atr.1268.

**Chen, Y., Chen, G. and Wu, K.** (2016). 'Evaluation of Performance of Bus Lanes on Urban Expressway Using Paramics Micro-simulation Model', *Procedia Engineering*. Elsevier B.V., *137*, pp. 523–530. doi: 10.1016/j.proeng.2016.01.288.

**Cheu, R.-L. *et al.*** (1998). 'Calibration of FRESIM for Singapore Expressway Using Genetic Algorithm', *Journal of Transportation Engineering*, *124*(6), pp. 526–535. doi: 10.1061/(ASCE)0733-947X(1998)124:6(526).

**Chiappone, S. *et al.*** (2016). 'Traffic simulation models calibration using speed-density relationship: An automated procedure based on genetic algorithm', *Expert Systems with Applications*, *44*, pp. 147–155. doi: 10.1016/j.eswa.2015.09.024.

**Chimba, D., Sando, T. and Kwigizile, V.** (2010). 'Effect of bus size and operation to crash occurrences', *Accident Analysis and Prevention*. Elsevier Ltd, *42*(6), pp. 2063–2067. doi: 10.1016/j.aap.2010.06.018.

**Choudhury, C. F. *et al.*** (2006). 'Modeling Cooperative Lane Changing and Forced Merging Behavior', *Transport Science*, pp. 1–16.

**Choudhury, C., Ramanujam, V. and Ben-Akiva, M.** (2009). 'Modeling Acceleration Decisions for Freeway Merges', *Transportation Research Record: Journal of the Transportation Research Board*, *2124*, pp. 45–57. doi: 10.3141/2124-05.

**Chung, K., Rudjanakanoknad, J. and Cassidy, M. J.** (2007). 'Relation between traffic density and capacity drop at three freeway bottlenecks', *Transportation Research Part B: Methodological*, *41*(1), pp. 82–95. doi: 10.1016/j.trb.2006.02.011.

**Ciuffo, B., Punzo, V. and Torrieri, V.** (2008). 'Comparison of Simulation-Based and Model-Based Calibrations of Traffic-Flow Microsimulation Models', *Transportation Research Record: Journal of the Transportation Research Board*, *2088*, pp. 36–44. doi: 10.3141/2088-05.

**Clabaux, N., Fournier, J. Y. and Michel, J. E.** (2014). 'Powered two-wheeler drivers' crash risk associated with the use of bus lanes', *Accident Analysis and Prevention*. Elsevier Ltd, *71*, pp. 306–310. doi: 10.1016/j.aap.2014.05.021.

**Conran, C. A.** (2017). *Modeling Microscopic Driver Behavior under Variable Speed Limits: A Driving Simulator and Integrated MATLAB-VISSIM Study*. Virginia Polytechnic Institute and State University. Available at: https://vtechworks.lib.vt.edu/bitstream/handle/10919/78234/Conran_CA_T_2017.pdf?sequence=1.

**Cunradi, J. *et al.*** (2016). *Major Corridors Study Final Report 2016*.

**Currie, G. *et al.*** (2014). 'Bus accident analysis of routes with/without bus priority', *Accident Analysis and Prevention*. Elsevier Ltd, *65*, pp. 18–27. doi: 10.1016/j.aap.2013.12.002.

**Currie, G. and Lai, H.** (2008). 'Intermittent and Dynamic Transit Lanes: Melbourne, Australia, Experience', *Transportation Research Record: Journal of the Transportation Research Board*, *2072*, pp. 49–56. doi: 10.3141/2072-06.

**D'Souza, C., Hounsell, N. B. and Shrestha, B. P.** (2012). 'Using automatic vehicle location (AVL) data for evaluation of bus priority at traffic signals', *IET and ITS Conference on Road Transport Information and Control (RTIC 2012)*. Institution of Engineering and Technology, pp. 21–21. doi: 10.1049/cp.2012.1550.

**Daamen, W., Loot, M. and Hoogendoorn, S.** (2010). 'Empirical Analysis of Merging Behavior at Freeway On-Ramp', *Transportation Research Record: Journal of the Transportation Research Board*, *2188*, pp. 108–118. doi: 10.3141/2188-12.

**Dabiri, S. and Abbas, M.** (2016). 'Arterial traffic signal optimization using Particle Swarm Optimization in an Integrated VISSIM-MATLAB simulation Environment', *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*. IEEE, pp. 766–771. doi: 10.1109/ITSC.2016.7795641.

**Dadashzadeh, N. and Ergun, M.** (2018). 'Spatial bus priority schemes, implementation challenges and needs: an overview and directions for future studies', *Public Transport*. Springer Berlin Heidelberg, *10*(3), pp. 545–570. doi: 10.1007/s12469-018-0191-5.

**Daganzo, C. F. and Laval, J. A.** (2005). 'Moving bottlenecks: A numerical method that converges in flows', *Transportation Research Part B: Methodological*, *39*(9), pp. 855–863. doi: 10.1016/j.trb.2004.10.004.

**Danaher, A. R.** (2010). *TCRP Synthesis No. 83: Bus and Rail Transit Preferential Treatments in Mixed Traffic*. Washington, DC: Transportation Research Board. doi: 10.17226/13614.

**DfT** (2007). *The Use of Bus Lanes by Motorcycles*, *Traffic Advisory Leaflet*. London. Available at: https://tfl.gov.uk/modes/driving/red-routes/rules-of-red-routes/bus-lanes/motorcycles-in-bus-lanes.

**DfT** (2015). *Parking Policy and Enforcement; Operational Guidance to Local Authorities :* London. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/496987/operational-guidance.pdf.

**Donoughe, K. and Katz, B.** (2015). 'Evaluation of fatal school bus related crashes and near-term crash mitigation strategies', *IATSS Research*. Elsevier Ltd, *38*(2), pp. 135–141. doi: 10.1016/j.iatssr.2014.12.003.

**Dowling, R., Skabardonis, A. and Alexiadis, V.** (2004). 'Traffic Analysis Toolbox Volume III : Guidelines for Applying Traffic Microsimulation Modeling Software', *Rep. No. FHWA-HRT-04-040, U.S. DOT, Federal Highway Administration, Washington, D.C*, *III*(July), p. 146.

**Duduta, N. *et al.*** (2014). *Traffic Safety on Bus Priority Systems*, *EMBARQ*. Washington DC. Available at: https://www.wrirosscities.org/sites/default/files/Traffic-Safety-Bus-Priority-Corridors-BRT-EMBARQ-World-Resources-Institute.pdf.

**Durrani, U., Lee, C. and Maoh, H.** (2016). 'Calibrating the Wiedemann's vehicle-following model using mixed vehicle-pair interactions', *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, *67*, pp. 227–242. doi: 10.1016/j.trc.2016.02.012.

**Eichler, M.** (2005). *Bus Lane with Intermittent Priority: Assessment and Design*. University of California, Berkeley. Master Thesis.

**Eichler, M. and Daganzo, C. F.** (2006). 'Bus lanes with intermittent priority: Strategy formulae and an evaluation', *Transportation Research Part B: Methodological*, *40*(9), pp. 731–744. doi: 10.1016/j.trb.2005.10.001.

**EMBARQ** (2018). *Metrobus Ridership in Istanbul*, *Global BRT Data website*. Available at: https://brtdata.org/location/europe/turkey/istanbul (Accessed: 15 March 2018).

**Erik, M., Pedersen, H. and Pedersen, M. E. H.** (2010). 'Good parameters for particle swarm optimization', *Technical Report HL1001, Hvass Laboratories*, *HL1001*, pp. 1–12. Available at: http://www.hvass-labs.org/people/magnus/publications/pedersen10good-pso.pdf.

**Espejel-Garcia, D. *et al.*** (2017). 'A Comparison among Manual and Automatic Calibration Methods in VISSIM in an Expressway (Chihuahua, Mexico)', *Open Journal of Civil Engineering*, *07*(04), pp. 539–552. doi: 10.4236/ojce.2017.74036.

**Essex County Council** (2017). *Bus Lanes and Bus Gate Enforcement and Penalty charge*, *Essex County Council*. Essex. Available at: https://www.essex.gov.uk/Transport and Roads/bus-lanes/Pages/Default.aspx (Accessed: 3 August 2018).

**Farid, Y. Z., Christofa, E. and Collura, J.** (2015). 'Dedicated Bus and Queue Jumper Lanes at Signalized Intersections with Nearside Bus Stops', *Transportation Research Record: Journal of the Transportation Research Board*, *2484*, pp. 182–192. doi: 10.3141/2484-20.

**Feng, W., Figliozzi, M. and Bertini, R. L.** (2015). 'Empirical Evaluation of Transit Signal Priority through Fusion of Heterogeneous Transit and Traffic Signal Data and Novel Performance Measures', *Transportation Research Board 94th Annual Meeting*, *500*(January 2015). doi: 10.3141/2488-03.

**FHWA** (2006). *Bus-Only Shoulders: A Transit Advantage*, *Minnesota Department of Transportation*. Available at: http://www.dot.state.mn.us/metro/teamtransit/pdf/bosupdate.pdf.

**Fonseca, C. M. and Fleming, P. J.** (1993). 'Genetic Algorithms for Multiobjective Optimization: Formulation, Discussion and Generalization', *Icga*, *93*(July), pp. 416–423. doi: citeulike-article-id:2361311.

**Furth, P. and Muller, T. H.** (2000). 'Conditional Bus Priority at Signalized Intersections: Better Service with Less Traffic Disruption', *Transportation Research Record: Journal of the Transportation Research Board*, *1731*(1), pp. 23–30. doi: 10.3141/1731-04.

**Gan, A.** (2009). 'Design of Transit Signal Priority at Signalized Intersections with Queue Jumper Lanes', *Journal of Public Transportation*, *12*(4), pp. 117–132. doi: 10.3141/1925-27.

**Gardner, G.** (1991). *The performance of busway transit in developing cities*, *TRRL Research Report 329*. Crowthorne, Berkshire: UK Transport and Road Research Laboratory.

**Gardner, K. *et al.*** (2009). *Interaction of buses and signals at road crossings - review of bus priority at traffic signals around the world*. V2.0, *UITP: Interaction of buses and signals at road crossings*. V2.0. Belgium: International Association of Public Transport (UITP); Bus Committee (Working Program Bus Committee 2007-2009 – Technical Cluster "Extra-vehicular technology"). Available at: https://trid.trb.org/view/907320.

