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**Scheduling Lane Conversions for Bus Use on City-Wide Scales and in  
Time-Varying Traffic**

by

Nathalie Saade

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering - Civil and Environmental Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Michael Cassidy, Co-chair  
Assistant Professor Weihua Gu, Co-chair  
Professor Carlos Daganzo  
Professor Xin Guo

Fall 2017

**Scheduling Lane Conversions for Bus Use on City-Wide Scales and in  
Time-Varying Traffic**

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Nathalie Saade

## Abstract

Scheduling Lane Conversions for Bus Use on City-Wide Scales and in Time-Varying Traffic

by

Nathalie Saade

Doctor of Philosophy in Engineering - Civil and Environmental Engineering

University of California, Berkeley

Professor Michael Cassidy, Co-chair

Assistant Professor Weihua Gu, Co-chair

The dissertation explores what can occur when select street lanes throughout a city are periodically reserved for buses. Simulations of an idealized city were performed to that end. The city's time-varying travel demand was studied parametrically. In all cases, queues formed throughout the city during a rush, and dissipated during the off-peak period that followed. Bus lanes were activated all at once across the city, and were eventually deactivated in like fashion. Activation and deactivation schedules varied parametrically as well. Schedules that balanced the trip-time savings to bus riders against the added delays to car travelers were thus identified.

Findings reveal why activating conversions near the start of a rush can degrade travel, both by car and by bus. Balance was struck by instead activating lane conversions much closer to the subsidence of rush demand. Most of the time savings to bus riders accrued after the conversions had been left in place for only 30 mins. Leaving them for longer durations often brought modest additional savings to bus travelers. Yet, the added delays to cars often grew large.

These findings held even when buses garnered high ridership shares, whether or not those higher shares were induced over time. Activating conversions early in a rush was found to make sense only if commuters shifted from cars to buses in high numbers. Findings also unveiled how to fine-tune activation and deactivation schedules to suit a city's congestion level. Guidelines are offered for scheduling conversions in real settings. Discussion on how these schedules might be adapted to daily variations in city-wide traffic states is offered as well.

To my family, for their love and support.

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# Chapter 1

## Introduction

Where unused space is in short supply, cities often convert regular street lanes to exclusive bus lanes during select times of day. By traveling in converted lanes, buses can bypass car queues. Yet, a converted lane will reduce the street's car-carrying capacity. The challenge thus lies in converting lanes in ways that strike a balance between the benefits extended to buses, and the damage done to cars.

Cities presently strike that balance by limiting the spatial extents over which conversions are deployed; i.e. lanes are converted on a few select streets, rather than throughout a city in wholesale fashion (e.g. [71]). Yet, as the world's population marches toward greater urbanization, crowded cities of the future might benefit from more physically-expansive networks of converted bus lanes. A challenge would thus entail when to schedule these city-wide conversions in time.

### 1.1 Dissertation Overview

The dissertation explores the impacts of city-wide bus lane conversion schedules on bus and car traffic under non-steady state conditions. The analysis is performed using simulations based on macroscopic traffic flow theory.

Current practice is to put conversions in place for periods that either: span a morning or evening rush; or persist for longer durations that include both rush periods and the hours between [1]. The present findings show that neither practice is appropriate when deploying conversions on large, city-wide scales. Schedules for activating and deactivating lane conversions in this wholesale fashion call instead for fuller consideration of traffic's time-varying nature.

Simulations show that a city would do well to fine-tune its schedules to accommodate

its level of rush-period congestion. Yet for nearly every congestion level studied, activating lane conversions near the end of a rush balanced benefits and costs better than did scheduling activations near the rush's start. Findings were insensitive to the ridership shares that buses garnered when those riders were not pulled from cars. Exceptions occurred only when commuters shifted from cars to buses in large numbers.

## 1.2 Dissertation Organization

A brief overview of the evolution of bus lane conversions along with current issues regarding their implementation are covered in Chapter 2. Key related studies pertaining to bus lane conversions are described in Chapter 3. The methodology including the experimental setup for performing the analysis is provided in Chapter 4. Numerical findings including parametric analyses are presented in Chapter 5. In Chapter 6, matters pertaining to real-world implementation are discussed. A brief discussion and future directions are presented in Chapter 7.

## Chapter 2

# Evolution of Bus Lane Conversions

The world's first designated bus lane was created in Chicago in 1939 [39]. Soon afterwards, bus lanes started emerging in Europe and particularly in Paris [66]. In the mid 1950s, congestion severely grew as cars became the increasingly dominant mode of transportation (shown in Figure 2.1). The resulting decline in bus ridership levels forced many cities to abandon their bus-only lanes (e.g. Atlanta and Baltimore) [46].

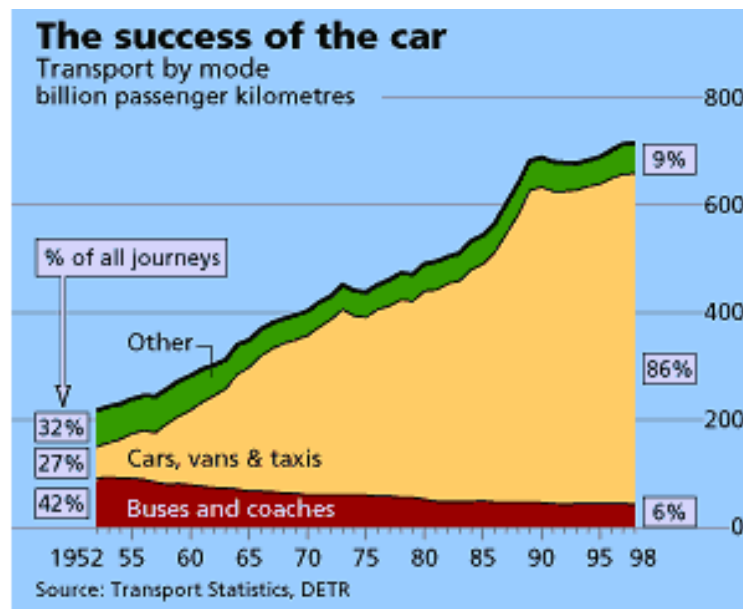


Figure 2.1: Evolution in Mode Share

In the face of deteriorating traffic conditions, the only viable option for transit improvement was: bus lane conversions, a far less disruptive alternative to fully dedicated lanes. The latter remain to this day troublesome especially in congested cities where bus ridership levels are not extremely high. London's M4 fully dedicated bus lanes, which were removed in 2010,

expose the unsustainable nature of fully dedicated bus lanes in congested cities dominated by car travel [3].

Apart from limiting damage to car traffic, bus lane conversions are often preferred to the fully dedicated alternative because they are cost effective and provide cities with flexibility in scheduling.

In 1956, Nashville became the first city to implement bus lane conversions on its right-hand lanes during morning and evening peak hours [49]. Many cities have thereafter successfully implemented bus lane conversions.

## 2.1 Overview of Current Bus Lane Conversions

Bus lane conversions are currently prevalent in cities of varying features (e.g. Seoul, Paris, San Francisco, etc.). Table 2.1 shows the popularity of different lane conversion schedules for a few cities: the table gives the percentage of bus lane conversions from all implemented bus lanes in each city such that conversions are scheduled for either daytime hours or peak period only [1]. Fully dedicated lanes are not shown in this table, meaning that the proportion of all bus lanes that is unaccounted for in this table is considered a fully dedicated bus lane.

Hours of Operation	London	Los Angeles	New York	San Francisco	Seoul	Sydney
Daytime hours on weekdays	25%		40%	11%	32%	18%
Peak period only on weekdays	46%	100%	58%	23%	24%	70%

Table 2.1: Proportion of Different Bus Lane Conversion Schedule in Various Cities

Bus lane conversions can be implemented as either curbside or offset lanes. Curbside lanes allow buses to utilize the lane closest to the curb and thus parking at the curb is prohibited during conversion hours (e.g. bus lanes on Bush St. and Sacramento St. in San Francisco). Conversely, offset bus lanes allow for curb parking as they reserve one lane away from the curb for bus travel (e.g. bus lanes on Geary St. and Sansome St. in San Francisco). Figure 2.2 shows the two types of bus lanes.

We take a closer look at a few examples of the most prominent bus lane conversions that are currently in operation and highlight some differences in lane conversion implementations across cities.



(a) Curbside Bus Lane (Clay St., San Francisco)



(b) Offset Bus Lane (Church St., San Francisco)

Figure 2.2: Curbside and Offset Bus Lanes

## San Francisco

San Francisco, which has long been acclaimed a transit forward city, was one of the first cities to push for giving priority to transit over other motor vehicles in 1973 [7].



Close to 720,000 passengers (about 25% of total commuters across all modes) currently use Muni every day [21] and the numbers are projected to increase over the coming years [59]. As a result, the city has continuously focused on transit-oriented developments and currently maintains 6 miles of peak-hour bus lane conversions [1]. A 2016 survey has revealed that bus passengers are satisfied with the Muni bus service with 65% of respondents citing shorter trip times following the implementation of bus-only lanes as one of their primary reasons for satisfaction [21].

## Los Angeles

Bus ridership in Los Angeles is reported to reach close to 900,000 which exceeds the ridership in San Francisco [51]. Despite the high ridership levels, Los Angeles has struggled to find support for its bus-only lanes due to fear of heavy congestion.

Following several years of extensive debates, LA Metro approved in 2015 an extension of its very few bus lane conversions to 7.7 miles of peak-hour bus lanes on Wilshire Boulevard [44]. The lanes operate from 7 to 9 a.m. and 4 to 7 p.m. on weekdays [44]. More than 25,000 passengers currently board the bus on Wilshire Boulevard daily at peak hours [47]. Following the success of bus lane conversions along Wilshire Boulevard, LA citizens are pushing for implementing lane conversions along Vermont Avenue, the second busiest bus corridor behind Wilshire [34].

## New York City

New York City was one of the first cities to implement bus lane conversions: in 1970, it established a contraflow bus lane on Lincoln Tunnel which operated during morning peak hours [64]. The bus lane is considered one of the busiest lanes in the United States and is still successful to this day as over 100 bus carriers use it compared to 25 in 1970 [65].

Since then, New York City has been one of the most active cities in expanding its bus network: currently, 12 exclusive bus service routes have been implemented throughout New York City with only part of those routes operating during specific hours only [55]. Many bus lanes that started operation as peak period lanes were later extended to all-day operation following favorable performance results. For example, bus lane conversions on Webster Avenue, which were originally peak period lanes, were converted to all-day dedicated bus lanes in 2013 [55]. The Webster Avenue bus lane conversions have been reported to increase bus ridership by more than 7%, and reduce travel times by up to 23% [56].

The case studies above are but a few of the success stories of bus lane conversions in diverse congested cities [41, 1].

## 2.2 Ongoing Debates about Bus Lane Conversions

While successful in a wide range of settings, bus lane conversions have also stirred debates in many cities that tried to adopt them (e.g. Portland, Santa Monica, Washington D.C., etc). On the one hand, advocates of bus lane conversions urge cities to improve bus travel, and on the other, opponents claim that restricting the number of car lanes will prove disastrous to car traffic [11, 69]. The divide in opinions is only growing larger as general traffic is forecasted to rise over the next few years.

A recent instance of debates regarding the adoption of bus lane conversions occurred in the city of Santa Clara in California. In early 2015, Santa Clara's Valley Transportation Authority (VTA) faced strong opposition after putting together a \$233 million proposal for a 13.9 mile Bus Rapid Transit (BRT) corridor along El-Camino that would provide faster transportation between Palo Alto and Santa Clara [61]. Due to concerns about further impeding traffic conditions along the corridor, VTA replaced its BRT proposal with bus lane conversions. The lane conversions would operate on 1 out of 3 lanes in each direction and only during peak traffic hours: 7am to 9am and 3pm to 7pm, Monday through Friday [53]. The idea of bus lane conversions helped placate opposition because it is less damaging to car travel and could be implemented at a lower cost (around \$100 million) [9]. However, the public still voiced skepticism that lane conversions would aggravate traffic conditions along the corridor and would cause undesirable diversions onto neighborhood streets. After extensive meetings among the VTA's Policy Advisory Board and the affected city councils, no consensus was reached among the concerned parties and the bus lane conversions pilot has been suspended as of late 2016.

