2012

Identifying the performance parameters of importance in the design of Bus Rapid Transit: an experimental framework using microscopic simulation

Renaud BAYLE

Supervisors

Professor Corinne MULLEY

Doctor Alejandro TIRACHINI

Institute of Transport and Logistic Studies (ITLS), University of Sydney

Abstract

Bus Rapid Transit (BRT) is acknowledged to be an emerging mode of public transport and has the ability to deliver fast and high quality urban mobility. A BRT networks consist of six major components, namely the running ways, the stations, the vehicles, the fare collection, the ITS technologies, and the service and operating plans and it is the combination of these six dimensions that defines a BRT system and its quality.

Using microscopic simulation as the experimental framework for a calibrated and coded corridor within the Metropolitan network in Sydney, Australia, the impact of these parameters is explored. The objective of this work is to identify which parameters are most important to BRT system performance. Several scenarios including the increasing capacity of vehicles, changing frequency and the introduction of bus lanes have been designed and measures used from the output of the microsimulation to compare with a baseline scenario. The research findings point to the importance of particular components in the design of a BRT system and in particular the frequency of the services, the number of bus stops within the network, the presence of bus lanes and the demand applied on the network.

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1 General introduction

Providing effective public transport is a major concern in many - not to say all - developed and developing cities, particularly since transport habits change. For some city residents who can afford to have a private vehicle, public transport only accounts as another alternative to car. But for others it is the only way to access employment, education and all the urban amenities, especially when distance exceed the limits usually accepted in terms of walking and cycling (Wright and Hook 2007).

In most cities, bus services are recognized to be the public mode that moves the greatest amount of passengers, in comparison to other public transport modes (Hensher 1999). Nevertheless they are considered as unreliable and inconvenient. Indeed they operate mainly in mixed traffic areas, and subsequently in competition with cars and trucks. The fact that bus services share infrastructure with other means of transport has highly contributed to the deterioration of bus image, to the detriment of other transportation alternatives.

As a response, decisions makers - such as politicians and public officials - and transport planners have often decided to implement rail systems (heavy and light rail for instance). There is no denying that such alternatives can provide fast and high urban mobility, however the costs of rail infrastructure are proved to be very high, compelling cities to set up such systems only over a few kilometres in a defined area. This system being thus very limited, it results in a mean of transport that barely meets the needs of a given population in terms of urban mobility.

An alternative, called Bus Rapid Transit (BRT), is growing in popularity throughout the world for a few decades now, and is said to have the "ability to implement mass transportation capacity quickly and at low to moderate cost" (Deng and Nelson 2010).

The objective of this report is to identify and to analyse the impact on performance of parameters that distinguish different Bus Rapid Transit systems. The purpose of the analysis is to inform as to which factors might be most important in designing and implementing BRT in the future. Microscopic simulation is used to provide the experimental framework as this allows variation to be observed for a constant corridor.

The report is organised as follows. The following section provides the background knowledge about BRT and the literature basis for the microsimulation experiments. It includes, among other things, the main components of BRT systems and an overview of the simulations already performed about such systems and recorded in the literature. This is followed by a description of the simulation framework, results and analysis. The final section concludes the report.

2 Literature Review

Definition and Concept of Bus Rapid Transit

Defining Bus Rapid Transit in a few words or sentences appears to be a quite hard task, for there are plenty different definitions of BRT throughout the literature. The main ideas do not vary from a definition to another, but each author conveys a different standpoint. If BRT is “an integrated system of facilities, equipment, services and amenities that improves the speed, reliability, and identity of bus transit” according to Levinson *et al.* (2007), it is rather “a rapid mode of transportation that can combine the quality of rail transit and the flexibility of buses” for Thomas (2001). According to Wright and Hook (2007), BRT is “a bus-based mass transit system that delivers fast, comfortable and cost-effective urban mobility”, whereas, for Deng and Nelson (2010), it is more “an emerging form of mass transit, which ties the speed and reliability of a rail service with the operating flexibility and lower cost of a conventional bus service”.

There is an obvious common feature in all these definitions, which is the fact that BRT belongs to mass transit. This term alludes to “a large-scale system of public transport serving a city or metropolitan area, characterized by fast running speed, high passenger-carrying capacity and mostly operating on an exclusive right-of-way” (Deng and Nelson 2010). Heavy rail (or Mass Rapid Transit, MRT), light rail (or Light Rapid Transit, LRT), monorail and BRT are included in this definition.

Figure 1 : Bogota's Bus Rapid Transit system (Colombia)

Figure 2: Example of heavy rail, New York City Subway (United States)

Figure 3: A light rail system in Madrid (Spain)

BRT is nowadays a very widespread concept: we can see examples of this means of transport all over the world, *e.g.* in the USA, Brazil, Canada, China, Mexico, Australia, *etc.* In Europe, a concept known as BHLS, that is to say Bus with High Level of Service, is very close in meaning to the concept of BRT. There are of course some differences between those two concepts, because the context is not the same in Europe and in North America for instance - where BRT has widely proved to be a cost-effective means of transport. Indeed the urban context, as well as the way to address mobility in cities, is different in these territories (Finn *et al.* 2011). This can explain why BRT and BHLS have specific characteristics. However, the mainstay remains the same: building a bus-based system inspired by the performance and quality of rail to address urban mobility.

Eventually it can be added that this mean of transport suffers from the mention of the word ‘bus’ in its designation. Hensher argues that this really works against it in the end, and explains that the main reason for this phenomenon is that “the word ‘bus’ is immediately interpreted as buses in mixed traffic competing with cars and trucks” (Hensher D.A., *ABC Magazine Opinion Piece: Food for Thought, OP 56*, e-mail communication, May 2012). According to him, “we should no longer be talking about BRT but about Dedicated Corridor Transit (DCT)”. This would indeed place “the matter fairly and squarely where it belongs”.

History of BRT

The first steps towards BRT concept was the appearance in the United States in the 60s of high-occupancy lanes and exclusive bus lanes, but the setting up of a real dedicated busway over a few kilometres goes back to 1972, in Lima (Peru).