**Garg, H.** (2016). 'A hybrid PSO-GA algorithm for constrained optimization problems', *Applied Mathematics and Computation*. Elsevier Inc., *274*, pp. 292–305. doi: 10.1016/j.amc.2015.11.001.

**Gavanas, N. *et al.*** (2013). 'Assessment of bus lane violations in relation to road infrastructure, traffic and land-use features: The case of Thessaloniki, Greece', *European Transport - Trasporti Europei*, (55), pp. 1–20.

**Gipps, P. G.** (1986). 'A model for the structure of lane-changing decisions', *Transportation Research Part B: Methodological*, *20*(5), pp. 1–3.

**Gómez-Lobo, A. and Briones, J.** (2014). 'Incentives in Bus Concession Contracts: A Review of Several Experiences in Latin America', *Transport Reviews*. Taylor & Francis, *34*(2), pp. 246–265. doi: 10.1080/01441647.2014.895451.

**Gopalakrishnan, K.** (2010). 'Neural Network–Swarm Intelligence Hybrid Nonlinear Optimization Algorithm for Pavement Moduli Back-Calculation', *Journal of Transportation Engineering*, *136*(6), pp. 528–536. doi: 10.1061/(ASCE)TE.1943-5436.0000128.

**Greguric, M., Ivanjko, E. and Mandzuka, S.** (2014). 'Cooperative ramp metering simulation', *Information and Communication Technology, Electronics and Microelectronics (MIPRO), 2014 37th International Convention on*, pp. 970–975. doi: 10.1109/MIPRO.2014.6859709.

**Gu, W. and Cassidy, M. J.** (2013). 'Maximizing bus discharge flows from multi-berth stops by regulating exit maneuvers', *Transportation Research Part B: Methodological*. Elsevier Ltd, *56*, pp. 254–264. doi: 10.1016/j.trb.2013.08.005.

**Guler, S. I., Gayah, V. V and Menendez, M.** (2016). 'Bus priority at signalized intersections with single-lane approaches : A novel pre-signal strategy', *Transportation Research Part C*. Elsevier Ltd, *63*, pp. 51–70. doi: 10.1016/j.trc.2015.12.005.

**Guler, S. I. and Menendez, M.** (2014). 'Analytical formulation and empirical evaluation of pre-signals for bus priority', *Transportation Research Part B: Methodological*. Elsevier Ltd, *64*, pp. 41–53. doi: 10.1016/j.trb.2014.03.004.

**Guler, S. I. and Menendez, M.** (2015). 'Pre-signals for bus priority: basic guidelines for implementation', *Public Transport*. Springer Berlin Heidelberg, *7*(3), pp. 339–354. doi: 10.1007/s12469-015-0104-9.

**Hale, D. K. *et al.*** (2015). 'Optimization-based assisted calibration of traffic simulation models', *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, *55*, pp. 100–115. doi: 10.1016/j.trc.2015.01.018.

**Hall, F. L. and Agyemang-Duah, K.** (1991). 'Freeway Capacity Drop and the Definition of Capacity', *Transportation Research Record*, (1320), pp. 91–98.

**Hassani, A. and Treijs, J.** (2009). 'An Overview of Standard and Parallel Genetic Algorithms', *IDT Workshop on Interesting Results in Computer Science and Engineering, Mälardalen University*, pp. 1–7. Available at: https://pdfs.semanticscholar.org/ff16/8d2d0bb304c1aaf1b5f1a48aa5012e55c7a8.pdf.

**Haupt, R. L. and Haupt, S. E.** (2006). *Practical genetic algorithms*. 2nd Editio, *Studies in Computational Intelligence*. 2nd Editio. Hoboken, New Jersey: John Wiley & Sons, Inc. doi: 10.1007/11543138_2.

**HCM** (2000). *Highway Capacity Manual*, *Environmental Protection*. Washington, DC: Transportation Research Board. doi: 10.1061/(ASCE)HY.1943-7900.0000746.

**HCM** (2010). *Highway Capacity Manual: Vol.1 Concepts*. 5th edn. Washington, DC: Transportation Research Board. Available at: http://hcm.trb.org/?qr=1.

**He, H., Guler, S. I. and Menendez, M.** (2016). 'Adaptive control algorithm to provide bus priority with a pre-signal', *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, *64*, pp. 28–44. doi: 10.1016/j.trc.2016.01.009.

**Hegyi, A., De Schutter, B. and Hellendoorn, J.** (2005). *Optimal Traffic Control in Freeway Networks With Bottlenecks*, *IFAC Proceedings Volumes*. IFAC. doi: 10.3182/20050703-6-CZ-1902.02039.

**Hensher, D. A.** (1998). 'The imbalance between car and public transport use in urban Australia: why does it exist?', *Transport Policy*, *5*(4), pp. 193–204. doi: 10.1016/S0967-070X(98)00022-5.

**Hensher, D. A. and Waters, W. G.** (1994). 'Light rail and bus priority systems: Choice or blind commitment?', *Research in Transportation Economics*, *3*, pp. 139–162. doi: 10.1016/S0739-8859(09)80008-5.

**Hernández, C. R. and Mehndiratta, S. R.** (2015). 'Bus Concession Contracts—Lessons from Bogota's Transmilenio & the Integrated Public Transit System (SITP)', in *Transportation Research Board 94th Annual Meeting*. Washington DC: Transportation Research Record. Available at: http://docs.trb.org/prp/15-2951.pdf.

**Hollander, Y. and Liu, R.** (2008). 'The principles of calibrating traffic microsimulation models', *Transportation*, *35*(3), pp. 347–362. doi: 10.1007/s11116-007-9156-2.

**Hourdakis, J., Michalopoulos, P. and Kottommannil, J.** (2003). 'Practical Procedure for Calibrating Microscopic Traffic Simulation Models', *Transportation Research Record: Journal of the Transportation Research Board*, *1852*, pp. 130–139. doi: 10.3141/1852-17.

**Ibarra-Rojas, O. J. *et al.*** (2015). 'Planning, operation, and control of bus transport systems: A literature review', *Transportation Research Part B: Methodological*. Elsevier Ltd, *77*, pp. 38–75. doi: 10.1016/j.trb.2015.03.002.

**IMM** (2017). *Istanbul 2016 Transport Annual Report*. Istanbul. Available at: https://tuhim.ibb.gov.tr/media/2131/imm_transport_report.pdf.

**INRIX** (2017). *INRIX Global Traffic Scorecard - Most Congested cities in the World*. Available at: http://inrix.com/scorecard/ (Accessed: 30 October 2018).

**Jacques, K. ST. and Levinson, H. S.** (1997). *TCRP No. 26: Operational Analysis of Bus Lanes on Arterials*, *USA National Academy of Sciences*. Washington, DC: Transportation Research Board.

**Jaensirisaka, S., Klungboonkrongb, P. and Udomsri, R.** (2013). 'Development of Bus Rapid Transit (BRT) in Khon Kaen, Thailand', in *Proceedings of eastern Asia Society for Transportation Studies*.

**Jayatilleke, A. U. *et al.*** (2010). 'Traffic rule violations of private bus drivers and bus crashes in Sri Lanka: A case-control study', *Traffic Injury Prevention*, *11*(3), pp. 263–269. doi: 10.1080/15389581003639711.

**Jin, W. L.** (2010). 'A kinematic wave theory of lane-changing traffic flow', *Transportation Research Part B: Methodological*. Elsevier Ltd, *44*(8–9), pp. 1001–1021. doi: 10.1016/j.trb.2009.12.014.

**Jin, W. L.** (2013). 'A multi-commodity Lighthill-Whitham-Richards model of lane-changing traffic flow', *Transportation Research Part B: Methodological*, *57*, pp. 361–377. doi: 10.1016/j.trb.2013.06.002.

**Joskowicz, I. F.** (2012). *Dynamic Bus Lane, Ph.D. Thesis*, *The University of Texas at Arlington*. The University of Texas at Arlington,. Available at: https://uta-ir.tdl.org/uta-ir/handle/10106/11055.

**Kanagaraj, V. *et al.*** (2015). 'Trajectory Data and Flow Characteristics of Mixed Traffic', *Transportation Research Record: Journal of the Transportation Research Board*, *2491*, pp. 1–11. doi: 10.3141/2491-01.

**Kantoğlu, T. S.** (2013). *Design of Bus Priority Lanes and Pilot studies in Istanbul*. Istanbul Technical University. Available at: https://polen.itu.edu.tr/xmlui/handle/11527/6953.

**Kennedy, J. and Eberhart, R.** (1995). 'Particle swarm optimization', *Neural Networks, 1995. Proceedings., IEEE International Conference on*, *4*, pp. 1942–1948 vol.4. doi: 10.1109/ICNN.1995.488968.

**Kepaptsoglou, K. *et al.*** (2011). 'Bus lane violations: An exploration of causes', *European Transport - Trasporti Europei*, *48*(48), pp. 87–98.

**Kesten, A. S., Ergün, M. and Yai, T.** (2013). 'An Analysis on Efficiency and Equity of Fixed-Time Ramp Metering', *Journal of Transportation Technologies*, *03*(May), pp. 48–56. doi: 10.4236/jtts.2013.32A006.

**Kesten, A. S., Goksu, G. and Akbas, A.** (2013). 'Dynamic ramp metering approach for an urban highway using microscopic traffic simulation', in *2013 13th International Conference on ITS Telecommunications (ITST)*. IEEE, pp. 90–96. doi: 10.1109/ITST.2013.6685527.

**Kh Abdalhaq, B. and Abu Baker, M. I.** (2014). 'Using Meta Heuristic Algorithms to Improve Traffic Simulation', *Journal of Algorithms and Optimization*, *2*(4), pp. 110–128. Available at: https://www.researchgate.net/profile/Maher_Abu_Baker/publication/268334607_Using_Meta_Heuristic_Algorithms_to_Improve_Traffic_Simulation/links/5469749d0cf2f5eb1804ee02.pdf.

**Khondaker, B. and Kattan, L.** (2015). 'Variable speed limit: an overview', *Transportation Letters*, *7*(5), pp. 264–278. doi: 10.1179/1942787514Y.0000000053.

**Kim, H. J.** (2003). 'Performance of Bus Lanes in Seoul', *IATSS Research*. International Association of Traffic and Safety Sciences, *27*(2), pp. 36–45. doi: 10.1016/S0386-1112(14)60142-4.