Santa Clara is only one of many cities that have battled with finding support for bus lane conversions. The challenge lies in balancing benefits to bus passengers and damages to car travel. In this dissertation, we explore how bus lane conversion schedules can help cities overcome this obstacle in the hope of building more transit-friendly cities.

This dissertation only tackles the most prevalent cause of opposition to bus lane conversions: damage to car travel. In reality, implementing bus lane conversions presents many challenges that extend beyond impeding car travel and that are outside the scope of this dissertation.

## 2.3 Practical Challenges Outside the Scope of the Dissertation

We briefly present some of the challenges in the face of implementing bus lane conversions that are not restricted to car travel damage. These issues are provided here to give the

reader a comprehensive overview of the subject but will not be addressed in this study.

## **Enforcement**

Enforcement is key to the effectiveness of bus-only lanes and remains a recurrent challenge for most cities trying to implement conversions. The need for enforcement manifests itself mostly in cities where bus lanes are not heavily utilized, which entices car travelers to illegally travel on the lane.

The main difficulty remains in the limited legal realm in which transportation agencies may operate when dealing with bus lane violations. Law enforcement typically falls under the police jurisdiction, which means that a civilian transportation agency cannot be granted the power to enforce laws concerning the operation of vehicles that use bus lanes. As a result, cities have tried sharing the enforcement across multiple agencies depending on the nature of the bus lane violation. For example, on-the-ground enforcement of illegal driving in the bus lane is conducted by the police for most cities as occurs in London and San Francisco, but is done under contract or direct supervision of the city's transportation agency [1]. Moreover, some cities have reclassified bus lane violations as civil infractions so that they can be enforced by civilian agents and automated cameras. This is the case for cities like Seoul where camera-based enforcement is conducted by the transportation agency [1]. When the bus lane violation involves illegal parking in the bus lane, it is typical for enforcement to be carried out by transportation agencies or parking units of local governments [1].

Although many cities have tried to divide responsibilities among transportation agencies and the police department, coordinating between all the different powers to enforce bus lanes still remains a challenge.

## **Commercial Deliveries**

In many cities, vehicles are not allowed to stop in the bus lanes which makes commercial deliveries particularly problematic. For instance, the issue has been a major concern for New York City, where driveways and minor services streets are mostly non-existent. The city has thus opted to restrict its bus lane hour operation in order accommodate midday deliveries. For example, the Fordham Road bus lane which is operational from 7am to 7pm permits commercial deliveries on its south side from 10am to 12pm, and on its north side from 12pm to 2pm [2].

## **Parking**

In dense cities, curbside bus-only lanes typically prohibit parking during the peak-hours of the day as occurs in New York City [54]. This can lead to scarcer parking spaces in congested

cities and can potentially cause more congestion by drivers who circulate in the city to find parking.

## **Cost**

Even though no physical separation needs to be constructed for bus lane conversions, the city still has to provide the appropriate bus-only signage which can be costly. Moreover, the city would also preferably paint the lanes which has been proven to massively boost transit efficiency in the case of San Francisco [38]. Painting the pavement alone was estimated to cost \$200,000 for the West Seattle Bridge bus lane [32]. Therefore, cost is certainly an important factor to consider when implementing lane conversions.

# Chapter 3

## Key Related Studies

Bus lane conversions have been studied in the literature at two levels of granularity: (i) the road segment level, and (ii) the network level. This chapter first offers an overview of research on bus lane conversions at both levels (Sections 3.1 - 3.2). Gaps in the literature are described in Section 3.3. Tools used in the analysis are reviewed in Section 3.4.

### 3.1 Bus Lane Conversions at the Road Segment Level

Research exploring the impacts of bus lane conversions at the road segment level is detailed below. The studies highlight the potential bus benefits that result from lane conversions in terms of reduced travel time, improved reliability, and increased ridership levels. Most of the previous research also shows that the damage to car travel can be significant. Growing concern about this damage led to the emergence of intermittent lane conversions detailed shortly. Findings typically came via a mix of simulation and field experiments.

One of the earliest experiments on bus lane conversions was conducted for four peak-hour bus lanes implemented in 1980 in Bangkok, Thailand [63]. The lanes had a total length of 59 miles and generally operated during the morning (6:30am to 9am) and evening (3pm to 6:30pm) peaks. Travel time surveys conducted using license plate and stopwatch recordings showed that the peak-hour lanes decreased bus travel time and increased reliability. The improvement in travel time ranged from 0.7% to 23% depending on the site (arterial or street segment). The lanes had mixed impacts on car travel times, which were shown to increase in one site (by around 28%), remained unchanged in a few others, and even decreased in some areas (by up to 47%). The study concluded that peak-hour bus lanes are favorable to bus travel and in general do not adversely affect cars except in congested areas. However, the range of reported impacts is extremely wide which renders the experiment results unclear. It is also uncertain whether the reported impacts are solely the result of bus lane conversions: the analysis reported an increase in bus ridership and traffic volumes, the effects of which were not isolated from the impacts of lane conversions.

Many studies also relied on real data for exploring the impacts of bus lane conversions. Black et al [5] studied the allocation of street space between different modes on urban arterials in steady-state conditions. Data was collected for the first bus lane in Seoul which operated during the morning peak. Findings showed that the bus lane decreased user costs which include travel times for passengers across all modes. Travel times were coarsely estimated based on traffic flows using Davidson's formula [22] which is not appropriate for modeling dynamic traffic conditions.

Jepson & Ferreira [36] also assessed bus priority treatments on an arterial but resorted to simulation to account for delays at signalized intersections. Findings showed that bus lanes are difficult to justify in highly saturated traffic conditions due to the damage caused to car traffic. At lower levels of saturation, bus delay savings - albeit less substantial - are found sufficient to balance the detrimental effects of the bus lane on car traffic.

Surprenant & El-Geneidy [62] studied the impacts of peak-hour only on bus travel. Automated vehicle location and passenger counts data were recorded for two parallel corridors with bus lane conversions in Montreal, Canada. Estimates of bus travel time showed savings of 1.3% to 2.2% in total bus running time and an increase in bus service reliability.

Shalaby [60] analyzed the impacts of bus lane conversions using both field data and simulations. The study explored lane conversions for an arterial on Bay Street in Downtown Toronto, Canada. The bus lane operated between 7am and 7pm on weekdays. Findings showed that bus travel improved after implementing conversions, with the largest reported savings being a decrease in travel time by 9% for the afternoon peak period. The adjacent car travel suffered damages to travel time with a largest increase of 15% during the morning peak. While the deterioration of car travel outweighed the improvements in bus performance, the study found bus lane conversions to be promising because the authors measured an increase in bus ridership levels which they expect to persist in the future. It was deemed unclear whether the ridership increase resulted from modal shifts from adjacent car travel or from induced bus demand.

Currie et al [14] highlighted the importance of a comprehensive evaluation of impacts on all users when considering road space allocation schemes. The work proposed a preliminary approach for evaluating the full range of costs and benefits to all passengers using both an economic and a dynamic traffic flow model. Microsimulations applied to an arterial road in Melbourne, Australia showed that, besides improving bus travel times, bus lane conversions could result in a decrease in car ridership. This in turn reduces operating costs, accidents, congestion and negative environmental impacts by an amount valued at \$48,000.

Many studies proposed variants to dedicated bus lanes that are intended to be less detrimental to car traffic even in the absence of modal shifts to bus use. Viegas & Lu [68] introduced Intermittent Bus Lanes (IBL) which prohibit cars from entering a lane in front of an approaching bus. The strategy was implemented in Lisbon, Portugal and experiments

showed high compliance as well as positive reaction from car passengers Viegas et al [67]. Eichler & Daganzo [23] later proposed a variant of IBL named Bus Lanes with Intermittent Priority (BLIPs) which operate by forcing traffic out of a lane one link at a time using Variable Message Signs on an as-needed basis. The conversion persists only for short periods needed to individually serve a buses' passage through that link. The study found that that BLIPs reduced bus delays by minimizing damaging interactions between buses and cars. Analytical formulas were provided to determine the changes in travel time resulting from BLIPs for buses and cars. For further reference on variants of IBL and BLIP implementations on a road segment, see [13, 8, 10].

## 3.2 Bus Lane Conversions at the Network Level

Bus lane conversion studies at the network level remain less extensive than those at the road segment level. The two main questions that arise when exploring lane conversions at the network level are: the spatial allocation problem (i.e. where should the lanes be located), and the scheduling problem (i.e. when should these lanes be activated).

Mesbah et al [50] explored how to optimally select lanes to be converted across large, city-scale networks. The study proposed bilevel mathematical programs that can be used to minimize total travel time for both car and bus passengers. The upper level of the optimization consisted of an objective function that was formulated from a system managers' perspective. The lower level included models to account for mode choice, user equilibrium and transit assignment. The work estimated travel times using a linear function of flows that is only appropriate in steady-state conditions. Moreover, the provided numerical application of the model is performed in uncongested conditions.

Research in [27] pursued city-wide designs assuming that lanes can be converted on an intermittent, as-needed basis, as might ideally occur with perfectly managed Bus Lanes with Intermittent Priority (BLIPs); see [23]. The work focused on the optimal allocation of road space with the objective of minimizing the total cost of transportation, including the costs of infrastructure, travel time, and access. The study identified the modal splits needed to minimize the overall cost and the pricing schemes that would bring about these splits. The work assumed that city traffic was congested, but with conditions that changed little over time.

To our knowledge, the only previous attempt to study the scheduling problem for city-wide lane conversions in non-steady-state traffic appears in [70]. It formulated analytical models to determine not only which lanes to be converted during a 1-h rush, but also when to schedule the activations and deactivations. The models estimated trip-completion rates on a city network as a function of its vehicle accumulations alone. Yet in non-stationary traffic,

the system state at time  $t$  also depends on the proportion of each vehicle's trip completed at  $t$ . A detailed description of the function's suitable application is provided in Sec 3.4. For further detail, the reader can refer to pp. 51-53 of [17].

Optimizing travel times in congestion is not the only objective for solving the spatial allocation problem for bus lane conversions; various other objectives have been studied. Hadas & Ceder [31] formulated the spatial allocation optimization with the objective of increasing bus network connectivity. The latter helps increase the reliability of transfers and improves schedule adherence. Recently, Zheng et al. [71] proposed a simulation-based approach that finds the optimal amount of road space that should be allocated to bus lane conversions as well as the distribution of those lanes in the network. The optimization is performed with the objective of keeping traffic states in the uncongested branch of the MFD. This is achieved through increases in modal shifts that arise from allocating more space to lane conversions. The work thus combines a logit model for predicting modal shift levels under different amounts of road space allocation and a microsimulation for evaluating congestion. Simulations of a real Swiss city network showed that the most efficient strategy consists in allocating 15% of the road space to buses. However, the model used may be considered too simplistic because the utility functions rely on travel times only, which in reality may not prove to be an elastic linear relation. Moreover, the work does not take into account the impacts of bus lanes during the onset of the rush which is an issue of current concern and the main reason preventing the implementation of bus lanes in many cities.

### 3.3 Gaps in the Literature

While bus lane conversions have been widely researched, they have yet to be examined at the network level under non-steady state congested conditions that are characteristic of a rush. Such conditions are important to consider because the primary cause for opposing bus lane conversions is the ensuing increase in congestion for car traffic.

The present work thus fills a gap in the literature by exploring the impacts to both cars and buses of city-wide lane conversions under non-steady state conditions.

Moreover, the work contributes to the body of knowledge by focusing on studying bus lane conversion schedules as opposed to their spatial allocation. Lanes are assumed to be implemented city-wide in response to the anticipated rise in travel demand.

The main challenge faced in studying city-wide lane conversions in non-steady state is: modeling traffic in dynamic conditions. A brief overview of the tools used is given next.