Soon after, in 1974, the first bus-based public transport network was developed in Curitiba (Brazil), using busway corridors scattered about the city. This was the first step forward towards the concept of Bus Rapid Transit. From now on, Curitiba’s BRT represents an example throughout the world, with its network that has today about 57 kilometres long exclusive busways. Wright and Hook (2007) stress the irony of this scientific breakthrough: indeed the city initially meant to set up a rail-based metro system. However, lacking the resources to develop such an option, Mayor Lerner’s team (Curitiba’s mayor at that time) created “a low-cost yet high-quality alternative utilising bus technology”.

Figure 4: Curitiba's Bus Rapid Transit system, *Source: Wright and Hook (2007)*

Following the success of Curitiba’s bus-based system, a few cities took the initiative in implementing BRT systems during the 1970s, especially in North and South America. The examples of Sao Paulo (Brazil), Goiania (Brazil) and Pittsburgh (United States) respectively in 1975, 1976 and 1977 can be quoted. However, the systems appeared to be less sophisticated than the one set up in Curitiba.

About two decades later, the setting up of TransMilenio in Bogota (Colombia) changed drastically BRT perception. Indeed in December 2000 Bogota’s BRT, called TransMilenio, began operation, and gave the whole world evidence that BRT could provide high-capacity and high-quality mass transit. Today its network consists of nine interconnecting BRT lines, with a total length of 84 kilometres running throughout the city. And its daily ridership adds up to about 1.6 million.

The main components of a BRT system

They are usually six major elements in a BRT system, which can be distinguished into three groups. The following inventory is taken from the report *Characteristics of Bus Rapid Transit for Decision-Making* written by the Federal Transit Administration and the United States Department of Transportation (Diaz *et al.* 2004).

The first of the three groups is the **infrastructure**, which collects the structure and the commodities that are essential to enable the operation of the transportation system. Here are included:

- <u>The running ways</u>. BRT systems can operate either on mixed-flow lanes, designated arterial lanes, at-grade transitways or on fully grade-separated exclusive transitways, keeping in mind that it is not necessarily the same type of running way along the whole route of the BRT.
  If a BRT system wants to compete with light rail, such as trams, it is often acknowledged that it must operate on an exclusive transitway.

Figure 6: Example of a designated arterial lane, Boston Silver Line, *Source: Diaz et al. (2004)*

Figure 5: Example of a fully grade-separated exclusive transitways, East Busway, Pittsburgh, *Source: Diaz et al. (2004)*

- <u>The stations</u>. BRT stations can be a simple stop, an enhanced stop, a designated station, an intermodal terminal or transit centre. The architecture and design of these stations are usually different from those utilised for standard buses, in order to improve the performance of this service and create a real identity for BRT concept.

Figure 8: Example of an enhanced stop, Los Angeles, *Source: Diaz et al. (2004)*

Figure 7: Example of a designated station, Brisbane South East Busway, *Source: Diaz et al. (2004)*

Second is the **rolling stock**, with the <u>vehicles</u> designed to operate on this infrastructure. These have a great influence on the speed, performance, capacity, environmentally friendliness and comfort of the service. Comfort must not be forgotten, because it is a very relevant parameter that can influence passengers when willing to choose between different transportation modes. The importance of comfort was revealed by Baltes (2003), while studying the Lynx LYMMO, a BRT system in Orlando (United States). He built a regression model to analyse the importance that customers place on specific service elements of BRT, and concluded that comfort was an important factor. Indeed, in this model the only parameter 'comfort' succeeded in explaining 56% of the variance of overall customer satisfaction.

Zimmerman and Levinson (2004) distinguish "seven basic areas" relevant to the design of BRT vehicles, including:

- Capacity and external dimensions (length, width, number of seats, *etc.*),
- Internal configuration,

Figure 9: Interior of an Irisbus Civis Specialized BRT vehicle, TEOR, Rouen (France), ***Source: Zimmerman and Levinson (2004)***

- Doors (placement, number and width),
- Floor height (low floor, partial low floor and high floor),
- Propulsion systems (internal combustion, dual mode diesel/electric, internal combustion/electric hybrid, *etc.*),
- Guidance (mechanical and electronic), that can allow "vehicles to travel safely at high speeds without increasing the width of the travel lanes" (Pahs *et al.* 2002)
- And Aesthetics, Identity and Branding (exterior look and design, *etc.*).

The combination of all these parameters plays an important part in optimizing BRT services. For instance, hybrid propulsion systems tend to reduce noise levels, and therefore increase passengers riding comfort. Zimmerman and Levinson also review the dimensions and capacities of typical U.S. and Canadian BRT vehicles, showing that the highest capacity used for these vehicles is equal to 130 passengers per bus (pax/bus), using 24 meters long vehicles. Besides, they highlight the importance of the number of doors available for boarding/alighting, saying that this factor can help reduce dwell times.

Third and last is the **operation**, which conveys the idea of managing the transportation service. Here are included:

- <u>The fare collection</u>, *i.e.* payment of the fare (there is fare verification, which consists in the confirmation that the fare has been actually paid). Several devices are used in bus services, which are either off-board or on-board payment: cash payment to the bus driver, paper media, magnetic stripes and smart cards, keeping in mind that smart card is the quickest fare collection system for the time being. Off-board fare collection, like smart cards, is often singled out in terms of BRT services. Indeed, Tirachini and Hensher stated in 2011 that “a quick fare collection system could provide shorter dwell times at bus stops” (and hence shorter travel times) and also reduce the phenomenon of bus congestion (treated as queuing delays at bus stops in the paper).