**Kim, S.-J., Kim, W. and Rilett, L.** (2005). 'Calibration of Microsimulation Models Using Nonparametric Statistical Techniques', *Transportation Research Record: Journal of the Transportation Research Board*, *1935*, pp. 111–119. doi: 10.3141/1935-13.

**Kim, Sangyoup *et al.*** (2012). 'Determination of accident modification factors for the median bus lanes on urban arterials', *International Journal of Urban Sciences*, *16*(1), pp. 99–113. doi: 10.1080/12265934.2012.662588.

**Kittelson & Assoc Inc.** (2013). *TCRP NO. 165: Transit Capacity and Quality of Service Manual, Third Edition*. Third. Washington, DC: Transportation Research Board. doi: 10.17226/24766.

**Kogdenko, N.** (2011). *Successfulness of Bus Rapid Transit systems in Asia Ex-post evaluation*. University of Groningen. Available at: https://www.ecn.nl/publications/PdfFetch.aspx?nr=ECN-O--11-013.

**Kotsialos, A., Kosmatopoulos, E. and Papageorgiou, M.** (2004). *EUropean RAmp Metering Project (EURAMP) - Current status of ramp metering*. 507645.

**Kovvali, V. *et al.*** (2007). 'Video-Based Vehicle Trajectory Data Collection Video-Based Vehicle Trajectory Data Collection', in *TRB 86th Annual Meeting Compendium of Papers CD-ROM*. Washington, D.C.: Transport Research Record, pp. 1–18. Available at: https://trid.trb.org/view/801154.

**Kušić, K. *et al.*** (2016). 'Comparison of two controllers for variable speed limit control', *Proceedings Elmar - International Symposium Electronics in Marine*, *2016-Novem*, pp. 101–106. doi: 10.1109/ELMAR.2016.7731764.
**Kwon, J. and Varaiya, P.** (2008). 'Effectiveness of California's High Occupancy Vehicle (HOV) system', *Transportation Research Part C: Emerging Technologies*, *16*(1), pp. 98–115. doi: 10.1016/j.trc.2007.06.008.
**Laval, J. A. and Daganzo, C. F.** (2006). 'Lane-changing in traffic streams', *Transportation Research Part B: Methodological*, *40*(3), pp. 251–264. doi: 10.1016/j.trb.2005.04.003.
**Laval, J. and Daganzo, C.** (2005). 'Multi-lane hybrid traffic flow model: a theory on the impacts of lane-changing maneuvers', *84th Transportation Research Board's* ..., (October). Available at: http://www.ce.berkeley.edu/~daganzo/mlhm TRB05.pdf.
**Leclercq, L., Laval, J. A. and Chiabaut, N.** (2011). 'Capacity drops at merges: An endogenous model', *Transportation Research Part B: Methodological*. Elsevier Ltd, *45* `(9), pp. 1302–1313. doi: 10.1016/j.trb.2011.05.007.
**Lee, J.-B. and Ozbay, K.** (2009). 'New Calibration Methodology for Microscopic Traffic Simulation Using Enhanced Simultaneous Perturbation Stochastic Approximation Approach', *Transportation Research Record: Journal of the Transportation Research Board*, *2124*, pp. 233–240. doi: 10.3141/2124-23.
**Levinson, H.** (2001). 'Bus transit in the 21st century: some perspectives and prospects', *Transportation Research Record*, *1760*(01), pp. 42–46. doi: 10.3141/1760-06.
**Levinson, H. *et al.*** (2002). 'Bus Rapid Transit: An Overview', *Journal of Public Transportation*, *5*(2), pp. 1–30. doi: 10.5038/2375-0901.5.2.1.
**Levinson, H., Adams, C. and Hoey, W.** (1975). *TCRP No. 155: Bus Use of Highways Planning and Design Guidelines*, *National Research Council*. Washington, DC: Transportation Research Board.
**Levinson, H. S. *et al.*** (2003). 'Bus rapid transit: Synthesis of case studies', *Transportation Research Record*, (1841), pp. 1–11. doi: 10.3141/1841-01.
**Liang, Z., Ouyang, J. and Yang, F.** (2018). 'A hybrid GA-PSO optimization algorithm for conformal antenna array pattern synthesis', *Journal of Electromagnetic Waves and Applications*. Taylor & Francis, *32*(13), pp. 1601–1615. doi: 10.1080/09205071.2018.1462257.
**Lighthill, M. J. and Whitham, G. B.** (1955). 'On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads', *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *229*(1178), pp. 317–345. doi: 10.1098/rspa.1955.0089.
**Lim, A.** (2017). *Bus-lane violations down ; priority measures up*, *The Straits Times*. Singapore. Available at: https://www.straitstimes.com/singapore/transport/bus-lane-violations-down-priority-measures-up (Accessed: 30 September 2018).
**Lin, P., Ph, D. and Wang, Y.** (2014). 'Combinatorial Optimization of Multiple Buses Docking at BRT Station with Multiple Sub-stops and Docking Bays for Guangzhou BRT system', *Transportation Research Board's 93nd Annual Meeting, Washington, D.C.*

**Lin, Y. *et al.*** (2015). 'Transit signal priority control at signalized intersections: a comprehensive review', *Transportation Letters*, *7*(3), pp. 168–180. doi: 10.1179/1942787514Y.0000000044.

**Lin, Y., Yang, X. and Zou, N.** (2017). 'Passive transit signal priority for high transit demand : model formulation and strategy selection', *Transportation Letters*. Taylor & Francis, *7867*(July), p. 0. doi: 10.1080/19427867.2017.1295899.

**Lindgren, R. *et al.*** (2006). 'Toward Demonstrating Predictability of Bottleneck Activation on German Autobahns', *Transportation Research Record*, *1965*(1), pp. 12–22. doi: 10.3141/1965-02.

**Litman, T.** (2015). *When Are Bus Lanes Warranted? Considering Economic Efficiency, Social Equity and Strategic Planning Goals*. Available at: http://www.vtpi.org/blw.pdf.

**Liu, Z. *et al.*** (2013). 'Bus stop-skipping scheme with random travel time', *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, *35*, pp. 46–56. doi: 10.1016/j.trc.2013.06.004.

**Liverpool City Council** (2014). *Liverpool Transport Corridors & Bus Lane Suspension*, *Liverpool City Council*. Liverpool, UK. Available at: http://councillors.liverpool.gov.uk/documents/s140386/Appendix 3 - Mott McDonald Bus Lane Review Documents.pdf.

**Lu, B. and Viegas, J.** (2003). 'Improving Bus Movement on Predicted Bus Message', *IFAC Proceedings Volumes*, *36*(14), pp. 191–196. doi: 10.1016/S1474-6670(17)32418-7.

**Lu, X. *et al.*** (2014). 'Freeway Micro-simulation Calibration : Case Study Using Aimsun and VISSIM with Detailed Field Data', *Transportation Research Board 93rd Annual Meeting. January 12-16, Washington, D.C.*, (June), pp. 1–17.

**Lu, Z. *et al.*** (2016). 'A video-based approach to calibrating car-following parameters in VISSIM for urban traffic', *International Journal of Transportation Science and Technology*. Tongji University, *5*(1), pp. 1–9. doi: 10.1016/j.ijtst.2016.06.001.

**Ma, J., Dong, H. and Zhang, H.** (2007). 'Calibration of Microsimulation with Heuristic Optimization Methods', *Transportation Research Record: Journal of the Transportation Research Board*, *1999*, pp. 208–217. doi: 10.3141/1999-22.

**Ma, T. and Abdulhai, B.** (2002). 'Genetic Algorithm-Based Optimization Approach and Generic Tool for Calibrating Traffic Microscopic Simulation Parameters', *Transportation Research Record: Journal of the Transportation Research Board*, *1800*, pp. 6–15. doi: 10.3141/1800-02.

**Ma, W., Liu, Y. and Han, B.** (2013). 'A rule-based model for integrated operation of bus priority signal timings and traveling speed', *Journal of Advanced Transportation*, *47*(3), pp. 369–383. doi: 10.1002/atr.1213.

**Mahendran, A. *et al.*** (2014). *Bus Detection for Adaptive Traffic Signal Control*. Washington, DC: US DOT University Transportation Center. Available at: http://utc.ices.cmu.edu/utc/CMU Reports 2013 2/Final UTC-report.pdf.

**Mangones, S. C., Fischbeck, P. and Jaramillo, P.** (2017). 'Safety-related risk and benefit-cost analysis of crash avoidance systems applied to transit buses: Comparing New York City vs. Bogota, Colombia', *Safety Science*. Elsevier Ltd, *91*, pp. 122–131. doi: 10.1016/j.ssci.2016.08.003.

**Markou, I., Papathanasopoulou, V. and Antoniou, C.** (2018). 'Dynamic Car–Following Model Calibration Using SPSA and ISRES Algorithms', *Periodica Polytechnica Transportation Engineering*. doi: 10.3311/PPtr.8616.

**Martin, P., Levinson, H. S. and Texas Transportation Institute** (2012). *TCRP No. 151: A Guide for Implementing Bus on Shoulder (BOS) Systems*. Washington, DC: Transportation Research Board. doi: 10.17226/22809.

**Mckibbin, D.** (2014). *Enforcing Bus Lanes*. 20/15. Available at: http://www.niassembly.gov.uk/globalassets/documents/raise/publications/2015/regdev/2015.pdf.

**Menendez, M. and Daganzo, C. F.** (2007). 'Effects of HOV lanes on freeway bottlenecks', *Transportation Research Part B: Methodological*, *41*(8), pp. 809–822. doi: 10.1016/j.trb.2007.03.001.

**Menneni, S., Sun, C. and Vortisch, P.** (2008a.). 'Microsimulation Calibration Using Speed-Flow Relationships', *Transportation Research Record: Journal of the Transportation Research Board*, *2088*(February 2015), pp. 1–9. doi: 10.3141/2088-01.

**Menneni, S., Sun, C. and Vortisch, P.** (2008b.). 'Microsimulation Calibration Using Speed-Flow Relationships', *Transportation Research Record: Journal of the Transportation Research Board*, *2088*, pp. 1–9. doi: 10.3141/2088-01.

**Mezura-Montes, E. and Coello Coello, C. A.** (2011). 'Constraint-handling in nature-inspired numerical optimization: Past, present and future', *Swarm and Evolutionary Computation*. Elsevier B.V., *1*(4), pp. 173–194. doi: 10.1016/j.swevo.2011.10.001.