### 3.4 Tools for Modeling Traffic in Urban Networks

In order to model vehicle trips in an urban network, we will rely on aggregate relations between traffic variables such as the network flow  $q$  and density  $k$  (or equivalently accumulation  $n$ ). Stable relations between these variables can be described using a Macroscopic Fundamental Diagram (MFD) or, in some conditions, a Network Exit Function (NEF). In this section, we describe in detail the aforementioned models and explain why one can only use the MFD rather than the NEF for modeling traffic in non-steady state conditions.

A macroscopic theory of city traffic relations between flow  $q$ , density  $k$  and exit rates was introduced in [15, 17]. These works showed how the use of spatially aggregated measures of traffic performance can be used to model and control urban gridlock. The macroscopic theory was later refined in [19] to predict the MFD. The latter relates flow  $q$  and density  $k$  such that  $q = Q(k)$ . Conditions governing the existence of well-defined MFDs as well as simulation and experimental tests regarding their properties can be found in [6, 37, 48, 18, 25, 42, 57]. The MFD was shown to model multi-modal networks like ours: Gonzales et al [28] observed through simulation an MFD for multimodal systems of cars and buses in the city center of Nairobi, Kenya.

The relationship between exit rate and density was later named the NEF by Gonzales & Daganzo [27]. The NEF is a rescaled version of the MFD and relates the vehicle accumulation in the network,  $n$ , to the rate that vehicles complete their trips on it,  $f$ . The NEF assumes that the average length of trips should not change over time [17]. Hence, the rate of trip completions  $f$  can be obtained by dividing the total traveled distance by all vehicles in the network by the average trip length  $d$  across all vehicles. More formally, the trip completion rate is expressed as  $f = \frac{1}{d}Q(\frac{n}{l})$  where  $l$  represents the entire length of the network [17].

The NEF may be used to model dynamic scenarios only if conditions change slowly over time compared to the maximum duration of a passenger's trip [17]. This is because when conditions change slowly over time, the state of the network can be described by the vehicle accumulation and average speed. However, in rapidly changing dynamic conditions, the state of the system also depends on the proportion of the trip length that each vehicle traveled. If one were to apply the NEF in rapidly changing conditions such as at the onset of rush demand, trip completion rates will be overestimated. This is because at the onset of rush demand most vehicles in the network have just started their trip and only few have exited. As a result, the distribution of the ratio of traveled distances to trip lengths by all vehicles is not uniform. Analogously, the NEF will underestimate the trip completion rate when congestion starts to dissipate.

Dealing with dynamic traffic conditions during a rush not only prevented us from depending on static trip completion rates but also precluded us from formulating analytical models. The reason behind this is that in dynamic conditions that are characteristic of a rush, trip

completion rates vary along each passenger's trip length depending on traffic conditions at every point in time. The trip completion rate of passengers is thus impacted by travelers who arrive during the course of their trip, which renders the model intractable.

Since the MFD is invariant to changes in demand, routes and origin destination tables, Daganzo & Lehe [20] point out that it can be used to model networks as an aspatial queuing system with only arrival and exit curves. The MFD can thus be incorporated in microsimulations that track individual trips as a computationally-efficient (and still physically-realistic) means to obtain city-wide traffic states at short time intervals. The authors used this approach to develop city-wide congestion-pricing schemes in non-steady-state traffic. This dissertation follows the hybrid model in [20] which represents traffic on both the micro- and macro- levels. More details on the methodology are provided in Chapter 4.

# Chapter 4

## Methodology

Car and bus travel are modeled using simulation to address the challenge of estimating trip completion rates in non-steady-state traffic. The model was coded in-house to track the individual trips of all travelers. A trip was thus completed, and the traveler removed from the network, upon arrival to her destination.

Since the present work resorts to simulation rather than analytical models of the kind in [70], no attempt is made to obtain optimal policies. Insights for scheduling city-wide conversions that roughly balance benefits (to buses) against costs (to cars) are unveiled via parametric tests instead.

MFDs of the kind shown in Figure 4.1 were incorporated into the simulation model. Note how this diagram provides the time-varying average vehicle speed on the network,  $v(t)$ , as a function of the time-varying total accumulation across all its links,  $n(t)$ . Thus, for example, each MFD's broad, horizontal apex therefore unveils how  $v(t)$  diminishes as queues caused by traffic signals expand; see [19]. The model is coded in-house, and the process is detailed shortly.

The reader can think of the larger MFD in Fig. 4.1 as the one used to describe traffic when both buses and cars are mixed together in the absence of converted lanes. The mixed-traffic MFD used in the present work was taken from [26]. Its parameters, such as vehicle free-flow speed,  $v_{ff}$ , and network capacity,  $Q_{max}$ , were selected in the above reference to describe traffic in downtown San Francisco; and roughly account for influences of vehicular turning maneuvers, traffic signals and other factors.

To describe network-wide conditions when converted lanes were put into place, the mixed-traffic MFD was reduced in size so as to describe only cars traveling in the lanes that remained open to them. We assume that the capacity reduction caused by lane conversions is homogeneous across the network such that the larger MFD can be rescaled in size proportionally to the lane-kms taken from cars and given to buses. The reduction factor,  $f_r$ , is thus expressed

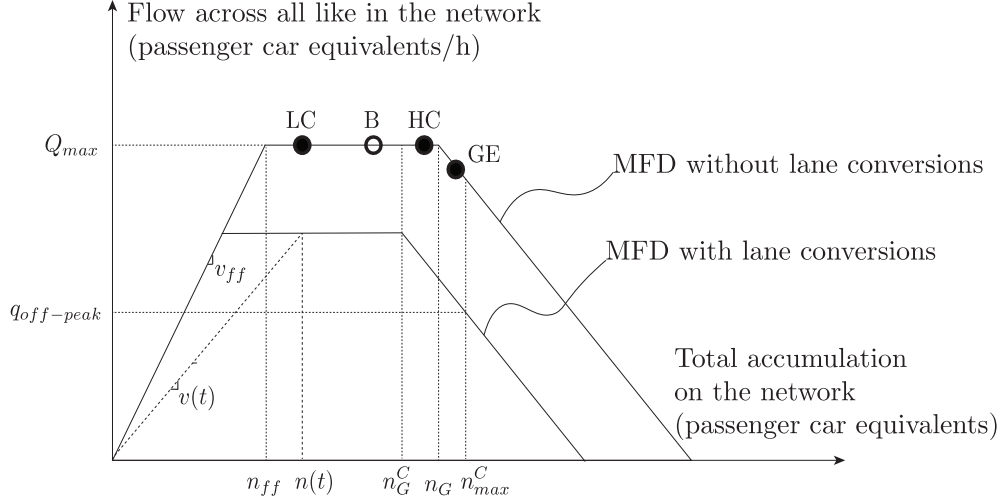


Figure 4.1: Macroscopic Fundamental Diagram

as follows where a lane-link refers to one lane on a link<sup>1</sup>:

$$f_r = 1 - \frac{\text{Number of Lane-Links Converted to Bus Only}}{\text{Total Number of Lane-Links in the Network}}$$

$$f_r = 1 - \frac{(\text{Number of Lane-Links on Each Bus Route} \times \text{Number of Bus Routes})}{\text{Total Number of Lane-Links in the Network}}$$

The idea is reflected in the smaller MFD in Fig. 4.1<sup>2</sup>.

The tests were performed for a dense network of streets typical of a walkable city [52]; see sec. 4.1. In real settings of this kind, travelers by car can skirt rather easily past the network's queues as they gradually emerge early in a rush. This sort of adaptive routing tends to spread vehicles more evenly over the network, which supports the present use of MFDs (e.g. see [18, 24]). The hypothetical city is described in sec. 4.2. Further details surrounding the present use of MFDs are offered in sec. 4.3.

<sup>1</sup>Since only one out of many lanes on a link is converted to bus use, the level of granularity associated with lane-links is necessary to accurately determine the proportion of road space used by buses.

<sup>2</sup>More will be said in due course about the accumulation thresholds labeled in the figure as  $n_{ff}$ ,  $n_G^C$ ,  $n_G$ , and  $n_{max}^C$

## 4.1 Experimental Setup

Cases were considered in which trip destinations lie within an idealized, square-shaped city with an area of  $30 \text{ km}^2$ ; see Fig. 4.2. City streets: were laid out in a perfect grid with block lengths of 100 m; served 2-way travel; and had 3 lanes for each direction. Street intersections were controlled by traffic signals.

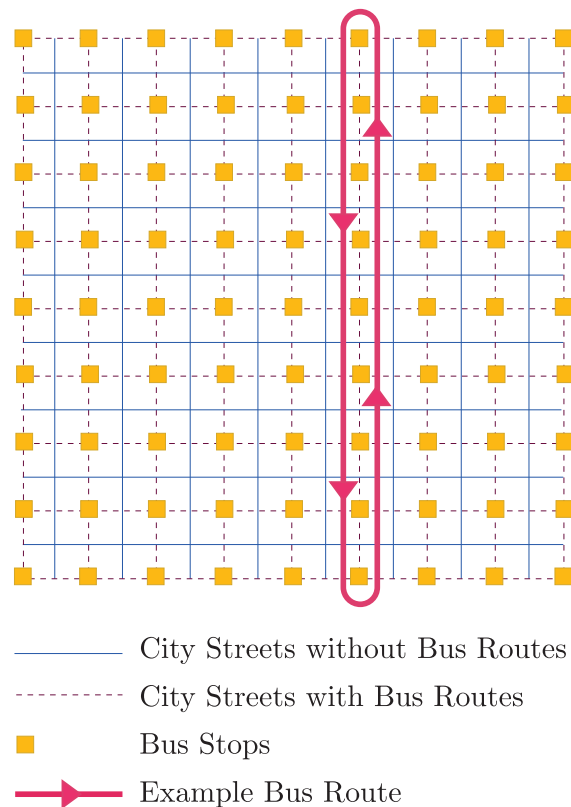


Figure 4.2: Grid Network

Each trip by car served only a single occupant: the driver. Of those trips, 50% originated within city limits in uniformly-distributed fashion. The other 50% originated outside the city. In effect, trip origins of the latter class were uniformly distributed across the city's perimeter. Regardless of origin, cars traveled to destinations that were uniformly distributed inside city boundaries. Trip lengths inside those boundaries uniformly ranged from 5 to 8.5 km to capture the pernicious effects of longer trips within a network [20].

Streets also served articulated buses that each: had a carrying-capacity of 200 patrons; circulated continuously within the city's boundaries; and dwelled at every stop along its route to load and unload passengers. Buses were assumed to dwell at stops without impeding car

flows. The assumption is conservative in the sense that it diminishes the value of converting lanes for the exclusive use of buses.

As per recommendations in [30], 28 bus routes were laid-out at spacings of 200m so as to provide uniform coverage throughout the city. Routes therefore ran N-S and E-W in turns, and along every other street in the city’s network. Each route had a total length of 11 km, which is twice the width of the square city. Bus stops along each route were spaced at 200m as well. Each route is served by a fixed number of buses that circulate continuously in the network and that provide an average headway of 10 mins throughout the simulation<sup>3</sup>.

Bus travelers had origins that were uniformly distributed across the system’s many bus stops. Their trip lengths were uniformly distributed like that of car drivers; i.e. from 5 to 8.5 km. Roughly 30% of travelers endure a single transfer during their trip. This is imposed in the simulation by giving each passenger a probability of transferring equal to 0.3. This number is consistent with observations of real transit smart card data in [35] from 100 million trips in the city of Seoul. No attempt was made to diminish the time spent in transferring by coordinating the bus schedules. This simplification will under-report the value of lane conversions, because these conversions improve the buses’ ability to adhere to the schedule.

Whether by car or bus, time-varying demand for city-bound trips always took the piecewise-linear form shown in Fig. 4.3. The cumulative curve in that figure presents total trips made by passengers via buses and cars combined, and across all origins, both inside and outside city boundaries. The percentage of the time-varying demand which traveled by bus, referred to as the bus ridership percentage, was one of the inputs examined in parametric fashion. In most of the studied scenarios, the bus ridership percentage was set to 10%, meaning that 10% of each of the rush and off-peak demand traveled by bus and the remaining 90% traveled by car.