Figure 11: Example of a magnetic stripe, *Source: Diaz et al. (2004)*

Figure 10: Example of a smart card, *Source: Diaz et al. (2004)*

- <u>The use of Intelligent Transportation Systems (ITS)</u>. These are advanced transportation technologies that are used by the operators in order to increase the quality of the service, its safety and its efficiency. Today there are twenty-one ITS technologies that can be set up into BRT systems (Kulyk and Hardy 2003). These can be distinguished in six groups, like for instance Vehicle Prioritization (Signal Priority, *etc.*), IVI Technology (Collision Warning, Collision Avoidance, *etc.*), Passenger Information (Vehicle Schedule, *etc.*) or Operations Management. Using such technologies can lead to a lot of improvements and benefits in terms of service performance and reliability. By way of examples, Signal Priority tends to prevent vehicles from having to stop at intersections, and therefore reduces service delays. The use of IVI Technology helps to decrease crashes frequency, and hence provides more reliable services.

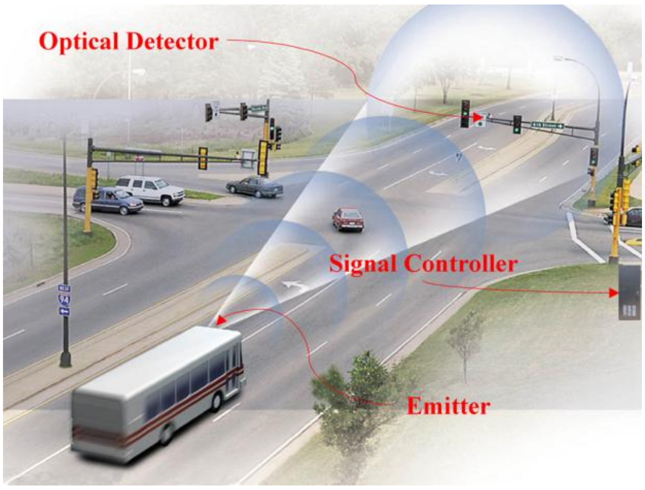

Figure 12: The functioning of Signal Priority

- The service and operating plans. This component is essential, in the sense that it can affect the way passengers perceive the service. BRT service needs to fulfil several criteria which are: it has to be frequent, rapid, efficient, reliable, comfortable, and easy and quick to understand.

By reference to the above elements, BRT can be regarded as a system with six dimensions. However, it is the mix of these six dimensions that defines a specific BRT system and its performance. In fact, these six dimensions can be combined at different levels of 'quality' which is why, in the real world, a continuum of quality of BRT systems is observed. An often neglected seventh dimension can also be identified as relevant in defining a BRT system: this is the overall network in which the BRT system is implemented. This dimension is a dimension which interacts with the six others. Indeed, the interactions between the BRT system and the network are crucial, and have considerable impact on the overall performance.

It must be born in mind that the elements discussed above are not specific to BRT systems, and are used in standard bus services but it is the combination at higher quality values that allows BRT to be set apart from other transport modes.

Moreover, it is fundamental to understand that two BRT systems that would have exactly the same components and features would not necessarily have the same performance and be as successful. Indeed, there are other set of issues and parameters that have to be taken into account when regarding the efficiency of such systems, for example the network or the economic context in which they are implemented.

Finally, it seems clear that a preferred alternative for Bus Rapid Transit systems would combine the following features: low floor, environmentally friendly and well-designed vehicles that would promote BRT's image and identity, travel on fully dedicated transitways with no competition with other means of transport and stop at intermodal terminals, and that would use smart card off-board fare collection and the maximum number of ITS technologies in order to help along the operation process. However there is not a single BRT system in the world that fulfils all these conditions (Hensher and Golob 2008). And of course the previous scenario remains quite hypothetical.

Some experts of Bus Rapid Transit have nevertheless tried to see to what extent it was possible to get closer to this preferred alternative. A document called *The BRT Standard Version 1.0* (Hook *et al.* 2012) suggests a scale of notation of BRT networks. In fact, an ideal scenario has been built using the best features of BRT systems (such as the use of off-board fare collection for instance). A certain amount of points is attributed to each of these features, the sum of all the points being 100. It is then possible to work out the "grade" of any given BRT system by checking if the registered features are present (or not) within the network, and by allocating (or not) the points for these components. Systems that obtain more than 85 points are considered as being part of the Gold Standard. This initiative is supposed to "encourage municipalities to at least consider the key features of the best BRT systems", and it is hoped "that a few cities will be inspired to go beyond what has been done before" (Hook *et al.* 2012).

The performance of a BRT system

The performance of BRT systems can be analysed using five key ideas, *i.e.* Travel Time, Reliability, Image and Identity, Passenger Safety and Security, and System Capacity. These are the five notions identified and explained by Diaz *et al.* (2004) in their report *Characteristics of Bus Rapid Transit for Decision-Making*. The explanations that follow are mainly extracted from this report.

Before breaking them down, here is a table taken from the same report that shows the influence of the previous components on the performance of a BRT system.

	System Performance				
	Travel Time Saving	Reliability	Identity and Image	Safety and Security	Capacity
Running Way					
Running Way Segregation	✱	✱	✱	✱	✱
Running Way Marking			✱		
Running Way Guidance	✱		✱	✱	
Stations					
Station Type	✱		✱	✱	✱
Platform Height	✱	✱	✱	✱	✱
Platform Layout	✱	✱			✱
Passing Capability	✱	✱			✱
Station Access			✱	✱	
Vehicles					
Vehicle Configurations	✱	✱	✱	✱	✱
Aesthetic Enhancement			✱	✱	
Passenger Circulation Enhancement	✱	✱	✱	✱	✱
Propulsion Systems	✱		✱		
Fare Collection					
Fare Collection Process	✱	✱	✱		✱
Fare Transaction Media	✱	✱	✱	✱	✱
Fare Structure	✱		✱		✱
Intelligent Transportation Systems					
Vehicle Prioritization	✱	✱	✱		✱
Driver Assist and Automation Technology	✱	✱	✱	✱	✱
Support Technologies					✱
Operations Management	✱	✱		✱	✱
Passenger Information	✱	✱	✱	✱	
Safety and Security Systems				✱	
Service and Operating Plans					
Route Length		✱			
Route Structure	✱		✱		
Span of Service		✱			
Frequency of Service	✱	✱		✱	✱
Station Spacing	✱	✱			

Table 1: Influence of BRT elements on the overall system performance, *Source: Diaz et al. (2004)*

Looking at this table, it is important to understand that the effectiveness of a component can be increased or decreased with its combination with other ones. Thus it is not really meaningful to study each feature separately while analysing BRT systems. Indeed it is more the overall combination of these components that dictates the performance of a BRT.