**Miller, M. A.** (2009). *Bus Lanes/Bus Rapid Transit Systems on Highways: Review of the Literature, California PATH Working Paper UCB-ITS-PWP-2009-1*. UCB-ITS-PWP-2009-1. California, Berkeley. Available at: http://www.path.berkeley.edu/sites/default/files/publications/PWP-2009-01.pdf.

**Mirchandani, P. and Lucas, D.** (2004). 'Integrated Transit Priority and Rail/Emergency Preemption in Real-Time Traffic Adaptive Signal Control', *Intelligent Transportation Systems*, *8*(1), pp. 101–115. doi: 10.1080/15472450490437799.

**Munjal, P. and L. A. P.** (1971). 'Propagation of on-ramp density perturbations on unidirectional two-and three-lane freeways', *Transportation Research*, *5*(June 1969), p. 1971.

**Munjal, P. and Lawrence R. L.** (1971). 'Propagation of on-ramp density waves on uniform unidirectional multilane freeways', *Transportation Science*, *5*, pp. 257–266.

**NACTO** (2012). *Urban Street Design Guide*, *2015*. New York: National Association of City Transportation Officials. Available at: http://www.nyc.gov/html/dot/downloads/pdf/2012-nacto-urban-street-design-guide.pdf.

**NACTO** (2016). *Transit Street Design Guide*. 2nd edn. New York: National Association of City Transportation Officials. Available at: https://nacto.org/publication/transit-street-design-guide/.

**Nesheli, M. M., Ceder, A. (Avi) and Liu, T.** (2015). 'A Robust, Tactic-Based, Real-Time Framework for Public- Transport Transfer Synchronization', *Transportation Research Procedia*. Elsevier B.V., *9*(2007), pp. 246–268. doi: 10.1016/j.trpro.2015.07.014.

**Neves, J.** (2006). *The Impacts of Bus Lanes on Urban Traffic Environment*. University of Porto, Master Thesis.

**Nik, A. A., Nejad, F. M. and Zakeri, H.** (2016). 'Hybrid PSO and GA approach for optimizing surveyed asphalt pavement inspection units in massive network', *Automation in Construction*. Elsevier B.V., *71*(Part 2), pp. 325–345. doi: 10.1016/j.autcon.2016.08.004.

**ODOT** (2013). *Conflict of Interest (COI) Guidelines*. Oregon Department of Transportation, USA. Available at: http://www.oregon.gov/odot/business/procurement/docspsk/coiguidelines.pdf.

**Olstam, J., Habibovic, A. and Anund, A.** (2015). *Dynamic bus lanes in Sweden – a pre-study*. Lund Sweden. Available at: http://www.k2centrum.se/sites/default/files/fields/field_uppladdad_rapport/dynamic_bus_lanes_in_sweden.pdf.

**Ossen, S. and Hoogendoorn, S. P.** (2011). 'Heterogeneity in car-following behavior: Theory and empirics', *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, *19*(2), pp. 182–195. doi: 10.1016/j.trc.2010.05.006.

**Papageorgiou, M. *et al.*** (2008). 'A misapplication of the local ramp metering strategy ALINEA', *IEEE Transactions on Intelligent Transportation Systems*, *9*(2), pp. 360–365. doi: 10.1109/TITS.2008.922975.

**Papageorgiou, M., Hadj-Salem, H. and Blosseville, J. M.** (1991). 'ALINEA: A local feedback control law for on-ramp metering', *Transportation Research Record: Journal of the Transportation Research Board*, *1320*, pp. 58–64. doi: 10.1002/cncr.11316.

**Papamichail, I. and Papageorgiou, M.** (2008). 'Traffic-responsive linked ramp-metering control', *IEEE Transactions on Intelligent Transportation Systems*, *9*(1), pp. 111–121. doi: 10.1109/TITS.2007.908724.

**Paz, A. *et al.*** (2015). 'Calibration of traffic flow models using a memetic algorithm', *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, *55*(4), pp. 432–443. doi: 10.1016/j.trc.2015.03.001.

**Paz, A., Molano, V. and Gaviria, C.** (2012). 'Calibration of CORSIM models considering all model parameters simultaneously', *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, (1), pp. 1417–1422. doi: 10.1109/ITSC.2012.6338841.

**Peña, C. and Moreno, E.** (2014). 'Delay at Bus Stops of Transmilenio Transport System According to Parameters Measured" in situ". Case Study Bogotá-Colombia', *Procedia - Social and Behavioral Sciences*. Elsevier B.V., *160*(Cit), pp. 121–129. doi: 10.1016/j.sbspro.2014.12.123.

**Pirc, J., Turk, G. and Žura, M.** (2015). 'Using the robust statistics for travel time estimation on highways', *IET Intelligent Transport Systems*, *9*(4), pp. 442–452. doi: 10.1049/iet-its.2014.0123.

**Pirc, J., Turk, G. and Žura, M.** (2016). 'Highway travel time estimation using multiple data sources', *IET Intelligent Transport Systems*, *10*(10), pp. 649–657. doi: 10.1049/iet-its.2015.0211.

**PTV** (2017). *PTV VISSIM 10 User Manual*. PTV Planug Trasport Verker AG, Germany.

**Rahman, F., Sakamoto, K. and Kubota, H.** (2007). 'Decision Making Process Of Traffic Calming Devices; a comparative study', *IATSS Research*, *31*(2), pp. 94–106. doi: 10.1016/S0386-1112(14)60227-2.

**Ramadan, O. and Sisiopiku, V.** (2016). 'Impact of Bottleneck Merge Control Strategies on Freeway Level of Service', *Transportation Research Procedia*. Elsevier B.V., *15*, pp. 583–593. doi: 10.1016/j.trpro.2016.06.049.

**Roisman, R. and Koudounas, A.** (2017). *Bus Lane Enforcement Study*. Washington DC: Metropolitan Washington Council of Governments. Available at: https://www.mwcog.org/assets/1/28/10062017_-_Item_12_-_DO_NOT_PRINT_-_Bus_Lane_Enforcement_Study_Final_Report.pdf.

**Ryus, P. *et al.*** (2016). *TCRP No. 183: Guidebook on Transit-Supportive Roadway Strategies*, *USA National Academy of Sciences*. Edited by P. Ryus et al. Washington, DC: Transportation Research Board. doi: 10.17226/21929.

**Safran, J., Beaton, E. and Thompson, R.** (2014). 'Factors Contributing to Bus Lane Obstruction and Usage in New York City', *Transportation Research Record: Journal of the Transportation Research Board*.

**Sakamoto, K., Abhayantha, C. and Kubota, H.** (2007). 'Effectiveness of Bus Priority Lane as Countermeasure for Congestion', *Transportation Research Record: Journal of the Transportation Research Board*, *2034*(April), pp. 103–111. doi: 10.3141/2034-12.

**Schaffer, J. D. and Grefenstette, J. J.** (1989). 'Multi-Objective learning via genetic algorithms', *Journal of Chemical Information and Modeling*, *53*, p. 160. doi: 10.1017/CBO9781107415324.004.

**Shaaban, K., Khan, M. A. and Hamila, R.** (2016). 'Literature Review of Advancements in Adaptive Ramp Metering', *Procedia Computer Science*. Elsevier Masson SAS, *83*(Ant), pp. 203–211. doi: 10.1016/j.procs.2016.04.117.

**Sharma, D., Gaur, P. and Mittal, A. P.** (2014). 'Comparative Analysis of Hybrid GAPSO Optimization Technique With GA and PSO Methods for Cost Optimization of an Off-Grid Hybrid Energy System', *Energy Technology & Policy*. Taylor & Francis, *1*(1), pp. 106–114. doi: 10.1080/23317000.2014.969450.

**Sheikhalishahi, M. *et al.*** (2013). 'A hybrid GA-PSO approach for reliability optimization in redundancy allocation problem', *International Journal of Advanced Manufacturing Technology*, *68*(1–4), pp. 317–338. doi: 10.1007/s00170-013-4730-6.

**Siam, M. R. K. *et al.*** (2018). 'VISCAL: Heuristic algorithm based application tool to calibrate microscopic simulation parameters', *Journal of Traffic and Transportation Engineering (English Edition)*. Elsevier Ltd, *5*(1), pp. 28–43. doi: 10.1016/j.jtte.2017.04.004.

**Skabardonis, A.** (2000). 'Control Strategies for Transit Priority', *Transportation Research Record: Journal of the Transportation Research Board*. California, Berkeley, *1727*(00), pp. 20–26. doi: 10.3141/1727-03.

**Stevanovic, A., Martin, P. and Stevanovic, J.** (2007). 'VisSim-Based Genetic Algorithm Optimization of Signal Timings', *Transportation Research Record: Journal of the Transportation Research Board*, *2035*(December 2014), pp. 59–68. doi: 10.3141/2035-07.

**Stevanovic, J. *et al.*** (2008). 'Stochastic optimization of traffic control and transit priority settings in VISSIM', *16*, pp. 332–349. doi: 10.1016/j.trc.2008.01.002.

**Strnad, I., Kramar Fijavž, M. and Žura, M.** (2016). 'Numerical optimal control method for shockwaves reduction at stationary bottlenecks', *Journal of Advanced Transportation*, *50*(5), pp. 841–856. doi: 10.1002/atr.1378.

**Strnad, I. and Žura, M.** (2011). 'Genetic algorithms application to EVA mode choice model parameters estimation', *International journal of mathematical models and methods in applied sciences*, *5*(3), pp. 533–541.

**Sun, J., Tang, K. and Zhang, S.** (2014). 'Online evaluation of an integrated control strategy at on-ramp bottleneck for urban expressways in Shanghai', *IET Intelligent Transport Systems*, *8*(8), pp. 648–654. doi: 10.1049/iet-its.2013.0131.

**Sun Jian, Ouyang Jixiang and Yang Jianhao** (2014). 'Modeling and Analysis of Merging Behavior at Expressway On-Ramp Bottlenecks', *Transportation Research Record Journal of the Transportation Research Board Transportation Research Board of the National Academies*, (2421), pp. 74–81. doi: 10.3141/2421-09.