The duration of the rush,  $\tau_{rush}$ , and its demand,  $q_{rush}$ , were also studied parametrically; see chapters 5 and 6. In all cases:  $\tau_{rush}$  and  $q_{rush}$  congested the city’s street network. Off-peak demand,  $q_{off-peak}$ , was always set to 55,000/h. This is less than the network’s car-carrying capacity, even in the presence of converted lanes. Demand dropped to zero at time  $t = 5h$ , so that all travelers completed their trips in the 8-h simulation performed for each case studied.

For each scenario studied (defined by a demand curve, a bus ridership percentage, and a rush duration), the fleet size was adjusted so that average bus headways never exceeded 10 mins (or equivalently, average patron waiting time at a stop never exceeded 5 mins). For the chosen scenario, onboard crowding turned out never to become an issue. The chosen fleet size under the do-nothing strategy for each scenario was then held constant for all the lane conversion strategies explored under that scenario. Appendix A provides a table detailing

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<sup>3</sup>Bus headways varied within each simulation due to slower cruising speed during the rush

the fleet size used for each scenario studied.

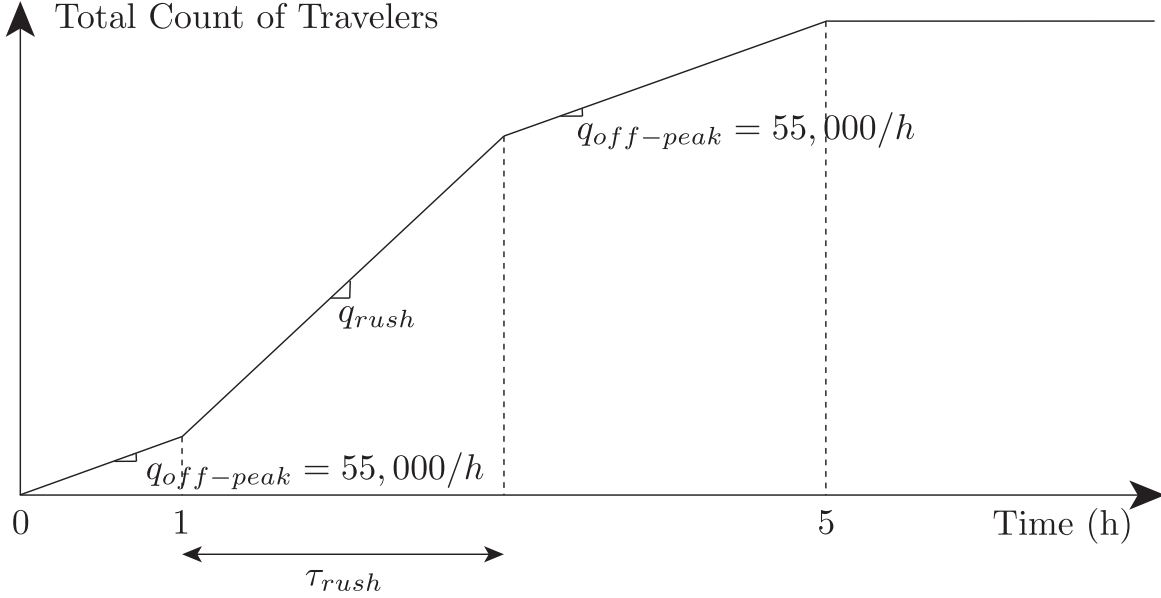


Figure 4.3: Demand Profile

## 4.2 Model Logic

Cars that originated within city boundaries entered the street network without delay. Those that instead originated outside the city waited their turns to enter at the boundary once congestion had filled city streets. As in [70], entry flows in this latter case were determined via the simple logic of the Cell Transmission Model; see [16] for details.

The present model tracked the number of cars to have entered the city network by  $t$ ,  $A^c(t)$ , as

$$A^c(t) = \sum_{i \in I_{car}} \mathbf{1}_{t \geq t_{ai}}$$

where:

$I_{car}$  is the set of car drivers

$t_{ai}$  is the time that driver  $i$  entered the city network; and

$\mathbf{1}_{t > t_{ai}}$  is an indicator function, that takes a value of 1 when the inequality holds, and 0 otherwise.

The model similarly monitored the number of cars to have completed their trips by  $t$ ,  $E^c(t)$ , as

$$E^c(t) = \sum_{i \in I_{car}} \mathbb{1}_{l_i^c(t)=0}$$

where:

Subscript  $l_i^c(t)$  is the physical distance remaining for driver  $i$ 's trip by  $t$ , such that the indicator function is 1 if the inequality holds, and 0 otherwise.

The  $l_i^c(t)$  was updated at time steps  $\Delta t = 30s$ , such that

$$l_i^c(t + \Delta t) = \max(0, l_i^c(t) - v(t) \times \Delta t) \text{ if } t \geq t_{ai}$$

where the reader will recall that  $v(t)$  is the average vehicle speed on the network at  $t$ .

In the absence of converted lanes, cars and (non-dwelling) buses all traveled at  $v(t)$ . Its value was estimated from the mixed-traffic MFD given the estimate of network accumulation,  $n(t)$ . The latter is the sum of cars accumulated at  $t$ ,  $n_c(t)$ , and the time-invariant number of continuously-circulating buses,  $n_b$ . The sum is expressed in passenger-car equivalents, with each bus requiring the street space used by 2 cars.<sup>4</sup> Thus,

$$n(t) = 2n_b + n_c(t) \tag{4.1}$$

$$n(t) = 2n_b + A^c(t) - E^c(t) \tag{4.2}$$

Whenever converted lanes were in place instead, the MFD was reduced by 1/6th, since one of three lanes was converted for bus use on every other street in the network. The reduced MFD was used to determine the  $v(t)$  for cars after setting  $n_b = 0$  in Equation 4.2. Buses traveled between stops in their own (converted and uncongested) lanes at free-flow speed  $v_{ff}$ .

Unlike cars, buses continuously circulated in the network which meant that they never entered or exited the network. Each bus' movements (cruising or dwelling) were thus modeled with reference to a bus stop. At the beginning of the simulation, buses were uniformly distributed in space across all routes and within each route to ensure a uniform bus service across the network. Each bus  $j$  was therefore associated with a bus stop at the start of the simulation denoted  $s_j(0)$ .

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<sup>4</sup>Use of a fixed passenger car equivalent (PCE) is a coarse way to describe mixed traffic, but seems an unavoidable consequence of using an MFD in the manner we have done. Use of a PCE is also consistent with conventional practice; e.g. see [4, 43, 58, 12]. And because buses constitute a small fraction of city traffic (never more than 0.3%), outcomes were insensitive to our choice of PCE.



Thereafter, the distance traveled by a bus  $j$  was updated at every time step  $\Delta t$  using:

$$d_j^b(t + \Delta t) = d_j^b(t) + v(t) \times \Delta t$$

where  $v(t)$  is equal to the speed from the mixed-traffic MFD when lanes are unconverted and equal to  $v_{ff}$  if lanes are converted.

A bus  $j$  was then considered to reach its next stop by time  $t + \Delta t$  whenever the distance traveled by the bus from its most recent stop exceeded the stop spacing. The most recent stop that bus  $j$  visited by time  $t$  is given by:

$$s_j(t) = \left\lfloor \frac{d_j^b(t)}{\text{stop spacing}} \right\rfloor \text{ mod number of bus stops per route}$$

If bus  $j$  was determined to reach the next stop at  $t + \Delta t$ , the bus was recorded as dwelling at the stop and its most recent stop was updated.

The duration of dwell times was modeled as follows. The dwell time for bus  $j$  which was located at stop  $s$  at time  $t$ , denoted  $\theta_{sj}(t)$  was calculated using:

$$\theta_{sj}(t) = \max(\text{time boarding bus } j \text{ at time } t \text{ and stop } s, \\ \text{time alighting bus } j \text{ at time } t \text{ and stop } s)$$

Since bus dwell times depend on the number of passengers boarding and alighting at each stop, we need to describe how bus passengers' trips were modeled before providing further details about dwell time computations.

The times that bus patrons spent in the network entailed (i) waiting at origin and transfer stops; and (ii) traveling onboard buses. The latter consisted of the travel times between stops and the dwell times at stops that were intermediate to a passenger's origin and destination. The simulation kept track of the number of passengers waiting at each stop  $s$ , denoted  $W_s(t)$ , the number of passengers riding each bus  $j$ , denoted  $R_j(t)$ , and the number of passengers exiting each bus  $j$  at stop  $s$ , denoted  $H_{sj}(t)$ .

Bus passengers were able to board the first bus they encountered at their origin or transfer bus stop provided that the bus had sufficient vacancies. The number of passengers who boarded bus  $j$  from stop  $s$  was given by:

$$B_{sj}(t) = \min(W_s(t), C - R_j(t) + H_{sj}(t))$$

where  $C$  is the bus capacity.

Upon completing their trip, passengers vacated their spots on buses at their destination or transfer stops.

With or without converted lanes in place, each bus dwelled at every stop along its route for a sufficient duration to serve all boarding and alighting passengers. Each passenger required 3 sec to board [45]. Alighting movements (e.g. through a rear bus door) were assumed to occur simultaneously with boardings and did not add to bus dwell times. The dwell time for bus  $j$  which was located at stop  $s$  at time  $t$ , denoted  $\theta_{sj}(t)$  was thus calculated using:

$$\theta_{sj}(t) = \max(B_{sj}(t) \times \text{boarding time per passenger}, H_{sj}(t) \times \text{alighting time per passenger})$$

# Chapter 5

## Numerical Analysis

This chapter explores schedule policies for a range of demand cases. Analyses start with a set of baseline conditions in which:  $\tau_{rush} = 2$  h;  $q_{rush} = 320,000$  trips/h; and nearly 200 continuously-circulating buses served a demand that was always 10% of the city’s time-varying total for all trips. Bus and car demands were thereafter varied in systematic fashion.

For each demand case studied, the People Hours Traveled (PHT) predicted under a select schedule policy were compared against those under a do-nothing alternative in which no lanes were converted. Differences in PHT are expressed as percentages, so that comparisons can be drawn across distinct schedule policies and demand cases. Differences are presented separately for buses and cars, so that both benefits and costs can be considered. Each outcome presented is the average from three simulations.<sup>1</sup>

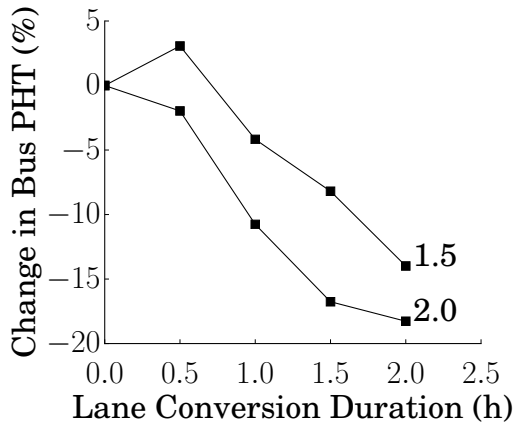
### 5.1 Activations Early in a Rush

The curves in 5.1 present outcomes for the baseline inputs. Note how each curve displays percent changes in PHT as a function of the duration for which the conversions were left in place. Importantly, these curves reflect impacts when conversions were activated early in the rush, as seems to be a common scheduling practice (e.g. see again [1]). As given by annotations, one curve in each figure corresponds to activations at time  $t = 1.5$  h. That time coincides with the emergence of network queueing. Each figure’s second curve corresponds to activations that occurred 30 mins later at  $t = 2.0$  h.