Returning to the five notions allows the performance of Bus Rapid Transit systems to be defined.

- **Travel Time Savings**. It is most certainly the aspect that customers care the most when boarding a public transport service, especially when they commuter from their home to their work, or vice versa. This travel time on a service can be dissected into four:
  - The running time, time spent in bus services travelling from station to station,
  - The dwell time, time spent in the vehicles at bus stops, waiting for passengers to board or alight,
  - The wait time, time spent at the beginning of the trip by customers at a bus stop waiting to board on a service,
  - The transfer time, time spent by passengers transferring between BRT services and other types of public transport mode.

  BRT operators try to reduce the travel time for passengers, in order to increase the attractiveness of the service.

- **Reliability**. This notion is commonly defined in the literature as the "variability of travel times" (Diaz *et al.* 2004). This has been confirmed by several authors, like Polus (1978) who argues that "the variability of travel time performance is posited as the best indicator of reliability". However, different approaches of this concept are possible: Bates *et al.* (2001) refer to schedule delays and adherence to timetables while speaking about reliability, whereas it is more a matter of passenger waiting times at transit stops for Bowman and Turnquist (1981). In any case, reliability mainly depends on "the ability to maintain consistent travel times and the availability of consistent service" (Diaz *et al.* 2004).
  It is important to understand how fundamental this parameter is because customers are more likely to use a service if they consider it to be reliable. In terms of Bus Rapid Transit, this implies to offer a service that displays great quality and performance (everything to do with the quality of service, such as frequency for instance, could thus be put here).

- **Identity and Image**. This item points out the capacity of a BRT service to be part of the transportation market and to fit with the context and the needs of a given area in terms of urban mobility. This is essential, because it can help users, and especially non-frequent ones, to locate easily BRT system access points (*e.g.* stops) and understand quickly BRT routing. In short it can help customers to understand as quickly as possible how the network works.

- **Safety and Security**. On the one hand safety reflects the freedom from hazards such as road accidents, injuries, *etc.* And on the other hand security reflects the freedom from criminal activities against customers and their property, *e.g.* thefts, violent acts, threats.

- **Capacity**. This notion is defined as the maximum number of passengers that can be carried by a BRT for a given time span and for a given direction, depending on specific conditions (type of vehicles, *etc.*). According to Diaz *et al.* (2004), "virtually all BRT elements affect capacity". By way of an example, even if frequency has already been quoted within the item *Reliability*, it can also be referred to here, because frequency somewhat has the ability to make capacity vary when trying to work out the capacity of a BRT line.

Advantages/Disadvantages of the setting up of a BRT system

Economic impacts

BRT cost-effectiveness identifies the advantage of BRT over other transportation modes. Indeed, as it was said previously, it is often recognized that, provided that the BRT service operates on an exclusive transitway, it can compete with light rail, and even heavy rail in some cases, in terms of performance. It is shown on Figure 13 that capacity for BRT systems can reach 40 000 passengers per hour per direction, matching this way or even sometimes exceeding the capacity of some rail networks.

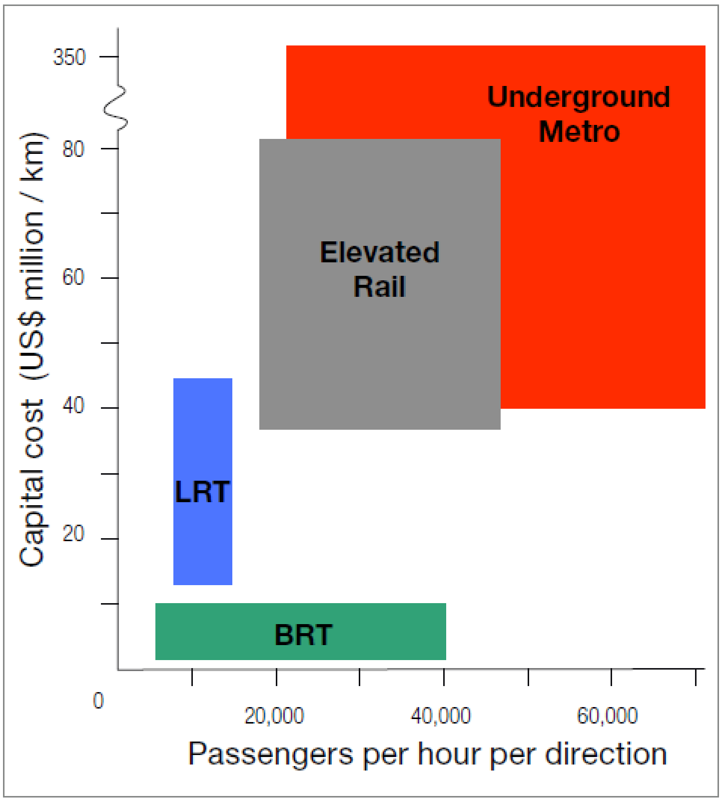

Figure 13: Passenger capacity and capital cost for mass transit options, *Source: Wright and Hook (2007)*

It must also be added that "the overall capital and operating costs for BRT systems are less than similar rail-based systems" (Deng and Nelson 2010). This statement has been confirmed by several authors: Wright and Hook (2007) argue that "a BRT system typically costs 4-20 times less than a LRT system and 10-100 times less than a Metro system". That is why the cost-effectiveness of BRT systems is often put forward as an argument for implementation.

By the way, this also means that with the same budget, Bus Rapid Transit can provide more network coverage than rail-based systems, an argument that is once again in favour of BRT.