**TfL** (2008). *Provisional guidance on bus lane (including tramway) enforcement in England outside London*, *Department for Transport*. London. Available at: http://www.hullcc.gov.uk/pls/portal/docs/PAGE/HOME/TRANSPORT AND STREETS/TRAVEL/PUBLIC TRANSPORT/BUSES/BUS LANES/CODE OF PRACTICE 2008 BUS LANE ENFORCEMENT.PDF.

**Thakuriah, P., Metaxatos, P. and Mohammadian, A.** (2014). *Bus Riding On Shoulders*. ICT-10-073. Illinois Center for Transportation Series No. 10-073. Available at: https://apps.ict.illinois.edu/projects/getfile.asp?id=3032.

**The NZ Transport Agency** (2010). 'Priority lanes Introduction', in *Integrated planning toolkit*. New Zealand: The NZ Transport Agency, pp. 1–32. Available at: https://www.nzta.govt.nz/assets/planning/process/trial-ip-toolkit-old/docs/priority-lanes.pdf.

**Todd, M. *et al.*** (2006). *Enhanced Transit Strategies: Bus Lanes with Intermittent Priority and ITS Technology Architectures for TOD Enhancement*. UCB-ITS-PRR-2006-2. California, Berkeley. Available at: http://escholarship.org/uc/item/8h1969p9.pdf.

**Toledo, T. and Zohar, D.** (2007). 'Modeling Duration of Lane Changes', *Transportation Research Record: Journal of the Transportation Research Board*, *1999*, pp. 71–78. doi: 10.3141/1999-08.

**TomTom** (2018). *TomTom Traffic Index - Most congested citites in the World*. Available at: https://www.tomtom.com/en_gb/trafficindex/?zanpid=8861_1551863726_9ced12adb4e0bd2673d7f7ddb8b78711&affiliate=143466 (Accessed: 30 October 2018).

**Townes, M. S. *et al.*** (1998). *TCRP No. 33: Transit-Friendly Streets: Design and Traffic Management Strategies to Support Livable Communities*. Edited by M. S. Townes et al. Washington, DC: Transportation Research Board.

**TRRL** (1993a.). *Design Guidlines for Busway Transit*, *Transport Road Research Laboratory*. Crowthorne Berkshire. doi: 0951-8987.

**TRRL** (1993b.). *Mass transit in developing cities*, *Transport Road Research Laboratory*. Crowthorne, Berkshire SYNOPSIS. doi: 10.1002/atr.5670270304.

**Tse, L. Y., Hung, W. T. and Sumalee, a** (2014). 'Bus lane safety implications: a case study in Hong Kong', *Transportmetrica a-Transport Science*, *10*(2), pp. 140–159. doi: 10.1080/18128602.2012.724470.

**TUIK** (2018a.). *Population and demoghraphy (Istanbul)*, *Turkish Statistics Institute*. Ankara. Available at: http://www.turkstat.gov.tr/PreTablo.do?alt_id=1059.

**TUIK** (2018b.). *Transportation statistics (Istanbul)*, *Turkish Statistical Institute*. Ankara. Available at: http://www.turkstat.gov.tr/PreTablo.do?alt_id=1051.

**Turkish Legislagion Office** (1997). *Turkey Roads Traffic Legislation*. 17.04.2015. Edited by (KGM) Turkey Ministry of Transportation. Turkey: Offical Gazete 23053. Available at: http://www.mevzuat.gov.tr/Metin.Aspx?MevzuatKod=7.5.8182&MevzuatIliski=0&sourceXmlSearch=Karayolları trafik yönetmeliği.

**U.S. FWHA** (2017). *Active Demand Management*. Available at: http://ops.fhwa.dot.gov/atdm/approaches/adm.htm (Accessed: 5 April 2017).

**UK Department for Transport** (2003). *Traffic Control System Design for All Purpose Roads (Compendium of Examples)*, *MCH 1969*. Hants: Crown. Available at: http://www.ukroads.org/webfiles/mch1969a.pdf.

**Varaiya, P. and Kurzhanskiy, A.** (2010). *Active Traffic Management: Approaches: Active Transportation and Demand Management - FHWA Operations*, *FHWA*. Available at: https://ops.fhwa.dot.gov/atdm/approaches/atm.htm (Accessed: 5 April 2017).

**Verma, A. *et al.*** (2017). 'Sensation Seeking Behavior and Crash Involvement of Indian Bus Drivers', *Transportation Research Procedia*. Elsevier B.V., *25*, pp. 4754–4766. doi: 10.1016/j.trpro.2017.05.487.

**Viegas, J. *et al.*** (2006). 'Demonstration of the intermittent bus lane in Lisbon', *IFAC Proceedings Volumes*, *39*(12), pp. 239–244. doi: 10.3182/20060829-3-NL-2908.00042.

**Viegas, J. and Lu, B.** (2001). 'Widening the scope for bus priority with intermittent bus lanes', *Transportation Planning and Technology*, *24*(2), pp. 87–110. doi: 10.1080/03081060108717662.

**Viegas, J. and Lu, B.** (2004). 'The Intermittent Bus Lane signals setting within an area', *Transportation Research Part C: Emerging Technologies*, *12*(6), pp. 453–469. doi: 10.1016/j.trc.2004.07.005.

**Viegas, J. M. J. and Lu, B.** (1997). 'Traffic Control System With Intermittent Bus Lanes', *IFAC Transportation System, Proceedings Volumes*. doi: 10.1016/S1474-6670(17)43930-9.

**Wan, X.** ***et al.*** (2013). 'Empirical Analysis of Speed Synchronization of Merge Vehicle from Entrance Ramp', *Transportation Research Board 92th Annual Meeting*. doi: 10.3141/2391-02.

**Wang, R.** ***et al.*** (2013). 'A Performance Evaluation of Bus Stop Placements near a Signalized Intersection by a Microscopic Traffic Simulation', *Eastern Asia Society for Transportation Studies*, *9*(2011).

**Weinstein Agrawal, A., Goldman, T. and Hannaford, N.** (2013). 'Shared-Use Bus Priority Lanes on City Streets : Approaches to Access and Enforcement', *Journal of Public Transportation*, *16*(4), pp. 25–41. doi: http://dx.doi.org/10.5038/2375-0901.16.4.2.

**World Economic Forum** (2018). *These are the cities with the worst noise pollution*, *WHO (World Economic Forum)*. Available at: https://www.weforum.org/agenda/2017/03/these-are-the-cities-with-the-worst-noise-pollution/ (Accessed: 15 March 2018).

**Wu, D.** ***et al.*** (2017). 'Evaluating Operational Effects of Bus Lane with Intermittent Priority under Connected Vehicle Environments', *Discrete Dynamics in Nature and Society*, *2017*. doi: 10.1155/2017/1659176.

**Wu, J. and Hounsell, N.** (1998). 'Bus priority using pre-signals', *Transportation Research Part A: Policy and Practice*, *32*(8), pp. 563–583. doi: 10.1016/S0965-8564(98)00008-1.

**Xu, H. and Zheng, M.** (2012). 'Impact of Bus-Only Lane Location on the Development and Performance of the Logic Rule-Based Bus Rapid Transit Signal Priority', *Journal of Transportation Engineering*, *138*(3), pp. 293–314. doi: 10.1061/(ASCE)TE.1943-5436.0000325.

**Yazıcı, M. A.** ***et al.*** (2013). 'A Bus Rapid Transit Line Case Study : Istanbul's Metrobus System', *Journal of Public Transportation*, *16*(1), pp. 153–177. doi: http://dx.doi.org/10.5038/2375-0901.16.1.8.

**Ye, X. and Ma, W.** (2013). 'Influence of Access Traffic on the Operational Efficiencies of Bus Lane and Main Road', *Procedia - Social and Behavioral Sciences*. Elsevier B.V., *96*(Cictp), pp. 1648–1658. doi: 10.1016/j.sbspro.2013.08.187.

**Ye, Z.** ***et al.*** (2016). 'Modeling level-of-safety for bus stops in China', *Traffic Injury Prevention*. Taylor & Francis, *17*(6), pp. 656–661. doi: 10.1080/15389588.2015.1133905.

**Yousif, S., Nassrullah, Z. and Norgate, S. H.** (2017). 'Narrow lanes and their effect on drivers' behaviour at motorway roadworks', *Transportation Research Part F: Traffic Psychology and Behaviour*. Elsevier Ltd, *47*, pp. 86–100. doi: 10.1016/j.trf.2017.04.016.

**Yu, M. and (David) Fan, W.** (2017). 'Calibration of microscopic traffic simulation models using metaheuristic algorithms', *International Journal of Transportation Science and Technology*. Tongji University and Tongji University Press, *6*(1), pp. 63–77. doi: 10.1016/j.ijtst.2017.05.001.

**Zhang, C., Bie, Y. and Qiu, T. Z.** (2017). 'Short-Term Demand Prediction at Freeway Bottleneck Under VSL Control', *4180*.

**Zhang, M. *et al.*** (2001). 'Evaluation of On-ramp Control Algorithms California PATH Research Report', (December). Available at: http://www.its.uci.edu/~wjin/publications/zhang2001metering.pdf.

**Zhao, J. and Liu, Y.** (2016). 'Integrated signal optimization and non-traditional lane assignment for urban freeway off-ramp congestion mitigation', *Transportation Research Part C: Emerging Technologies*, *73*, pp. 219–238. doi: 10.1016/j.trc.2016.11.003.

**Zhou, G., Gan, A. and Shen, L. D.** (2007). 'Optimization of Adaptive Transit Signal Priority Using Parallel Genetic Algorithm', *Tsinghua Science and Technology*, *12*(2), pp. 131–140. doi: 10.1016/S1007-0214(07)70020-2.

**Zhu, H. B.** (2010). 'Numerical study of urban traffic flow with dedicated bus lane and intermittent bus lane', *Physica A*. Elsevier B.V., *389*(16), pp. 3134–3139. doi: 10.1016/j.physa.2010.03.040.

**Zlatkovic, M., Stevanovic, A. and Reza, R. M. Z.** (2013). 'Effects of Queue Jumpers and Transit Signal Priority on Bus Rapid Transit', in *Transportation Research Board 92nd Annual Meeting*. Washington, DC: Transportation Research Board. Available at: https://trid.trb.org/view/1240521.