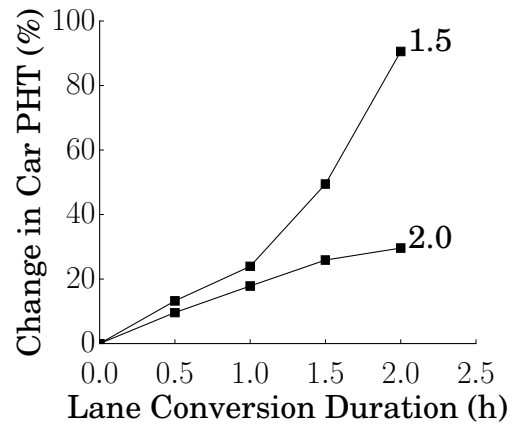
The curves in Fig. 5.1a were constructed for bus travelers (only). Note from the figure’s top curve that when activated at the onset of queueing and left in place for just 30 mins,

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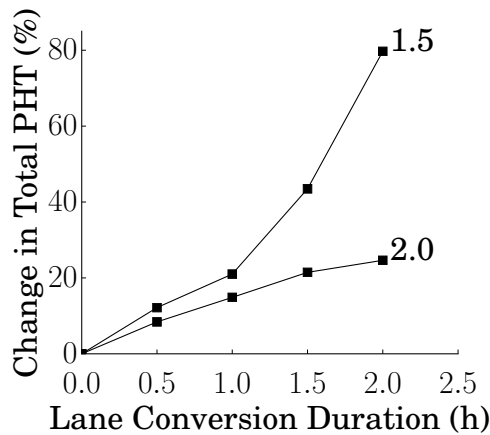
<sup>1</sup>Simulated outcomes varied slightly due to the variation in trip lengths and the randomness in trip generation. Our tests found that averaging three outcomes consistently produced errors that were well below 0.1% of the averages generated from 30 simulations.



(a) Change in Bus PHT



(b) Change in Car PHT



(c) Change in Total PHT

Figure 5.1: Change in PHT for Activations Early in a Rush for Buses, Cars and in Total

conversions caused bus-traveler PHT to grow by about 3% relative to the do-nothing strategy. This growth was due to the damage done after the conversions were deactivated: car queues were exacerbated by the network’s 30-min loss in car-carrying capacity; and buses were delayed when the elongated car queues spilled-onto what had formerly been bus lanes.<sup>2</sup>

The problem was mitigated by extending the duration for which conversions were left in place: note the top curve’s eventual downward slopes. These benefits occurred in part because the longer durations allowed more buses to bypass rapidly-expanding car queues. This

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<sup>2</sup>Activation times prior to the onset of network congestion not only further eroded bus-traveler PHTs following the deactivations, but also hastened the emergence of car queues. Those experiments are therefore excluded from presentation and further discussion.

compensated for the delays that buses encountered when converted lanes were deactivated.

The lower curve in Fig. 5.1a reveals that buses benefited by postponing activations to  $t = 2.0$  h. With that later activation, buses still bypassed car queues that had grown long with the passage of time. Moreover, the later-occurring activations meant that the attendant acceleration in car-queue growth was triggered nearer the rush's end. The lower off-peak demand,  $q_{off-peak}$ , therefore brought relief in more timely fashion, and deactivating the lanes was less damaging to buses. Leaving the conversions in place for longer durations helped (i.e. the lower curve in Fig. 5.1a always slopes downward) for the reason already stated.

The damage to car traffic was often severe, however, as evident in Fig. 5.1b. Note how things got especially bad for cars under the earlier activation time; and how they became worse by leaving the conversions for longer durations.

Since cars were the city's dominant travel mode, the high PHTs revealed in Fig. 5.1b translate to combined bus/car PHTs that are nearly as high. This is evident in Fig. 5.1c.

## 5.2 Activations Postponed

This section reveals how postponing activations even further in time can better balance benefits and costs. The boldly-drawn curves in Fig. 5.2 present the savings in bus-traveler PHT for four distinct activation times. Two of those times ( $t = 2.8$  h and  $2.9$  h) slightly preceded the subsidence of  $q_{rush}$  at  $t = 3$  h. The two other times ( $t = 3.0$  h and  $3.1$  h) occurred at and just after that subsidence. Note that when conversions were left in place for only 30 mins, PHT-savings under any of the four activation times were greater than under the earlier times shown previously in Fig. 5.1a.

Savings were greatest when activations came shortly before  $q_{rush}$  subsidence; i.e. note how the bold curves corresponding to  $t = 2.8h$  and  $2.9h$  lie below their other two counterparts in Fig. 5.2. Activations at those times enabled buses to bypass car queues during both: the final minutes of  $q_{rush}$  when those queues had by then grown long; and the off-peak period when residual queues gradually diminished. Further note how the two lower curves slope slightly downward when conversion duration was extended from 30 mins to 1 hr. This reveals that when the earlier-occurring conversions were deactivated after only 30 mins, buses thereafter encountered residual car queues. This was not the case when conversions were left for longer periods; i.e. note how the lower-two bold curves eventually trend horizontal.

The four thinly-drawn curves in Fig. 5.2 display PHT changes to car drivers. Impacts to car traffic were negative under all scheduling policies shown. Hence, the thin curves look like inverted versions of their boldly-drawn counterparts. Yet the damage to cars was typically

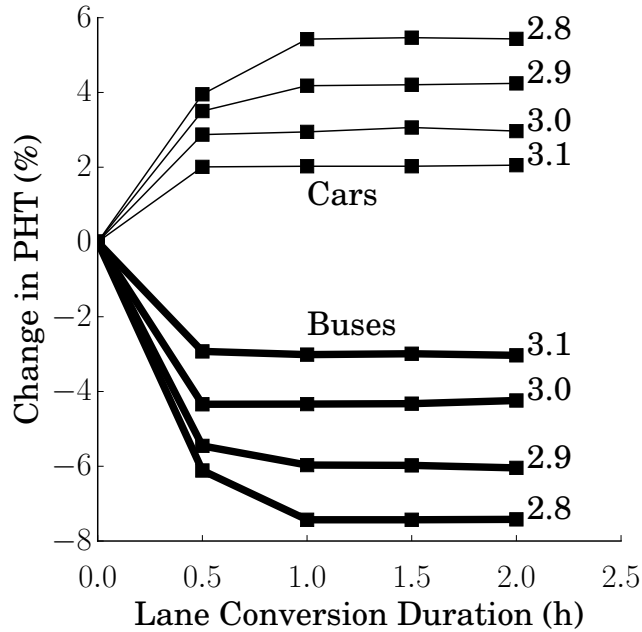


Figure 5.2: Change in PHT for Buses and Cars for Postponed Activations

far less severe than what occurred when lanes were converted early in the rush; refer again to Fig. 5.1b.

### 5.3 Bus Ridership Share and Induced Demand

Since buses garnered a numeric minority of trips made in the city, scheduling policies were robust to variations in that minority share. Postponing activations thus continued to balance benefits and costs when bus ridership exceeded baseline levels.

We illustrate by repeating the analysis of the previous two sections. This time, however, the bus system's modal share during the rush was bumped from the baseline 10% to 30%. In a first round of analysis, the higher share was assumed to be a feature of the city's travel demand from day one, meaning: that buses enjoyed high ridership even before a decision was made to convert some of the city's travel lanes. In a second round, the share was assumed to rise from 10% to 30% over time, as might occur if lane conversions were to gradually induce new bus trips.

To facilitate analysis of the latter case, percent changes in PHT were measured relative to a do-nothing strategy in which bus demand and fleet size remained at baseline levels.

Outcomes in this case were averaged over all travelers served in the 8-h simulation periods. In both rounds of analysis: higher ridership was accommodated by a bus fleet that was triple the baseline size<sup>3</sup>; and car demand was unchanged.

Outcomes were qualitatively like those of the baseline analyses. Predictions are summarized in Fig. 5.3. Shaded bars display the ranges over which PHT changed when conversions were put in place. The two darkly-shaded bars in each figure pertain to bus travel. One dark bar presents the range when higher bus share existed from day 1. The other when higher shares were induced over time. Lightly-shaded bars pertain to car drivers.

Figure 5.3a shows outcomes when conversions were activated at the onset of queueing at  $t = 1.5$  h. The PHT grew (by 4% and 14%) when conversions were left in place for just 30 mins. Improvements (of 23% and 16%) came when conversions were left for 2 hrs. Yet the costs to cars were always high; e.g. car costs grew by 89% when conversions were left in place for 2 hrs.

More balance again came by postponing activations. When conversions were activated just before  $q_{rush}$  subsidence: PHT reductions for bus travelers approached or exceeded 10%; and gains imposed on cars hovered at around 5%; see Fig. 5.3b. When activated just after that subsidence, bus savings were not as high, but neither were the costs to cars; see Fig. 5.3c.

## 5.4 Varying Congested States

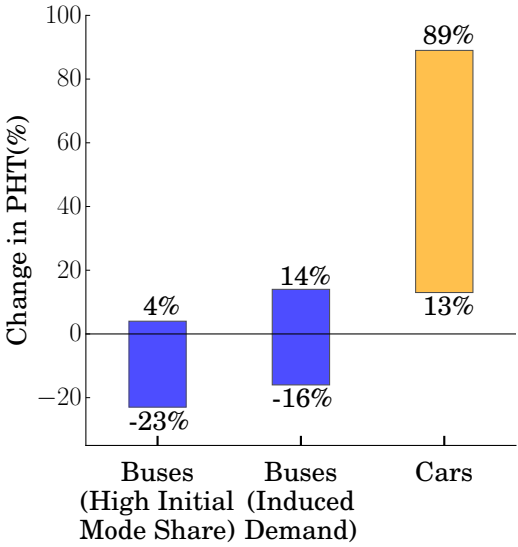
This section describes a battery of experiments in which  $q_{rush}$  was explored parametrically. Three rush-period rates were separately examined: 224,000, 352,000 and 384,000 vph. All other inputs remained at their baseline values.

Under do-nothing alternatives, each rate for  $q_{rush}$  ultimately produced one of the three congested states described by the darkened circles in Fig. 4.1. These points are labeled: “LC” for Lightly Congested; “HC” for Heavily Congested; and “GE” for Gridlock’s Early stage. Together with the Baseline case, labeled “B” in the figure, the states span the range of conditions for which city-wide conversions may be desirable. Other states would be undesirable for reasons explained below.

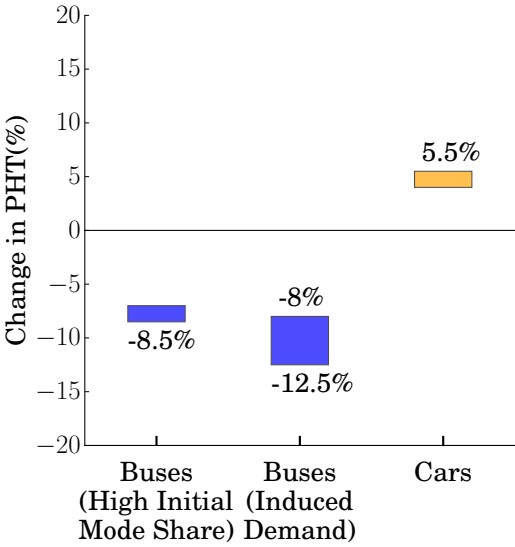
States lying well to the left of the four data points in Fig. 4.1 would not constitute suitable conditions, since buses stand little to gain from wholesale conversions in an uncongested city. Further consideration of Fig. 4.1 reveals why accumulations to the right of the data

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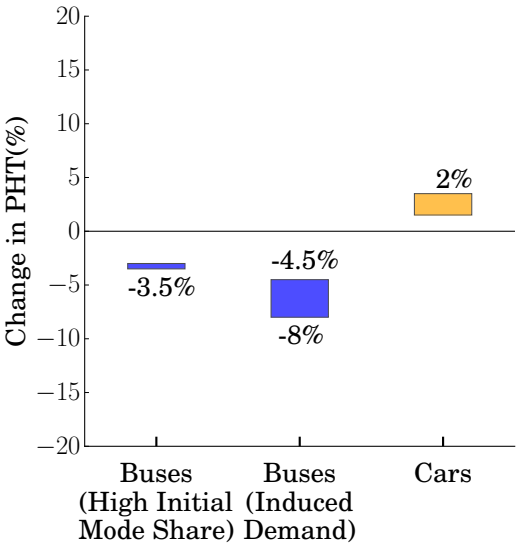
<sup>3</sup>The larger fleet was put into service over the entire simulation period. The persistently higher service frequency diminished bus-traveler PHT during the off-peak, but had negligible impacts on the 8-h average PHTs.