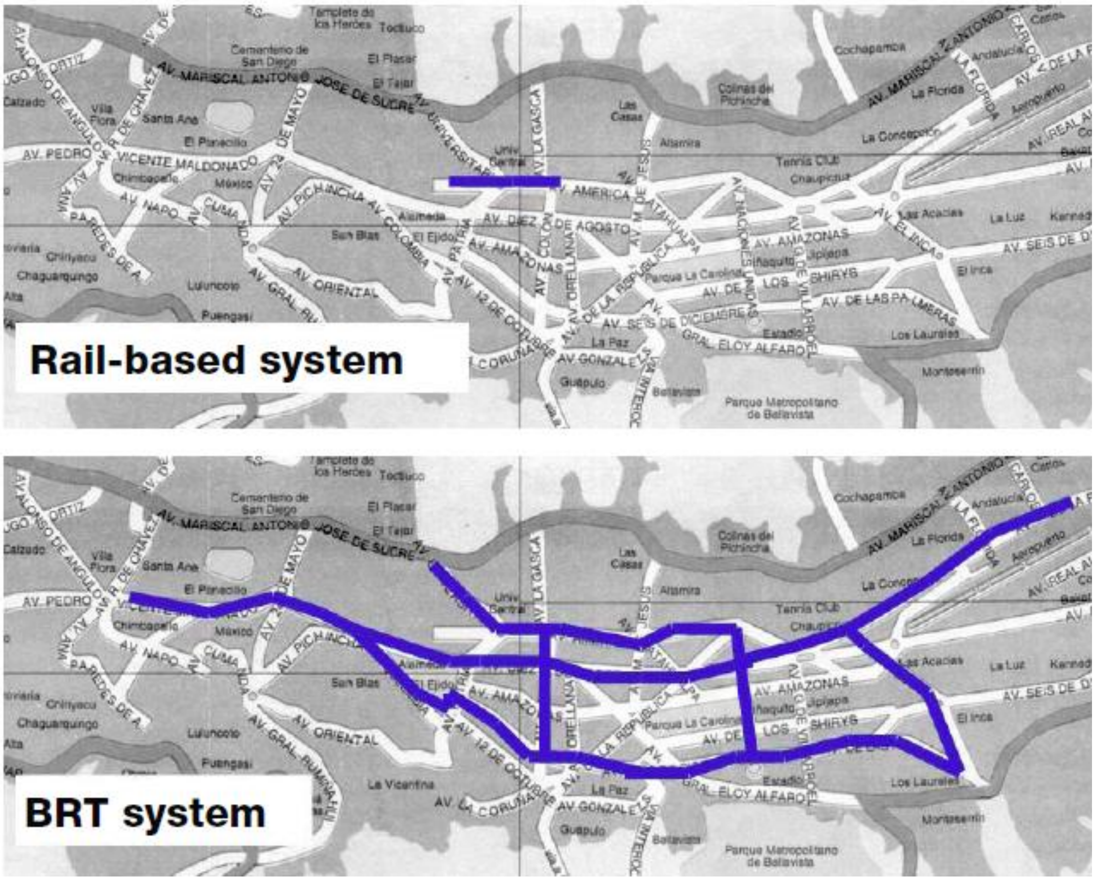

Figure 14: Graphical comparison of two transportation options at the same cost, *Source: Wright and Hook (2007)*

Figure 14 reveals the relative coverage of two different networks that have a similarity: they account for the same construction cost. This is another way of looking at this coverage issue, but this time from a more graphical point of view. A limited network of a few kilometres means that most of the trips generated by the people of this given city are not reachable using the transportation system. As the system extends across the city, more and more destinations can be reached, and thus the ability to travel without private vehicles becomes much higher.

The notion of cost-effectiveness is quite perilous to handle, and must be used with caution. Indeed it would not make any sense to compare BRT and rail-based systems construction costs, if these systems could not provide similar performance, in generating demand for instance. This issue was brought up by Currie in 2005 while investigating the attractiveness of BRT in comparison with other transportation modes. He concluded that “BRT systems can be as effective in attracting passengers as heavy and light rail” and thus “since BRT has been shown to have significant cost advantages over rail, an overall cost-effectiveness advantage may be claimed for BRT”.

Moreover infrastructure costs must also be handled with caution. Indeed some factors can make them vary and thus hasty comparisons can become quite detrimental. Labour costs for instance can explain big differences in infrastructure costs, for this parameter may vary a lot from one country to another. Another phenomenon pointed out by Hensher and Golob (2008) is “physical conditions prior to start of construction, which are difficult to define”. Indeed some BRT projects start from scratch, whereas others can convert existing roads into BRT transitways, distorting cost comparisons.

Speaking of labour costs, the setting up a BRT line may also in some cases imply employment generation, as Wright and Hook (2007) put it. Indeed, during the construction process, corridors utilised for Bus Rapid Transit are usually dramatically transformed, creating a certain amount of employment, in particular in civil engineering fields. During the operation process, the results are quite different and appear to be more mixed. Standard bus systems normally employ more staff than BRT systems, however "BRT vehicles actually involve three to four different shifts of employees operating the same vehicle" (Wright and Hook 2007). Thus the changes between standard bus services and BRT services in terms of number of employees seem to compensate.

Finally, it is sometimes assumed that BRT lines generate development of shops around transit stations, providing additional employment. But this conclusion has already been shown to need to be checked case by case.

Eventually, the last point that is relevant while studying BRT economic impacts is its flexibility, both during construction and operation stages. During the construction process, "BRT systems can often be implemented quickly and incrementally" (Levinson, Zimmerman, Clinger and Rutherford 2002). A quick implementation is a real asset for such a project from a Cost-Benefit Analysis point of view. Indeed, the smaller the construction time, the sooner the benefits generated by this project appear. Moreover, BRT projects can be completed in phases. It is the case for TransMilenio (Bogota) for instance. This represents also a great advantage for investments, which can thus be allocated in several tranches.

Moreover, since BRT systems are acknowledged to have faster implementation times than rail-based systems, investment risk, which is a main component in economic sustainability, is reduced for such projects (Campo 2010).

During the operation process, BRT flexibility is the result of the fact that Bus Rapid Transit is, as its name indicates, a bus-based system. And there is no denying that bus is much more flexible in its way of operating than rail for instance. Using bus services enables operators to change routes if an incident occurs on a given line, which is impossible for rail-based networks, once built.