**APPENDICES**

**APPENDIX A:** Developed Algorithm Codes for TSP in VisVAP
**APPENDIX B:** Developed Algorithm Codes for VSL+ALINEA in VisVAP
**APPENDIX C:** Developed Algorithm Codes for VSL+ALINEA/B in VisVAP

**APPENDIX A :** TSP Algorithm Codes in VisVAP

```
PROGRAM YILDIZ_TSP; /* C:\Users\ndadashz\Desktop\TSP\YILDIZ-TSP.vap */
/* EXPRESSIONS */
      Extend_Stg1_CARS := (Headway( 1 ) <= MAX_GAP);
      Extend_Stg2_BUS := (Headway( 21 ) <= MAX_GAP) OR (Headway( 22 ) <= MAX_GAP);
      CarDemand := (Occupancy( 1 ) > 0);
      BusDemand := (Occupancy( 2 ) > 0) OR (Occupancy( 21 ) > 0);
      CarQueue := Occupancy( 10 ) > 5;
      minGreenStg1 := T_green( 1 ) >= T_green_min (1);
      minGreenStg2 := T_green( 2 ) >= T_green_min (2);
/* MAIN PROGRAM */
S00Z001:  IF T_free( 1 ) = 1 THEN
S01Z002:    cycSecond := 1
      ELSE
S00Z002:    cycSecond := cycSecond + 1
      END;
S00Z004:  SetT( cycSecond );
S00Z005:  IF NOT (Any_interstage_active) THEN
S00Z006:    IF Stage_active( 1 ) THEN
S01Z006:      IF minGreenStg1 THEN
S02Z006:        IF CarQueue THEN
S03Z006:          IF Extend_Stg1_CARS THEN
S04Z006:            IF NOT (Stage_duration( 1 ) <= MAX_EXT1) THEN
S04Z007:              IF BusDemand THEN
S05Z007:                Interstage( 1 , 2 )
                      END
                    END
                  ELSE
                    GO S04Z007
                  END
                ELSE
                  GO S04Z007
                END
              END
            ELSE
S00Z009:      IF Stage_active( 2 ) THEN
S01Z009:        IF minGreenStg2 THEN
S03Z009:          IF Extend_Stg2_BUS THEN
S04Z009:            IF NOT (Stage_duration( 2 ) <= MAX_EXT2) THEN
```

```
S04Z010:          IF CarDemand THEN
S05Z010:           Interstage( 2 , 1 )
             END
            END
           ELSE
            GO S04Z010
           END
          END
         END
        END
       END
PROG_END.
```

**APPENDIX B:** VSL+ALINEA Algorithm Codes in VisVAP

```
PROGRAM VSL; /* C:\Users\ndadashz\Desktop\RM ALINEA_Q-0.20-150m + 2VSL\VSL.vap */
VAP_FREQUENCY 1;
CONST
      PCU_m = 2 (Minibus), PCU_b (bus) = 3, PCU_db (Metrobus) = 3.6
      DT = 1,
      ALFA = 0.5,
      Q_ON_100 = 4200,
      Q_ON_85 = 5000,
      Q_ON_70 = 5700,
      Q_OFF_100 = 3600,
      Q_OFF_85 = 4500,
      Q_OFF_70 = 5100;
/* ARRAYS */
/* SUBROUTINES */
/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
/* EXPRESSIONS */
/* MAIN PROGRAM */
S00Z001:  IF NOT initialized THEN
S01Z001:    initialized := 1;
S01Z002:    desired_Speed := 120;
S01Z003:    Set_desired_speed( 1 , 10, desired_Speed );
S01Z004:    Set_desired_speed( 11 , 10, desired_Speed );
S01Z005:    Set_desired_speed( 2 , 10, desired_Speed );
S01Z006:    Set_desired_speed( 12 , 10, desired_Speed );
S01Z007:    Set_desired_speed( 3 , 10, desired_Speed );
S01Z008:    Set_desired_speed( 13 , 10, desired_Speed );
S01Z009:    Set_sg_direct( 10, off );
S01Z010:    Start( evalInt )
      END;
S00Z014:  IF evalInt = 60*DT THEN
S01Z014:        qCarPrev := qCar; qBusPrev := qBus;  qBus_DoDeckPrev := qBus_DoDeck;
qMinibusPrev := qMinibus;
S01Z015:    qCar1 := Front_ends( 21 ) * 60 / DT;
S01Z016:    qCar2 := Front_ends( 22 ) * 60 / DT;
S01Z017:    qCar3 := Front_ends( 23 ) * 60 / DT;
S01Z018:    qCar := qCar1 + qCar2 + qCar3;
S01Z019:    qCarZ :=  (ALFA * qCar) + ((1.0 - ALFA)  * qCarPrev);
S01Z020:    Clear_Front_ends( 21 ); Clear_Front_ends( 22 );
S01Z021:    Clear_Front_ends( 23 );
```

```
S03Z015:    qBus1 := Front_ends( 221 ) * 60 / DT;
S03Z016:    qBus2 := Front_ends( 222 ) * 60 / DT;
S03Z017:    qBus3 := Front_ends( 223 ) * 60 / DT;
S03Z018:    qBus := qBus1 + qBus2 + qBus3;
S03Z019:    qBusZ :=  (ALFA * qBus) + ((1.0 - ALFA)  * qBusPrev);
S03Z020:    Clear_Front_ends( 221 ); Clear_Front_ends( 222 );
S03Z021:    Clear_Front_ends( 223 );
S05Z015:    qBus_DoDeck1 := Front_ends( 2221 ) * 60 / DT;
S05Z016:    qBus_DoDeck2 := Front_ends( 2222 ) * 60 / DT;
S05Z017:    qBus_DoDeck3 := Front_ends( 2223 ) * 60 / DT;
S05Z018:    qBus_DoDeck := qBus_DoDeck1 + qBus_DoDeck2 + qBus_DoDeck3;
S05Z019:    qBus_DoDeckZ :=  (ALFA * qBus_DoDeck) + ((1.0 - ALFA)  * qBus_DoDeckPrev);
S05Z020:    Clear_Front_ends( 2221 ); Clear_Front_ends( 2222 );
S05Z021:    Clear_Front_ends( 2223 );
S07Z015:    qMinibus1 := Front_ends(  22221 ) * 60 / DT;
S07Z016:    qMinibus2 := Front_ends( 22222 ) * 60 / DT;
S07Z017:    qMinibus3 := Front_ends( 22223 ) * 60 / DT;
S07Z018:    qMinibus := qMinibus1 + qMinibus2 + qMinibus3;
S07Z019:    qMinibusZ :=  (ALFA * qMinibus) + ((1.0 - ALFA)  * qMinibusPrev);
S07Z020:    Clear_Front_ends( 22221 ); Clear_Front_ends( 22222 );
S07Z021:    Clear_Front_ends( 22223 );
S01Z023:    Qb := qCarZ + PCU_b *qBusZ + PCU_db*qBus_DoDeckZ + PCU_m*qMinibusZ;
S01Z024:    Reset( evalInt ); Start( evalInt );
S01Z025:    IF desired_Speed >= 120 THEN
S02Z025:      IF Qb > Q_ON_70 THEN
S03Z025:        Set_sg_direct( 10, RedYellow );
S04Z025:        desired_Speed := 70;
S01Z042:        Set_desired_speed( 1 , 10, desired_Speed );
S01Z043:        Set_desired_speed( 11 , 10, desired_Speed );
S01Z044:        Set_desired_speed( 2 , 10, desired_Speed );
S01Z045:        Set_desired_speed( 12 , 10, desired_Speed );
S01Z046:        Set_desired_speed( 3 , 10, desired_Speed );
S01Z047:        Set_desired_speed( 13 , 10, desired_Speed );
S01Z049:        Record_value( 1, Qb );
S01Z050:        Record_value( 3, desired_Speed )
          ELSE
S02Z026:        IF Qb > Q_ON_85 THEN
S03Z026:          Set_sg_direct( 10, Yellow );
S04Z026:          desired_Speed := 85;
            GO S01Z042
```

```
              ELSE
S02Z027:          IF Qb > Q_ON_100 THEN
S03Z027:           Set_sg_direct( 10, Green );
S04Z027:           desired_Speed := 100;
                GO S01Z042
               ELSE
                GO S01Z042
               END
              END
             END
            ELSE
S01Z029:        IF desired_Speed = 100 THEN
S02Z029:         IF Qb > Q_ON_70 THEN
S03Z029:          Set_sg_direct( 10, RedYellow );
S04Z029:          desired_Speed := 70;
               GO S01Z042
              ELSE
S02Z030:          IF Qb > Q_ON_85 THEN
S03Z030:           Set_sg_direct( 10, Yellow );
S04Z030:           desired_Speed := 85;
                GO S01Z042
               ELSE
S02Z031:           IF Qb < Q_OFF_100 THEN
S03Z031:            Set_sg_direct( 10, Aus );
S04Z031:            desired_Speed := 120;
                 GO S01Z042
                ELSE
                 GO S01Z042
                END
               END
              END
             ELSE
S01Z033:         IF desired_Speed = 85 THEN
S02Z033:          IF Qb > Q_ON_70 THEN
S03Z033:           Set_sg_direct( 10, RedYellow );
S04Z033:           desired_Speed := 70;
                GO S01Z042
               ELSE
S02Z034:           IF Qb < Q_OFF_100 THEN
S03Z034:            Set_sg_direct( 10, Off );
```

```
S04Z034:            desired_Speed := 120;
                  GO S01Z042
                 ELSE
S02Z035:            IF Qb < Q_OFF_85 THEN
S03Z035:             Set_sg_direct( 10, Green );
S04Z035:             desired_Speed := 100;
                   GO S01Z042
                  ELSE
                   GO S01Z042
                  END
                 END
                END
               ELSE
S01Z037:          IF desired_Speed = 70 THEN
S02Z037:           IF Qb < Q_OFF_100 THEN
S03Z037:            Set_sg_direct( 10, Off );
S04Z037:            desired_Speed := 120;
                  GO S01Z042
                 ELSE
S02Z038:            IF Qb < Q_OFF_85 THEN
S03Z038:             Set_sg_direct( 10, Green );
S04Z038:             desired_Speed := 100;
                   GO S01Z042
                  ELSE
S02Z039:             IF Qb < Q_OFF_70 THEN
S03Z039:              Set_sg_direct( 10, Yellow );
S04Z039:              desired_Speed := 85;
                    GO S01Z042
                   ELSE
                    GO S01Z042
                   END
                  END
                 END
                ELSE
                 GO S01Z042
                END
               END
              END
             END
            END
```

```
%% PROGRAM ALINEA_22; /* C:\Users\ndadashz\Desktop\FINAL\ALINEA-125Occ22\ALINEA-
22.vap */
CONST
        MAX_LANE = 3,
        KR = 70,
        OCC_OPT = 0.22;
/* ARRAYS */
ARRAY
        detNo[ 3, 1 ] = [[11], [12], [13]];
/* SUBROUTINES */
/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
        IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
          prog_aktiv0vv := 1;
          DT := 1;
        ELSE IF( prog_aktiv = 2 ) AND ( prog_aktiv0vv <> 2 ) THEN
          prog_aktiv0vv := 2;
          DT := 1;
        END END;
/* EXPRESSIONS */
        CarDemand := Detection( 10 );
        BusDemand := Detection( 20 );
        BusCancel := Occupancy( 2 ) > 0;
        CarQueue := Occupancy( 100 ) > 5;

/* MAIN PROGRAM */
S00Z001:    IF NOT init THEN
S01Z001:      init := 1;
S01Z002:      Set_sg( 1 , green )
        END;
S00Z004:    cyc_sec := cyc_sec + 1;
S00Z005:    IF cyc_sec >= cyc_length THEN
S01Z005:      cyc_sec := 0
        END;
S00Z007:    Set_cycle_second( cyc_sec );
S00Z008:    laneNo := 1;
S00Z010:    IF laneNo < MAX_LANE THEN
S01Z010:      IF detNo[ laneNo, 1 ] > 0 THEN
S03Z010:        oout := oout + Occup_rate( detNo[ laneNo, 1 ]);
S03Z011:        laneNo := laneNo + 1;
            GOTO S00Z010
```

```
          END
        END;
S00Z013:    timer_dc := timer_dc + 1;
S00Z014:    IF timer_dc = (60 * DT) THEN
S01Z014:      timer_dc := 0;
S01Z015:      qRamp := (Front_ends( 1 )); Clear_front_ends( 1 );
S01Z016:      oout := oout / MAX_LANE / (60*DT);
S01Z017:      cqRamp := qRamp + KR * (OCC_OPT - oout);
S01Z018:      cyc_length := 60*DT / cqRamp;
S01Z019:      oout100 := oout * 100; RecVal( 1, oout100 );
S01Z020:      oout := 0
        END;
S00Z022:    IF cyc_length < 4 THEN
S01Z022:      IF BusDemand THEN
S02Z022:        Set_sg( 1 , amber );
S03Z022:        Set_sg( 1 , red )
          ELSE
S01Z023:        IF NOT (BusCancel) THEN
S01Z024:          Set_sg( 1 , green )
            END
          END
        ELSE
S00Z025:      IF CarDemand THEN
S01Z025:        IF BusDemand THEN
S02Z025:          Set_sg( 1 , amber );
S03Z025:          Set_sg( 1 , red )
            ELSE
S01Z026:          IF NOT (BusCancel) THEN
S01Z027:            IF CarQueue THEN
S02Z027:              Set_sg( 1 , redamber );
S03Z027:              Set_sg( 1 , green )
                ELSE
S02Z028:              IF cyc_sec = 0 THEN
S03Z029:                Set_sg( 1 , redamber );
S03Z030:                cyc_sec := 0
                  ELSE
S02Z029:                IF T_red( 1 ) >= cyc_length-3 THEN
                      GOTO S03Z029
                    ELSE
S00Z031:                  IF Current_state( 1, redamber ) THEN
```

```
S01Z031:            Set_sg( 1 , green )
                ELSE
S00Z032:            IF Current_state( 1, green ) THEN
S01Z032:             IF NOT (cyc_length < 4) THEN
S01Z033:              Set_sg( 1 , amber )
                  END
                 ELSE
S00Z034:             IF Current_state( 1, amber ) THEN
S01Z034:              Set_sg( 1 , red )
                  END
                 END
                END
               END
              END
             END
            END
           END
          ELSE
           GOTO S00Z031
          END
         END;
S00Z036:    RecVal( 2, cyc_length );
S00Z037:    qRampHour := qRamp * 60 / DT; RecVal( 3, qRampHour )
PROG_END.
```