(a) Activations at  $t = 1.5$  h



(b) Activations at  $t = 2.8$  h



(c) Activations at  $t = 3.1$  h

Figure 5.3: Change in PHT for Buses and Cars with High Initial Mode Share and Induced Demand for buses

points would render city-wide conversions highly inadvisable: if accumulation exceeded  $n_{max}^C$ , conversions would cause congested cars to circulate through the city at a constrained flow



that is lower than  $q_{off-peak}$ . Car traffic would hence grind toward a halt; and the subsidence of  $q_{rush}$  would not reverse this gridlock process.

In light of the above, we turn our attention now to the four data points, starting with the Lightly Congested “LC” state. Outcomes for this state are summarized in Figs. 5.4. The first of these figures confirms the pitfalls of activating conversions at the onset of network queueing. (Queues continued to emerge at around  $t = 1.5$  h.) The figure’s darkly-shaded bar shows that early conversions can degrade bus travel: bus-patron PHT grew by 3% when conversions were left in place for just 30 mins. Leaving them for longer durations improved this state of affairs: bus-traveler PHT dropped by 13% when conversions were left for 2 hrs. Yet, the lightly-shaded bar in the figure shows that early activations caused car-driver PHT to grow dramatically; e.g. by 65% for the 2-h conversion duration.

Greater balance came for the LC state by postponing activation until minutes before  $q_{rush}$  subsidence; see Fig. 5.4b. For all conversion durations, benefits to buses and costs to cars were modest; i.e. below 5%. Interestingly, further postponement of activations until after  $q_{rush}$  subsidence neither benefitted buses nor damaged cars: Fig. 5.4c shows that this postponement had no impacts whatsoever.

When rush-period traffic became more congested, the pitfalls of early activations grew substantially. For the Highly Congested “HC” state, leaving early activations in place for more than an hour triggered gridlock; see Fig. 5.5a. Postponing activations until just before  $q_{rush}$  subsidence could still produce sizable costs to car drivers; see the lightly-shaded bar in Fig. 5.5b. Further postponement until after that subsidence seemed to better balance benefits and costs; see Fig. 5.5c.

When congestion reached Gridlock’s Early “GE” stage, activating conversions any time prior to  $q_{rush}$  subsidence could trigger gridlock; see Figs. 5.6a and 5.6b. Conversions activated after that subsidence, however, brought measurable benefits to buses while limiting the damage to cars; see Fig. 5.6c.<sup>4</sup>

The above findings show that postponing activations becomes increasingly important as rush-period traffic becomes more congested. Conversion duration has an impact as well, and this is explored further in the following section.

## 5.5 Conversion Duration

First consider cases in which city traffic becomes very congested during the rush. Section 5.4 made clear that activations in these circumstances should occur after the subsidence of

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<sup>4</sup>The higher number of bus passengers in the GE case was accommodated by increasing the number of buses per route by 1.

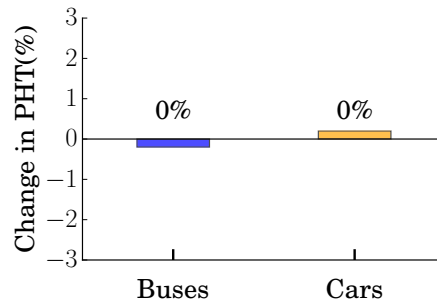
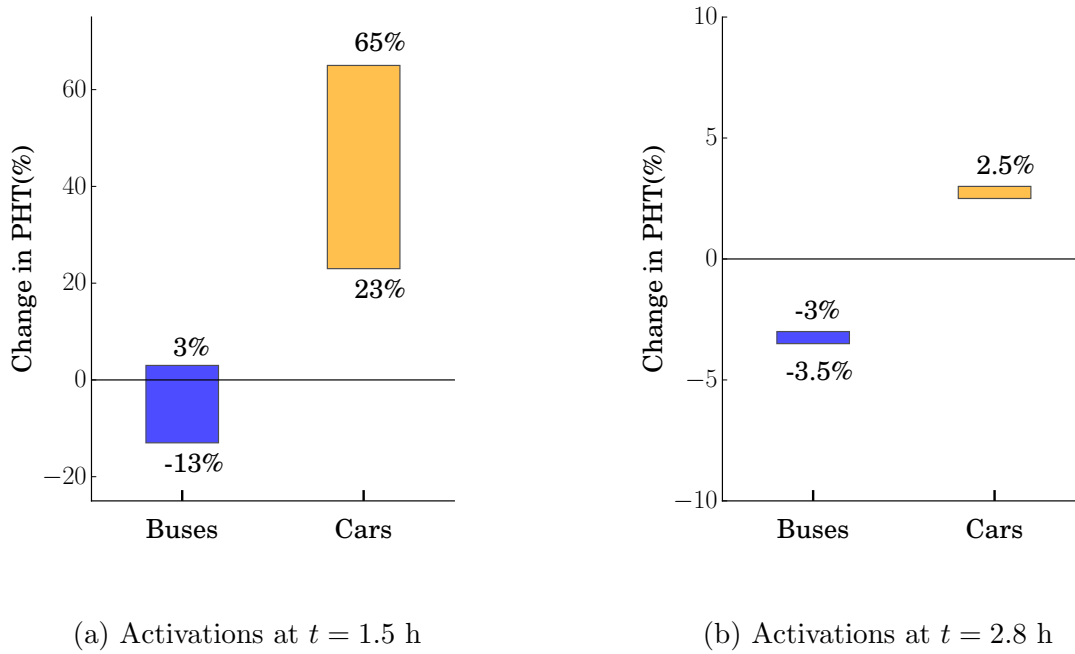
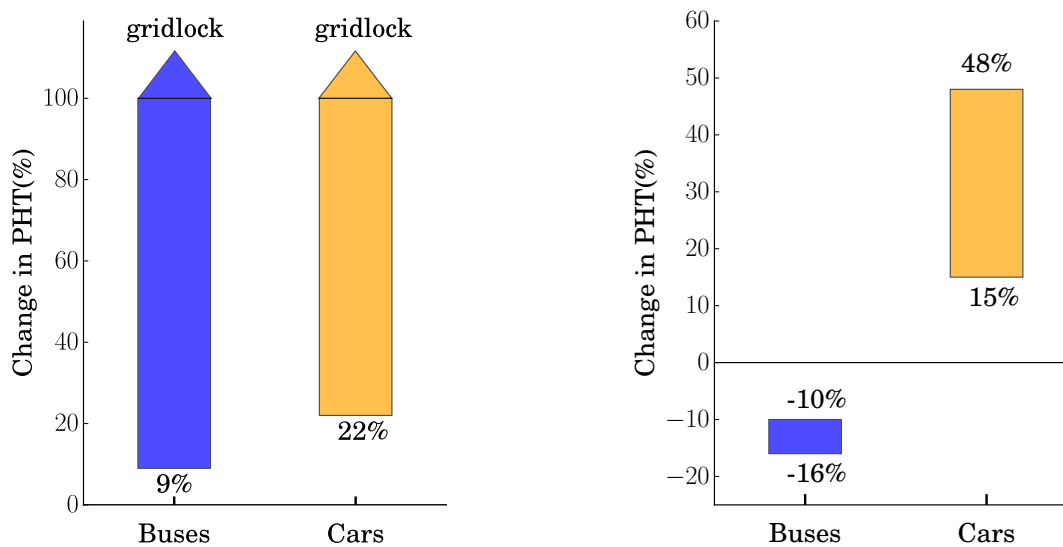


Figure 5.4: Change in PHT for Buses and Cars for LC

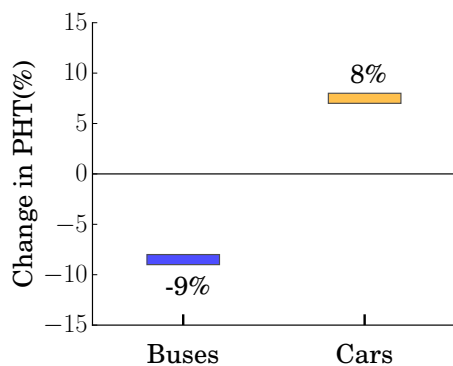
$q_{rush}$ . This being the case, the curves in Fig. 5.7 present outcomes for the HC and GE cases when activations occurred close on the heels of  $q_{rush}$  subsidence. Note from the bold curves that most of the benefits accrued to buses after having left conversions in place for only 30 mins. Modest additional benefits came by leaving conversions for 1 hr. As always, the benefits came at the expense of car traffic; see the thin curves in Fig. 5.7.

More interesting cases can occur when a city’s rush-period traffic is only lightly congested. Section 5.4 showed that benefits came in these instances only by activating conversions prior to  $q_{rush}$  subsidence. A scheduling policy along these lines would require a city to anticipate



(a) Activations at  $t = 1.5$  h

(b) Activations at  $t = 2.8$  h

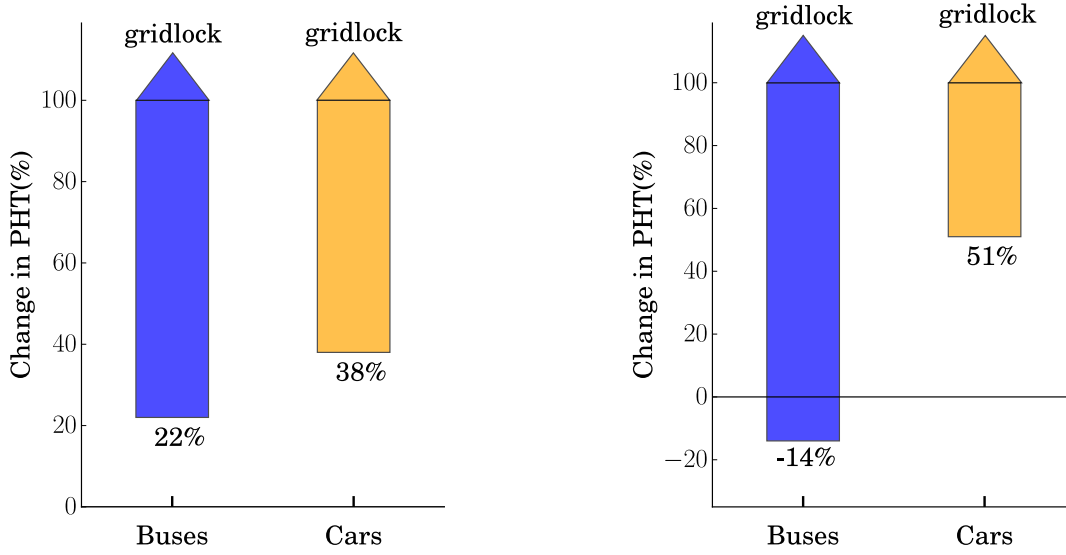


(c) Activations at  $t = 3.1$  h

Figure 5.5: Change in PHT for Buses and Cars for HC

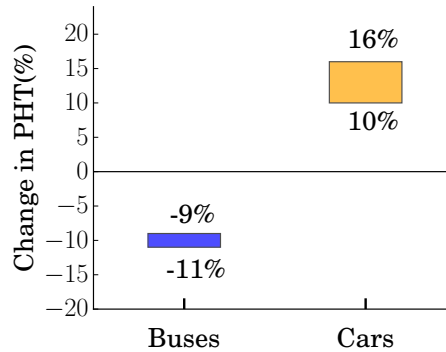
the subsidence time. A concern may arise on days when  $q_{rush}$  persists for longer periods than expected. After all, an elongated rush could ultimately cause severe congestion; and converted lanes could exacerbate the problem.