However and ironically, as it is said in several papers, BRT flexibility can also be seen as a "drawback" (Jarzab, Lightbody and Maeda 2002). Political will sometimes represents a barrier to BRT projects. In 1999 Hensher stated that "it would not be so glamorous, and so the politicians and planners might not be so willing to plan and promote it", while comparing a bus system with a light rail line. He nevertheless explained that, with the same amount of investments, a bus service would "produce more improvement in accessibility" than a single light rail line, an argument that is in favour of BRT.

Environmental impacts

According to Campo (2010), "the environmental impacts aspect is seen as a weaker point of BRT systems". Indeed, studies have given evidence that BRT systems in the United States produce higher emissions than similar rail-based systems (Puchalsky 2005). This mainly comes from the use of high-sulfur diesel in BRT propulsion systems.

Major improvements have been done by the industry in the last decades to provide vehicles with more efficient and cleaner fuels. A lot of progress has occurred in this area, and mentalities are changing in terms of environmentally friendliness. Nevertheless, only until recently have hybrid-electric buses and low-sulfur diesel been experimented in BRT systems. "This step is significant since research determines the potential of BRT to be effectively cleaner than rail technologies once cleaner fuels and hybrid technologies are generally adopted" (Campo 2010).

This study realised by Vincent and Jerram (2006) provides evidence that BRT can be a much more efficient transportation mode than LRT while speaking of reducing CO_2 emissions, provided that vehicles are equipped with hybrid and low-sulfur propulsion systems. Global warming is a major concern nowadays, and this paper indicates how Bus Rapid Transit can fit in the new transportation context, where environmental aspects are almost as important as performance aspects.

For the being time, it would be a bit hasty to conclude that environmental aspects are in favour of BRT, in comparison with other transportation modes like LRT for instance. But recent studies are quite optimistic on this subject, and the results provided by Vincent and Jerram (2006) show encouraging signs about the high potential for BRT to reduce transportation-related CO_2 emissions.

Another important topic that must be studied within the environmental aspects is the noise produced by traffic along BRT system corridors. Low noise vehicles are desirable for BRT projects, especially as corridors are often in interaction with residential areas.

A recent study written by Mishra, Parida and Rangnekar (2010) revealed that the observed noise levels along two BRT corridors in Delhi (India) were higher than CPCB standards (*i.e.* Central Pollution Control Board of India), highlighting the effects that noise has on people health, in particular stress, hearing damage, agitation, *etc.* It is nevertheless said that the CPCB standards can be reached by implementing a noise barrier to protect the residential areas that are closed to the corridor.

This is not an exceptional case, because Currie (2006) stated that Sydney Liverpool-Parramatta Transitway (SLPT), a bus-based transportation system that "qualifies for BRT status", also required protection from noise. According to him, this mainly comes from the fact that "SLPT does not have the same quality of right-of-way separation" that is exhibited in other BRT systems. Indeed, SLTP is set up within an area with "much existing urban development".

At first sight, noise could therefore be put as a disadvantage of BRT systems. However, a sense of nuance must be kept, because first it is not true for each BRT system (it highly depends on the nature of the environment in which the BRT is implemented). And second because there are several solutions that can be utilised to tackle this issue: set up a noise barrier, apply sound absorbing materials on the external walls of buildings, use hybrid vehicles that "can perform significantly better than other vehicles in terms of noise" (Zimmerman and Levinson 2004). Usually, a good design of a BRT system can help to partly reduce these impacts.

Urban impacts

BRT lines have sometimes impacts on the urban development of cities. This has been the case for instance for Curitiba, where BRT played "a catalysing role towards sustained economic development" (Wright and Hook 2007). Indeed, BRT elements, and more particularly stations, have had a great influence on the development of the different areas. The stations have become real exchange nodes, and have tended to attract commercial activities and residential development. Additional construction also occurred along bus arteries, revealing the real strength that has BRT in terms of urban development. Once again, this is not particular to BRT, and is quite widespread among mass transit systems. Indeed similar phenomena have been observed with heavy rail lines for instance and for metros.

Land development can also be an effect of mass transit systems, in particular Bus Rapid Transit. According to Deng and Nelson (2010), "since proximity to mass transit can greatly save time and money cost of commuting, properties near transport facilities generally become desirable for new development or redevelopment". However the impacts of mass transit on property value seem to be questionable. And throughout the literature it is hard to say whether a consensus of opinion has been found on this topic. In 2007 Du and Mulley showed that transport improvement programmes do not imply noticeable impacts on the value of property. Moreover proximity to mass transit systems can bring about negative impacts on property value, because of nuisance effects in the vicinity of stations, such as noise and pollution, which might decrease the value of property. Nevertheless Al-Mosaind, Kenneth and James (1993) stated that these negative effects were much weaker than the positive effects of accessibility. Therefore, according to Deng and Nelson (2010), "overall the presence of transport systems has positive effects on land development".

Some studies seem to confirm this statement: indeed, Rodriguez and Targa (2004) showed that TransMilenio (Bogota) made residential rental costs increase between 6.8% and 9.3% for every 5-minute walking time to BRT stations, after only two years of operation of the system. Another one produced by Levinson *et al.* (2003) about Brisbane's Southeast Busway gave evidence that property values close to BRT stations grew two or three times faster than those located in areas where there was no busways. These authors claim that this is "largely attributed to the busway construction".

Finally, according to some studies, BRT systems might have redistributive effects on development patterns and property values. That is what is explained by Jun (2012) in his article about Seoul (Korea), where some BRT services were introduced in 2004. He argues that "the BRT system was likely to contribute to the relocation of firms from suburban areas into the core city of Seoul, acting as a counterforce to employment suburbanization".

Therefore BRT systems seem to influence urban development and how activities split across cities. However, in some cases Bus Rapid Transit fails in promoting land development, and provides disappointing results. For instance, Cervero and Duncan (2002), who studied several mass transit systems in Los Angeles County, argued that BRT did not have positive effects on residential property value near stations.