**APPENDIX C:** VSL+ALINEA/B Algorithm Codes in VisVAP

```
PROGRAM VSL; /* C:\Users\ndadashz\Desktop\RM ALINEA_Q-0.20-150m + 2VSL\VSL.vap */
VAP_FREQUENCY 1;
CONST
        PCU_m = 2 (Minibus), PCU_b (bus) = 3, PCU_db (Metrobus) = 3.6
        DT = 1,
        ALFA = 0.5,
        Q_ON_100 = 4200,
        Q_ON_85 = 5000,
        Q_ON_70 = 5700,
        Q_OFF_100 = 3600,
        Q_OFF_85 = 4500,
        Q_OFF_70 = 5100;
/* ARRAYS */
/* SUBROUTINES */
/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
/* EXPRESSIONS */
/* MAIN PROGRAM */
S00Z001:   IF NOT initialized THEN
S01Z001:     initialized := 1;
S01Z002:     des_Speed := 120;
S01Z003:     Set_desired_speed( 1 , 10, desired_Speed );
S01Z004:     Set_desired_speed( 11 , 10, desired_Speed );
S01Z005:     Set_desired_speed( 2 , 10, desired_Speed );
S01Z006:     Set_desired_speed( 12 , 10, desired_Speed );
S01Z007:     Set_desired_speed( 3 , 10, desired_Speed );
S01Z008:     Set_desired_speed( 13 , 10, desired_Speed );
S01Z009:     Set_sg_direct( 10, off );
S01Z010:     Start( evalInt )
        END;
S00Z014:   IF evalInt = 60*DT THEN
S01Z014:        qCarPrev := qCar; qBusPrev := qBus;  qBus_DoDeckPrev := qBus_DoDeck;
qMinibusPrev := qMinibus;
S01Z015:     q_Car1 := Front_ends( 21 ) * 60 / DT;
S01Z016:     q_Car2 := Front_ends( 22 ) * 60 / DT;
S01Z017:     q_Car3 := Front_ends( 23 ) * 60 / DT;
S01Z018:     q_Car := qCar1 + qCar2 + qCar3;
S01Z019:     q_CarZ :=  (ALFA * qCar) + ((1.0 - ALFA)  * qCarPrev);
S01Z020:     Clear_Front_ends( 21 ); Clear_Front_ends( 22 );
S01Z021:     Clear_Front_ends( 23 );
```

```
S03Z015:     qBus1 := Front_ends( 221 ) * 60 / DT;
S03Z016:     qBus2 := Front_ends( 222 ) * 60 / DT;
S03Z017:     qBus3 := Front_ends( 223 ) * 60 / DT;
S03Z018:     qBus := qBus1 + qBus2 + qBus3;
S03Z019:     qBusZ :=  (ALFA * qBus) + ((1.0 - ALFA)  * qBusPrev);
S03Z020:     Clear_Front_ends( 221 ); Clear_Front_ends( 222 );
S03Z021:     Clear_Front_ends( 223 );
S05Z015:     qBus_DoDeck1 := Front_ends( 2221 ) * 60 / DT;
S05Z016:     qBus_DoDeck2 := Front_ends( 2222 ) * 60 / DT;
S05Z017:     qBus_DoDeck3 := Front_ends( 2223 ) * 60 / DT;
S05Z018:     qBus_DoDeck := qBus_DoDeck1 + qBus_DoDeck2 + qBus_DoDeck3;
S05Z019:     qBus_DoDeckZ :=  (ALFA * qBus_DoDeck) + ((1.0 - ALFA)  * qBus_DoDeckPrev);
S05Z020:     Clear_Front_ends( 2221 ); Clear_Front_ends( 2222 );
S05Z021:     Clear_Front_ends( 2223 );
S07Z015:     qMinibus1 := Front_ends(  22221 ) * 60 / DT;
S07Z016:     qMinibus2 := Front_ends( 22222 ) * 60 / DT;
S07Z017:     qMinibus3 := Front_ends( 22223 ) * 60 / DT;
S07Z018:     qMinibus := qMinibus1 + qMinibus2 + qMinibus3;
S07Z019:     qMinibusZ :=  (ALFA * qMinibus) + ((1.0 - ALFA)  * qMinibusPrev);
S07Z020:     Clear_Front_ends( 22221 ); Clear_Front_ends( 22222 );
S07Z021:     Clear_Front_ends( 22223 );
S01Z023:     Qb := qCarZ + PCU_b *qBusZ + PCU_db*qBus_DoDeckZ + PCU_m*qMinibusZ;
S01Z024:     Reset( evalInt ); Start( evalInt );
S01Z025:     IF desired_Speed >= 120 THEN
S02Z025:       IF Qb > Q_ON_70 THEN
S03Z025:         Set_sg_direct( 10, RedYellow );
S04Z025:         desired_Speed := 70;
S01Z042:         Set_desired_speed( 1 , 10, desired_Speed );
S01Z043:         Set_desired_speed( 11 , 10, desired_Speed );
S01Z044:         Set_desired_speed( 2 , 10, desired_Speed );
S01Z045:         Set_desired_speed( 12 , 10, desired_Speed );
S01Z046:         Set_desired_speed( 3 , 10, desired_Speed );
S01Z047:         Set_desired_speed( 13 , 10, desired_Speed );
S01Z049:         Record_value( 1, Qb );
S01Z050:         Record_value( 3, desired_Speed )
           ELSE
S02Z026:         IF Qb > Q_ON_85 THEN
S03Z026:           Set_sg_direct( 10, Yellow );
S04Z026:           desired_Speed := 85;
             GO S01Z042
```

```
              ELSE
S02Z027:           IF Qb > Q_ON_100 THEN
S03Z027:             Set_sg_direct( 10, Green );
S04Z027:             desired_Speed := 100;
                  GO S01Z042
                ELSE
                  GO S01Z042
                END
              END
            END
          ELSE
S01Z029:       IF desired_Speed = 100 THEN
S02Z029:         IF Qb > Q_ON_70 THEN
S03Z029:           Set_sg_direct( 10, RedYellow );
S04Z029:           desired_Speed := 70;
                GO S01Z042
              ELSE
S02Z030:           IF Qb > Q_ON_85 THEN
S03Z030:             Set_sg_direct( 10, Yellow );
S04Z030:             desired_Speed := 85;
                  GO S01Z042
                ELSE
S02Z031:             IF Qb < Q_OFF_100 THEN
S03Z031:               Set_sg_direct( 10, Aus );
S04Z031:               desired_Speed := 120;
                    GO S01Z042
                  ELSE
                    GO S01Z042
                  END
                END
              END
            ELSE
S01Z033:         IF desired_Speed = 85 THEN
S02Z033:           IF Qb > Q_ON_70 THEN
S03Z033:             Set_sg_direct( 10, RedYellow );
S04Z033:             desired_Speed := 70;
                  GO S01Z042
                ELSE
S02Z034:             IF Qb < Q_OFF_100 THEN
S03Z034:               Set_sg_direct( 10, Off );
```

```
S04Z034:            desired_Speed := 120;
                GO S01Z042
               ELSE
S02Z035:            IF Qb < Q_OFF_85 THEN
S03Z035:             Set_sg_direct( 10, Green );
S04Z035:             desired_Speed := 100;
                 GO S01Z042
                ELSE
                 GO S01Z042
                END
               END
              END
             ELSE
S01Z037:          IF desired_Speed = 70 THEN
S02Z037:           IF Qb < Q_OFF_100 THEN
S03Z037:            Set_sg_direct( 10, Off );
S04Z037:            desired_Speed := 120;
                GO S01Z042
               ELSE
S02Z038:            IF Qb < Q_OFF_85 THEN
S03Z038:             Set_sg_direct( 10, Green );
S04Z038:             desired_Speed := 100;
                 GO S01Z042
                ELSE
S02Z039:             IF Qb < Q_OFF_70 THEN
S03Z039:              Set_sg_direct( 10, Yellow );
S04Z039:              desired_Speed := 85;
                  GO S01Z042
                 ELSE
                  GO S01Z042
                 END
                END
               END
              ELSE
               GO S01Z042
              END
             END
            END
           END
          END
```

```
%% PROGRAM ALINEA_B_22; /* C:\Users\ndadashz\Desktop\FINAL\VSL+ALINEA+B-125Occ22\ALINEA-B-22.vap */
CONST
	MAX_LANE = 3,
	KR = 70,
	OCC_OPT = 0.22;
/* ARRAYS */
ARRAY
	detNo[ 3, 1 ] = [[11], [12], [13]];
/* SUBROUTINES */
/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
	IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
	  prog_aktiv0vv := 1;
	  DT := 1;
	ELSE IF( prog_aktiv = 2 ) AND ( prog_aktiv0vv <> 2 ) THEN
	  prog_aktiv0vv := 2;
	  DT := 1;
	END END;
/* EXPRESSIONS */
	CarDemand := Detection( 10 );
	BusDemand := Detection( 20 );
	BusCancel := Occupancy( 2 ) > 0;
	CarQueue := Occupancy( 100 ) > 5;

/* MAIN PROGRAM */
S00Z001:  IF NOT init THEN
S01Z001:    init := 1;
S01Z002:    Set_sg( 1 , green )
	END;
S00Z004:  cyc_sec := cyc_sec + 1;
S00Z005:  IF cyc_sec >= cyc_length THEN
S01Z005:    cyc_sec := 0
	END;
S00Z007:  Set_cycle_second( cyc_sec );
S00Z008:  laneNo := 1;
S00Z010:  IF laneNo < MAX_LANE THEN
S01Z010:    IF detNo[ laneNo, 1 ] > 0 THEN
S03Z010:      oout := oout + Occup_rate( detNo[ laneNo, 1 ]);
S03Z011:      laneNo := laneNo + 1;
	  GOTO S00Z010
```

```
       END
     END;
S00Z013:  timer_dc := timer_dc + 1;
S00Z014:  IF timer_dc = (60 * DT) THEN
S01Z014:    timer_dc := 0;
S01Z015:    qRamp := (Front_ends( 1 )); Clear_front_ends( 1 );
S01Z016:    oout := oout / MAX_LANE / (60*DT);
S01Z017:    cqRamp := qRamp + KR * (OCC_OPT - oout);
S01Z018:    cyc_length := 60*DT / cqRamp;
S01Z019:    oout100 := oout * 100; RecVal( 1, oout100 );
S01Z020:    oout := 0
     END;
S00Z022:  IF cyc_length < 4 THEN
S01Z022:    IF BusDemand THEN
S02Z022:      Set_sg( 1 , amber );
S03Z022:      Set_sg( 1 , red )
       ELSE
S01Z023:      IF NOT (BusCancel) THEN
S01Z024:        Set_sg( 1 , green )
         END
       END
     ELSE
S00Z025:    IF CarDemand THEN
S01Z025:      IF BusDemand THEN
S02Z025:        Set_sg( 1 , amber );
S03Z025:        Set_sg( 1 , red )
         ELSE
S01Z026:        IF NOT (BusCancel) THEN
S01Z027:          IF CarQueue THEN
S02Z027:            Set_sg( 1 , redamber );
S03Z027:            Set_sg( 1 , green )
             ELSE
S02Z028:            IF cyc_sec = 0 THEN
S03Z029:              Set_sg( 1 , redamber );
S03Z030:              cyc_sec := 0
               ELSE
S02Z029:              IF T_red( 1 ) >= cyc_length-3 THEN
                 GOTO S03Z029
                 ELSE
S00Z031:                IF Current_state( 1, redamber ) THEN
```

```
S01Z031:            Set_sg( 1 , green )
                  ELSE
S00Z032:            IF Current_state( 1, green ) THEN
S01Z032:             IF NOT (cyc_length < 4) THEN
S01Z033:              Set_sg( 1 , amber )
                    END
                   ELSE
S00Z034:             IF Current_state( 1, amber ) THEN
S01Z034:              Set_sg( 1 , red )
                    END
                   END
                  END
                 END
                END
               END
              END
             END
            ELSE
             GOTO S00Z031
            END
           END;
S00Z036:   RecVal( 2, cyc_length );
S00Z037:   qRampHour := qRamp * 60 / DT; RecVal( 3, qRampHour )
PROG_END.
```