Figure 5.8 is presented with the above in mind. Its curves were constructed for the  $q_{rush}$  that would have produced the “LC” state previously shown in Fig. 4.1, except that this time around the rush period,  $\tau_{rush}$ , was elongated from its baseline 2-h duration. Note that



(a) Activations at  $t = 1.5$  h

(b) Activations at  $t = 2.8$  h



(c) Activations at  $t = 3.1$  h

Figure 5.6: Change in PHT for Buses and Cars for GE

separate curves are presented for  $\tau_{rush}$  elongations of 10, 25 and 50%.

Further note that for the smaller elongations of 10 or 25%, growths in car-traveler PHT hovers around 10% when conversions were left in place for lengthier durations. The curves also show that the damages can be reduced by deactivating conversions after 30 mins or so. A city might therefore do well to deactivate conversions after short periods whenever: (i) real-time measurements indicate that  $\tau_{rush}$  has extended beyond its anticipated duration;

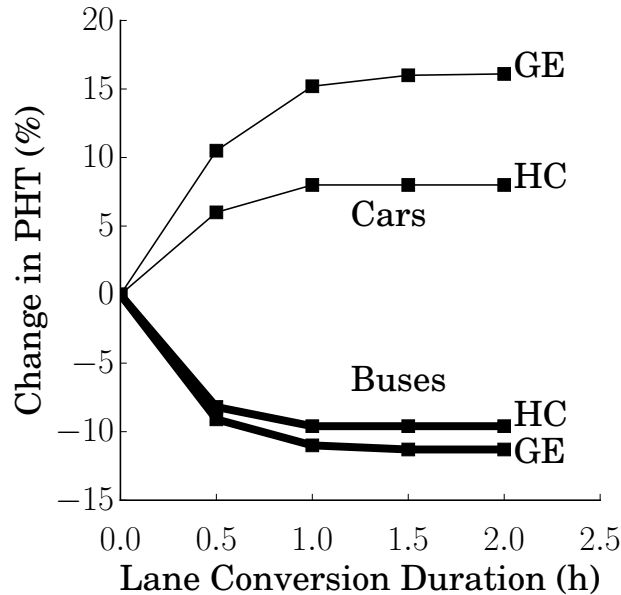


Figure 5.7: Change in PHT for Buses and Cars for HC and GE Cases with Activations at  $t = 3.1$  h

and (ii) there is reason to believe that that the elongation may ultimately be a lengthy one. Discussion on how real-time measurements can be used to infer an elongation of  $\tau_{rush}$  will be offered in sect. 6.2.

## 5.6 Modal Shifts

The state of affairs in the previous section was found to change if lane conversions motivated commuters to shift in large numbers from cars to buses. To illustrate, modal shifts were assumed to occur only among car drivers whose origins resided inside the city, since only those origins were served by bus routes. It was further assumed that shifts occurred only when conversions were in place, since a traveler would have little motivation to unilaterally migrate to buses at other times of day. All other inputs were kept at their baseline values; and changes in PHT were measured relative to the do-nothing strategy for baseline conditions.

The curves in Figs. 5.9a illustrate outcomes when activations occurred at the onset of network queuing. The two bold curves present PHT changes for bus travelers. One curve displays changes when 20% of eligible car drivers shifted to buses. The other displays changes

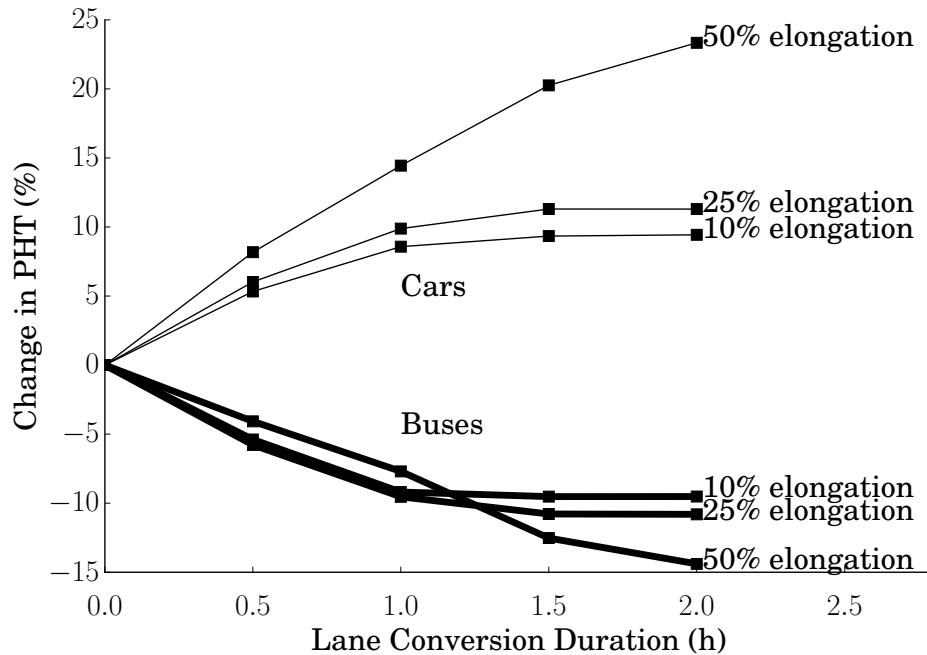


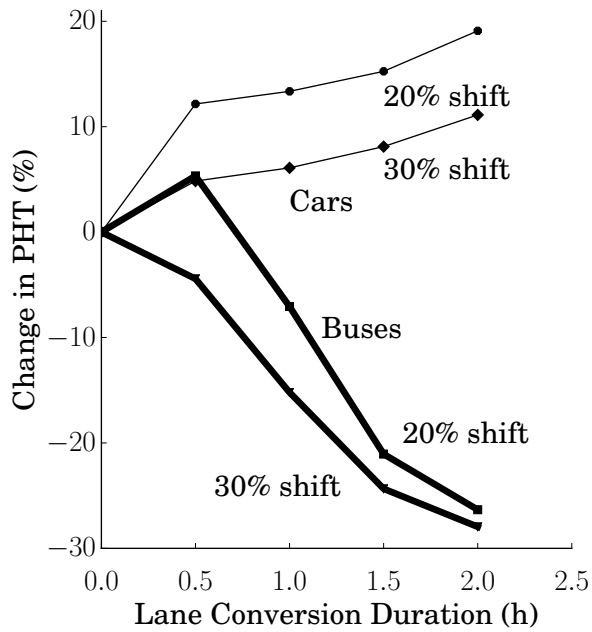
Figure 5.8: Change in PHT for Buses and Cars for LC Cases with Activations at  $t = 2.8$  h and Rush Elongations

under a 30% shift. The two thin curves similarly display PHT changes among those commuters who continued to drive by car.

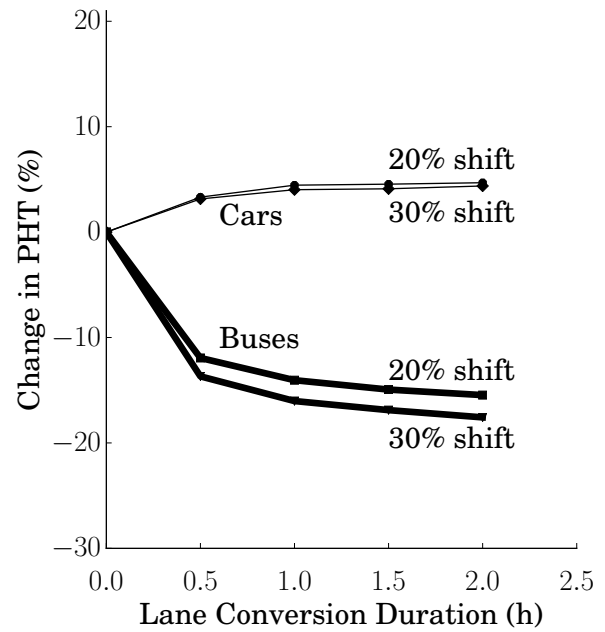
Note that with these large shifts, early activations greatly diminished bus-traveler PHT, provided that the conversions were left in place for about an hour or more. Yet, the damage to car traffic from this sort of policy could still be sizable.

Figure 5.9b shows what occurred when activations were postponed until minutes before  $q_{rush}$  subsided. Visual comparison of Figs. 5.9a and 5.9b shows that bus travelers tended to benefit less from the postponement when conversion durations were long. Yet, car drivers suffered less as well.

The findings suggest that if conversions were to motivate modal shifts, a city might initially postpone activations to occur late in a rush, and thereafter gradually slide them to earlier times of day. An activation time might ultimately be settled upon once the damage to cars reaches what the city judges to be a maximum permissible level. Further implementation issues will be discussed next.



(a) Activations at  $t = 1.5$  h



(b) Activations at  $t = 2.8$  h

Figure 5.9: Change in PHT for Buses and Cars with 20% and 30% Modal Shifts and Activations at  $t = 1.5$  h and  $t = 2.8$  h

# Chapter 6

## Deployment

This chapter addresses matters pertaining to implementations in real settings. Guidelines for scheduling city-wide activations and deactivations are offered first. Means of monitoring city traffic so as to adapt these guidelines to daily variations are discussed thereafter.

### 6.1 Guidelines

The following six rules of thumb stem from present findings. The rules therefore implicitly assume conditions akin to those presently studied. Thus, for example, a city's vehicle-carrying capacity,  $Q_{max}$ , is assumed to be such that  $q_{off-peak} < Q_{max} < q_{rush}$ ; and a city is assumed to be free from gridlock in the absence of converted lanes. Rules 1 - 4 pertain to the scheduling of activations; Rules 5 and 6 to deactivations.

Each rule considers one or more of the vehicle-accumulation thresholds previously shown in Fig. 4.1. The reader can refer back to that figure to aid in the discussion; and a city would presumably obtain these thresholds from its own MFDs. Most of the rules consider the city-wide vehicle accumulation that occurs moments before conversions are to be activated, henceforth denoted  $n(t_a)$ . This accumulation would be estimated from city-wide traffic measurements; see sec. 6.2.

*Rule 1 for an HC or GE state:* On days when  $n_G^C < n(t_a) < n_{max}^C$ , activate conversions after the observed subsidence of  $q_{rush}$ . The time might be postponed until  $n(t_a) < n_G^C$  to drive down the possibility that unforeseen events trigger gridlock.

*Rule 2 for moderate congestion like in the baseline:* On days when  $n_{ff} \ll n(t_a) < n_G^C$ , conversions can be activated either before the anticipated subsidence of  $q_{rush}$  or after that subsidence is inferred from measurements. The decision might be based on how the city



weighs the trade-offs between benefitting buses and penalizing cars.

*Rule 3 for LC conditions:* Whenever  $n_{ff} < n(t_a) \ll n_G^C$ , activate conversions prior to the anticipated subsidence of  $q_{rush}$ . In these LC cases, activations after  $q_{rush}$  subsidence would have little impact.

*Rule 4 for non-congested states:* Conversions need not be activated whenever  $n(t_a) < n_{ff}$ .

*Rule 5:* Conversions should always be deactivated before network accumulation reaches  $n_{max}^C$ . Failure in this regard can trigger a gridlock process that would not reverse itself when  $q_{rush}$  subsides. Deactivations might conservatively occur well before accumulation reaches  $n_{max}^C$  to drive-down the possibility that unforeseen events trigger gridlock.

*Rule 6:* Should a day's accumulation never approach  $n_{max}^C$ , conversion duration can be chosen based upon how a city weighs the trade-offs between benefits to buses and costs to cars; see again sec. 5.5 and recall that leaving conversions in place would have little impact once residual car queues fully dissipate.

Applying these rules on a daily basis would require that a city monitor and interpret its time-varying traffic conditions. Discussion on this matter is offered below.

## 6.2 Real-Time Monitoring

This section (i) offers brief discussion on how vehicle accumulation might be monitored across a city in real time; and (ii) illustrates how these real-time estimates can be used to schedule lane conversions. As regards item (i), we suppose that accumulations would be estimated at intervals of a few minutes or so. At each time step, estimates might be made for each link in a network via inductive loop detectors or other conventional technology, and summed over all links. Improvements can come by combining these estimates: with data from GPS-equipped fleets, such as buses or taxis, in the manner described in [26]; or via smartphones, as was done in [33]. In the near future, estimates might be further improved with the emergence of connected-vehicle technologies [29].