For the time being, results in terms of land development are quite mixed. Moreover, most of the existing studies have been performed on developing countries, and very few examples deal with areas located in developed countries. Thus, some additional studies may be needed to conclude whether BRT does have positive impacts on property values or not.

Social impacts

This aspect alludes to the ability of a transportation mode to facilitate accessibility and to promote social equity within a city. “Social impacts are generally positive as BRT systems give lower-income groups more access to public services and economic opportunities” (Wright and Hook 2007). Indeed, if fares are cheap, BRT networks can help low-income people, especially in developing cities, that cannot afford to own a private vehicle, to access employment for instance, therefore reducing social inequities. This aspect must be handled with caution, because low fares do not necessarily imply cheap transportation system: it also depends on individual incomes.

Another phenomenon in favour of BRT systems is that they are likely to become places where all groups meet and interact. Because of their performance, comfort and efficiency, these systems attract all kinds of customers: high and low-income people, young and old passengers, *etc.* This can ease tensions and make understanding easier between social groups.

It must though be born in mind that there are also some disadvantages to the fact of gathering people in a massive way. A paper written by Gilbert (2008) indicated that Bogota’s BRT, TransMilenio, had to face a “perpetual plague of public transport”. As BRT attracts all kinds of group, it also attracts pick-pockets. The feeling of insecurity grew among passengers and this urged TransMilenio’s operators to sign an agreement with the police to allocate officers at bus stations.

If this is indeed a real plague, this phenomenon is nevertheless not particular to Bus Rapid Transit, and is more a matter of mass transit. Indeed, the concentration of people that occur in these transportation modes tends to ease pick-pockets’ task, and attract thieves in an inescapable manner.

The possible ways to simulate BRT systems

Field experiments seem hardly possible before setting up public transport systems. Simulation therefore provides an experimental way of anticipating what might happen. A lot of progress has been done in this field in the last decades, and there are now plenty softwares, that allow users to run transportation-related simulations, for instance Paramics, Synchro, DYNAMIT, VISSIM, Commuter, TRANSYT, *etc.*

There are three possible scales of simulation, namely microscopic, mesoscopic and macroscopic. Each of these scales has specific characteristics and specific goals, and they all have their own advantages and disadvantages.

Macroscopic simulation

Macroscopic simulations attempt to model traffic at a general level, and are usually concerned with aggregated traffic flows. These models "describe the evolution of traffic over time and spacing using a set of differential equations" (Burghout 2004). They use aggregate data to portray the behaviour of a large number of vehicles as regards flow, density, speed, *etc.* As they do not focus on each driver, it is assumed that behaviours are identical among drivers. Having poor interests in the randomness of individuals' behaviour, macroscopic modelling can be considered as deterministic.

Given its ability to describe traffic flows, macroscopic simulation is used for instance for the analysis of large-scale networks, in terms of performance issues such as congestion.

Microscopic simulation

As for microscopic simulations, the overall approach is to describe traffic at a very high level of detail. Whereas macroscopic models consider traffic as a flow, microscopic models tend to describe the behaviour of vehicles individually and to analyse the interactions that occur within the network. Three different models generally govern vehicles behaviour: a car-following model (used to determine how vehicles follow one another on a given road), a route-choice model (that concerns the selection of routes between origins and destinations in the network) and a lane-change model (focused on how drivers make the decision to switch to another lane in given situations).

As microscopic modelling focuses on individuals, it requires very large resources as regards origin-destination data, but also flows, traffic signals, *etc.* Such models also require a calibration stage, in order for them to be adapted to the specific conditions of the network to which they are applied. Yu *et al.* (2006) highlight this phenomenon in their paper by stating that "to make the simulation models accurately replicate field traffic conditions, model calibration is crucial".

It is often acknowledged that these models give a realistic representation of traffic, and they are commonly used to inspect how users may react if new features are implemented in given road infrastructures, or to track and try to understand how congestion forms.

Mesoscopic simulation

A third and last type of transportation-related simulation is gaining popularity. These models are called mesoscopic models, and fill the gap between microscopic and macroscopic models as regards the detail of simulation achievable. According to Burghout (2004), they fall between "the aggregate level approach of macroscopic models and the individual interactions of the microscopic ones". In such models vehicles are modelled through varying forms, they can be either packets (that behave as one entity), cells or individual vehicles. Usually, in mesoscopic simulation, travel choices are simulated on a vehicle-by-vehicle basis, meaning that, while the ability to analyse the interactions between road infrastructures and drivers is lost, dynamic changes in route choice by drivers can be tracked.

In his paper in 2005, Burghout argues that "this makes mesoscopic models ideal for prediction applications, where the detailed modelling of route choice and other strategic driver choices are essential, but where the detailed modelling of driver interaction with the road network and other drivers is not needed".

Limitations of the different types of simulation

Each of these three scales of simulation has its limitations. If macroscopic and mesoscopic models are usually easier to calibrate than microscopic ones, due to their few and easily measurable parameters, "their application is limited to cases where the interaction of vehicles is not crucial to the results of the simulation" (Burghout 2004). In macrosimulation vehicles are not described individually and in mesosimulation they are described in an approximated way. As individual behaviour and interaction between users are removed, some generalisations inevitably occur and are very likely to bring about incorrect findings under certain circumstances. That is also why such models are generally used for large-scale networks, because the shortcomings due to their low level of details might not be important.

As for microscopic models, there is no denying that they have the ability to visualize results in a realistic way. However, they are generally "considered too time-consuming and costly" (Burghout 2004) because of the prior stages that they require before being actually able to run simulations, namely the coding and the calibration steps. It can also be added that a strong computational power is needed to run simulations at an adequate speed. Therefore "the size of the networks that can realistically be simulated with microscopic models is limited" (Burghout 2005).

The following table recaps the main differences between the three scales of traffic simulation.