**CURRICULUM VITAE**

**Name Surname** : Nima DADASHZADEH

**Place and Date of Birth** : Astara (Iran), 25/07/1987

**E-Mail** : dadashzadeh@itu.edu.tr

**EDUCATION** :

- **B.Sc.** : 2010, Islamic Azad University, Civil Engineering Faculty, Road and Transportation Eng. Department, Zanjan, Iran
- **M.Sc.** : 2013, Islamic Azad University, Civil Engineering Faculty, Road and Transportation Eng. Department, Zanjan, Iran

**PROFESSIONAL EXPERIENCE AND REWARDS:**

- 2018- Present **Traffic/Transport Engineer**, Traffic Technical Institute, Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia.
- 2017-18 **EU fund for Erasmus+ Exchange program**, Istanbul Technical University (Turkey) – University of Ljubljana (Slovenia)
- 2015-17 **Traffic/Transport Engineer**, Transportation Eng. Department, Civil Engineering Faculty, Istanbul Technical University, Istanbul, Turkey.
- 2014-15 **Research assistantship fund** by TÜBİTAK (Scientific and Technological Research Council of Turkey), Istanbul Technical University, Turkey.
- 2013 **Second class honors**, M.Sc. degree, Islamic Azad University, Zanjan, Iran.
- 2010 **Second class honors**, B.Sc. degree, Islamic Azad University, Zanjan, Iran.

**PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:**

- **Dadashzadeh, N.** & Ergun, M. 2018. Spatial Bus Priority Schemes, their implementation challenges and needs, *Public Transport* 10(3): pp 545-570, Springer, https://doi.org/10.1007/s12469-018-0191-5
- **Dadashzadeh, N.,** Ergun, M., Kesten, A., Žura, M. 2019. An automatic calibration procedure of driving behavior parameters in presence of high bus demand, *PROMET– Traffic & Transportation*, *Promet - Traffic & Transportation*, *31*(5), 1–14. https://doi.org/10.7307/ptt.v31i5.3100
- **Dadashzadeh, N.,** Ergun, M., Kesten, A., Žura, M. 2019: Improving calibration time of traffic simulation models using parallel computing techniques, IEEE 6th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), 5-7th June, 2019 Kraków, Poland
- **Dadashzadeh, N.,** Ergun, M., Kesten, A., Žura, M. 2019: A modified ramp-metering system for high bus demand, 22nd EURO Working Group on Transportation (EWGT), 17-20th Semtember, 2019 Barcelona, Spain (Accepted)

**OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:**

- **Dadashzadeh, N.,** Zakeri, J. A., Abbaszadeh, T., Eimani, H. 2015: An Investigation on the Roads Black Spots in Ardabil province and strategies to their improvement using GIS, proceeding of 2nd International Conference on Civil Engineering, Architecture & Urban Sustainable Development, October, 2015 Tabriz, Iran, in Persian. https://www.civilica.com/Study-ICICA01-ICICA01_0782.html
- **Dadashzadeh, N.,** Mirmohammadi, V., Azimi, J. 2015: A multiple criteria approach for evaluation of tunnel safety in Iran: A case study of Ardabil province, proceeding of 18th EURO Working Group on Transportation (EWGT), July, 2015 Delft University of Technology, Delft, Netherlands, https://doi.org/10.13140/RG.2.2.32120.29449
- **Dadashzadeh, N.,** Zakeri, J. A., Eimani, H. 2014: An investigation on the effect of axle load variation on the dynamic response of railway bridge, proceeding of 16th International Conference on Railway Transportation, October, 2014 Tehran, Iran – in Persian, https://www.civilica.com/Study-ICSAU03-ICSAU03_1504.html
- **Dadashzadeh, N.,** Zakeri, J. A., Eimani, H. 2013: Determination of the Critical velocity on railway bridges under one-way crossing of High-Speed trains, proceeding of International Conference on Civil Engineering, Architecture & Urban Sustainable Development, December, 2013 Tabriz, Iran – in Persian. https://www.civilica.com/Study-ICCAU01-ICCAU01_0012.html
- **Dadashzadeh, N.,** Zakeri, J. A., Eimani, H. 2013: Dynamic Analysis of Railway Bridges under the Simultaneously Crossing of Two High Speed trains (Opposite Direct), proceeding of 4th National Conference on Earthquake, & Structure, April, 2013 Kerman, Iran – in Persian. https://www.civilica.com/Study-CESCM04-CESCM04_142.html