Once obtained on a city-wide scale, it would make sense to process the estimated accumulations in time-series fashion, as exemplified in Fig. 6.1. Its curves present the time-varying accumulations,  $n(t)$ , simulated for the hypothetical city in Fig. 4.2 with our baseline inputs. Accumulations thresholds taken from the mixed-traffic (i.e. larger) MFD in Fig. 4.1 are shown in Fig. 6.1 as well.

As regards item (ii) above, the reader will note how the  $n(t)$  in Fig. 6.1 eventually exceeds  $n_{ff}$  by a comfortable margin, indicating that buses can benefit from aptly-scheduled lane conversions. Note too how  $n(t)$  peaks well below  $n_G^c$ , indicating that activations and deactivations can follow Rules 2 and 6 of the previous section, respectively. Hence, we elect to activate conversions at  $t = 3.1$  h (6 mins after the subsidence of  $q_{rush}$ ), and to deactivate them at  $t = 4.1$  h.

The dashed portion of the curve in Fig. 6.1 tracks how  $n(t)$  diminished as a result of that schedule. The curve portion shown in dotted fashion describes what occurred under the do-nothing strategy in which lanes were not converted. The horizontal displacements between the dashed and dotted curve portions reveal that residual car queues persisted for longer durations in the presence of converted lanes. Given the modestly-congested conditions produced by the baseline inputs, the extra car queueing was modest, as is clear in the figure.

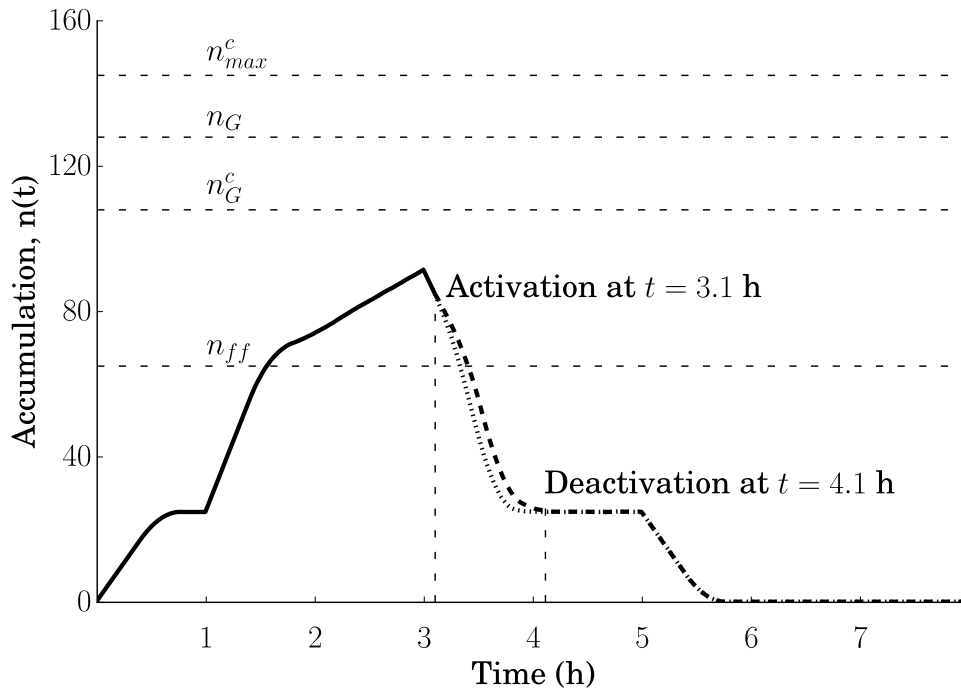


Figure 6.1: Accumulation Time-Series With and Without Conversions

# Chapter 7

## Conclusion

This section highlights the main findings of the dissertation and provides a brief discussion on potential future research avenues.

### 7.1 Dissertation Findings

The practice of periodically converting regular lanes for exclusive bus use is likely to continue for years to come. As cities of the future grow more congested, some may expand this practice by converting lanes on larger, city-wide scales. In anticipation of this, the dissertation has explored how cities might schedule wholesale conversions in ways that balance benefits to buses against costs to cars.

Findings came via simulation. This made it possible to model trip completions in physically-realistic ways, even when traffic conditions changed rapidly with time. On the downside, simulation placed limits on the range of inputs that could be explored in the work. Most notably, all experiments were conducted for the street geometry and layout in a single, idealized city. Still, some key features of our idealized city can be found in real cities. Those features included: a prolonged rush that congested all city streets, even in the absence of converted lanes; and a subsequent off-peak period when residual car queues gradually dissipated, even while converted lanes remained in place. Moreover, the parametric tests were broad enough to unveil the traffic demand patterns that ought to be considered when scheduling city-wide conversions.

The findings revealed that greater balance between benefits and costs usually came by activating conversions toward the end of the rush. Whether the activations might better occur shortly before or after the subsidence of rush demand depended upon how densely congested the city became during the rush. In most cases, the benefit-to-cost balance was safeguarded by leaving conversions in place for short durations of 30 mins or so. These find-

ings held whether or not buses garnered a high share of trips made in the city; and whether or not converted lanes gradually induced new trips by bus.

Things changed a bit only when bus riders migrated from cars in large numbers. With these migrations, bus riders sometimes reaped higher benefits when conversions were activated early in the rush. A city might choose when exactly these activations are to occur, and the duration that conversions are to be left in place, based upon what it judges to be an acceptable penalty to impose on cars.

The guidelines offered herein were formulated with the above findings in mind. They can, at the very least, serve as starting points for scheduling whole-sale conversions in a real city. Ways of collecting and interpreting measurements were also discussed, so that schedules might be adjusted in response to the city's traffic conditions that arise once conversions are deployed.

## 7.2 Future Work

In this section, we discuss future research avenues. We first explain how the present work can be extended to other applications such as BLIPs which were introduced in Chapter 3. We also study the impacts of BLIPs under baseline conditions. Furthermore, we present alternative measures besides PHT that may be of interest for evaluating the impacts of the bus lane conversions.

### Bus Lanes with Intermittent Priority (BLIPs)

The lane conversion strategies discussed in the dissertation all cause an increase in the total PHT relative to the do-nothing alternative. The total PHT can be reduced if BLIPs are used. As discussed in Chapter 3, the strategy consists of reserving lanes for buses only on the block where the bus is currently traveling. Therefore, no significant damage is done to cars in terms of capacity loss.

Our methodology can be extended to BLIPs under the following assumption of homogeneity: vehicles instantaneously redistribute themselves in the network in a homogeneous fashion when links are converted to bus use.

We simulate an all-day BLIP strategy under the aforementioned homogeneity assumption. Under baseline conditions, we find that BLIPs can achieve savings in total PHT of about 1% relative to the do-nothing alternative. This is illustrated by the leftmost red circle in Figure 7.1. For comparison, a lane conversion activation at  $t = 2.8\text{h}$  for a 30min duration with the previously studied implementation of bus lane conversions produces an increase in

total PHT of about 3%. This is shown by the leftmost blue square in Figure 7.1.

BLIPs also help in significantly increasing bus PHT savings. Figure 7.1 shows that BLIPs achieves bus PHT savings of 24% relative to the do-nothing alternative. While the previous implementations provided savings of 6% for a 30min activation at  $t = 2.8$ h. The car PHT increase is reduced from 4% with previously studied implementations of bus lanes to 1% with BLIPs.

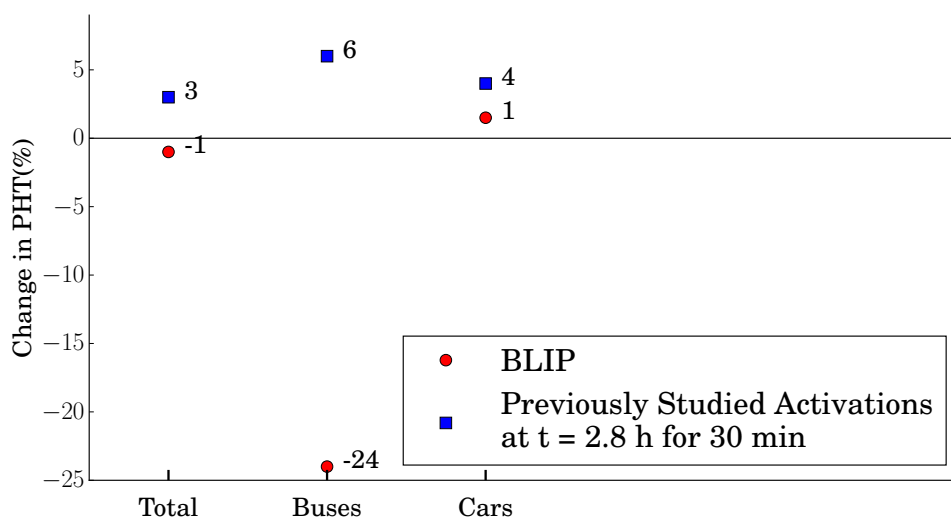


Figure 7.1: Change in PHT with BLIP for Buses and in Total

While our findings show that BLIPs can be more beneficial in terms of reductions both in total and bus passenger PHT, the homogeneity assumption is unrealistic. More accurate insights can come from relaxing this assumption for the purpose of modeling BLIPs. This can be done via microsimulation where vehicles are individually simulated with spatial considerations.

In reality, adopting a BLIP strategy can be challenging due to implementation and enforcement concerns. Variable Message Signs (VMS) have been previously proposed as a way to announce the activation of the bus only restriction and force traffic out of the bus lane. However, installing VMS on every few blocks can be costly.

## Bus Ridership

When lanes are converted to bus use, bus ridership is expected to increase because buses can travel in free flow during periods of conversion. The increase in ridership may come from car riders who are incentivized to switch to bus use when the network is congested, or from people who did not formerly travel due to high travel times. In this dissertation, the increase in bus ridership is only studied parametrically. Quantifying the bus ridership increase that can result from different conversion schedules would be beneficial for assessing the real impacts of these schedules.

Accurate measurements of bus ridership increase can ideally be found by collecting real field data. However, it may not be possible to test all conversion schedules in a city to collect bus ridership increase data especially that each conversion schedule would need to be tested for a sufficiently long duration. Alternatively, surveys from a representative sample can be used to construct behavioral models that can help predict bus ridership increase for each conversion schedule.

## Environmental Savings

New environmental policies that have recently emerged are urging for drastic reductions in greenhouse gas (GHG) emissions over the next few years. For example, the Global Warming Solutions Act (i.e. Assembly Bill 32) which was established in 2006 has called for reducing GHG emissions to 1990 levels by 2020. Therefore, it is becoming increasingly important to evaluate the impacts of bus lane conversion policies not only on travel time but also on the environment.

Today, light-duty vehicles (such as passenger cars and light trucks) account for about 50% of the overall transportation energy use and emissions [40]. Therefore, if bus lane conversions can motivate car passengers to switch to bus use, the number of cars on the road will significantly decrease and hence GHG emissions can be reduced.

The current model can be extended to evaluate the environmental impacts of different bus lane conversion once changes in bus and car ridership are quantified. Next, the traveled distance in each mode can be determined and consequently GHG emissions for each mode can be obtained. The GHG emission levels can then be compared to the do-nothing alternative where no bus lane conversions are in place.

# Appendix A

## Fleet Size

Scenario	Number of Buses Per Route	Total Number of Buses in the Network	Bus Ridership
Section 5.1 Activations Early in a Rush, 5.2 Activations Postponed, and Section 5.4 Varying Congested States for LC and HC only	7	196	10%
Section 5.3 Bus Ridership and Induced Demand	21	588	30%
Section 5.4 Varying Congested States for GE only	8	224	10%
Section 5.6 Modal Shifts with 20% shift	11	308	28%
Section 5.6 Modal Shifts with 30% shift	13	364	37%

Table A.1: Fleet Size for Each Scenario Studied

The fleet size is chosen such that the average patron wait time under a do-nothing strategy is maintained at the same level for each scenario.

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