	Traffic Simulation		
Scale of simulation	Microscopic	Mesoscopic	Macroscopic
Representation of traffic	Individual vehicles	Packets, cells, individual vehicles	Traffic flows
Required input volume of data	High	Intermediate	Low
Required computational power	High	Intermediate	Low
Significant network scale	Small	Intermediate	Large (*e.g.* city)
Example of softwares	VISSIM, Commuter, CORSIM	DYNAMIT, CONTRAM	Synchro, TRANSYT

Table 2: The main differences between the scales of traffic simulation

Simulations already performed on BRT systems

The literature does not provide much guidance as, there are only a few papers dealing with simulations about BRT systems and these are typically at a microscopic scale.

The literature generally focuses on particular aspects of already existing BRT systems. Siddique and Khan (2006), for example, investigated some BRT corridors in Ottawa (Canada) using a microsimulation software called NETSIM, in order to analyse the capacity of these transportation corridors. They built three different scenarios and compared them to draw conclusions about transitways capacity.

Other studies have used simulation tools in a public transport system context and provide information useful in studying BRT, even if they have not considered the BRT mode. For example, Fernandez (2010) explains in his paper how a microsimulation model called PASSION was used to analyse public transport stop operations (and more particularly bus stop operations). Using several input parameters (such as arrival time of services, boarding and alighting times, traffic signals, *etc.*), the model can work out numerous outputs: bus delays, bus stop capacity or even bus queue length. The main goal of this study was to understand how to “design vehicle and passenger infrastructure and manage operations to avoid oversaturation” at public transport stops (Fernandez 2010).

Another paper written by Fernandez, Cortes and Burgos (2010) reveals the functioning of another microsimulation tool, which was developed to simulate public transport components and operations. This tool is called MISTRANSIT, and consists in a “platform that allows the representation and control of fixed-route transit systems within a traffic microsimulation environment”. Several applications are possible using this platform, such as analysing traffic priorities for public transport vehicles, calculating the capacity of busways.

Conclusions

In summary, the literature reveals that Bus Rapid Transit is an emerging transportation mode that belongs to the type of mass transit systems. It has the ability to deliver fast and high-quality urban mobility at low to moderate cost, and can compete with rail-based systems, such as light rail and heavy rail, in terms of performance.

BRT systems are usually divided into six major components, namely the running ways, the stations, the vehicles, the fare collection, the ITS technologies, and the service and operating plans. These features allow Bus Rapid Transit to be set apart from other transportation modes. This emerging mean of transport certainly has some shortcomings, such as for example noise levels in some BRT corridors, but has also advantages on the other hand, like its cost-effectiveness or its flexibility. In addition, there is no denying that a well-designed BRT system can become a real asset for a city.

As it is not possible to resort to field experiments, simulation is used more often to attempt foreseeing what might happen when a transportation system is implemented within a given network. Three different scales can be used to model traffic: microscopic, mesoscopic and macroscopic levels although microscopic appears to be the most helpful in determining how individuals in vehicles might react to the introduction of BRT into a network.

3 The Military Road case study

The literature review identifies that building and calibrating the network for a microsimulation experiment can be very time consuming. This study benefited from a pre-calibrated network built for a section of road within the metropolitan area of Sydney in Australia. Whilst this network was originally built and calibrated prior to the Government announcement to investigate the feasibility of BRT on this corridor, the announcement has added relevance to this study.

The simulation study aims to provide information useful at the design stage of a BRT system by investigating variations in the parameters identified as important in the literature for system performance thereby contributing to the current literature.

Presentation of Commuter

Commuter is a microscopic simulation software. This tool was developed by Azalient, and analyses door-to-door trips made by people. It can model people travelling through all modes of transport: people driving, people walking, people cycling, people in taxis, people in buses, even people in buildings, *etc.* As it can describe the trips of each person through all modes, it is said to belong to nanosimulation, giving an incredibly high level of details (Azalient software engineering (n.d.), Retrieved: 28 May 2012, from http://azalient.com/1.php). Nanosimulation is in fact a special case of microsimulation. Whereas microsimulation deals more with vehicles, nanosimulation focuses on people.

Because it has the ability to separate each part of single trips and to provide very detailed results, this software enables to have a clear outline of the cost of each trip. Thus, the possible benefits of modified or new designs within the studied network can be estimated quite easily.

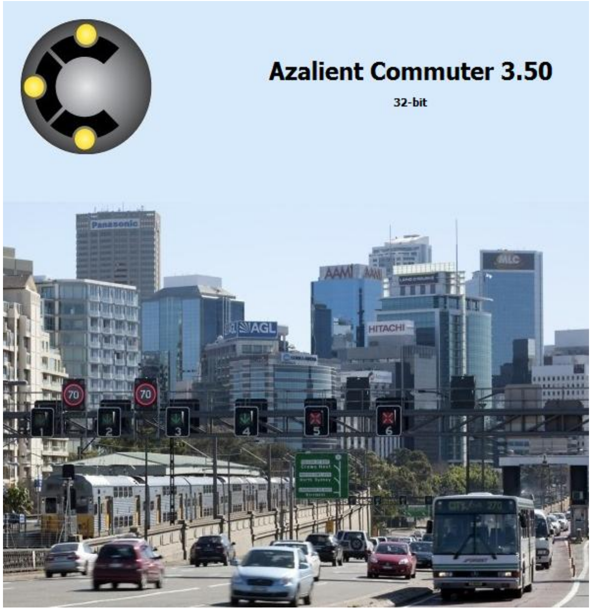

Figure 15: Entry image of Commuter v3.50 software

The main inputs of the software are the network, which has to be coded with great accuracy, the different types of modelled people, the demand, the services, *etc.*

As output, Commuter provides comprehensive results for the generated trips, such as overall numbers of trips, journey times for each mode and emissions. Moreover, the software allows users to visualize results in a very realistic manner using 3-D graphics.

Presentation and location of the Military Road

This work on Commuter utilises a pre-calibrated model and is focused on a practical case, namely the Military Road, which is a road situated in northern Sydney and which links for instance Manly to Sydney CBD.

The studied stretch, as shown on the following figure, is about two kilometres long and is in fact composed of a section of the Military road and a section of the Spit road. The stretch really analysed is located between the two landmarks, in red on the zoom provided in Figure 16.

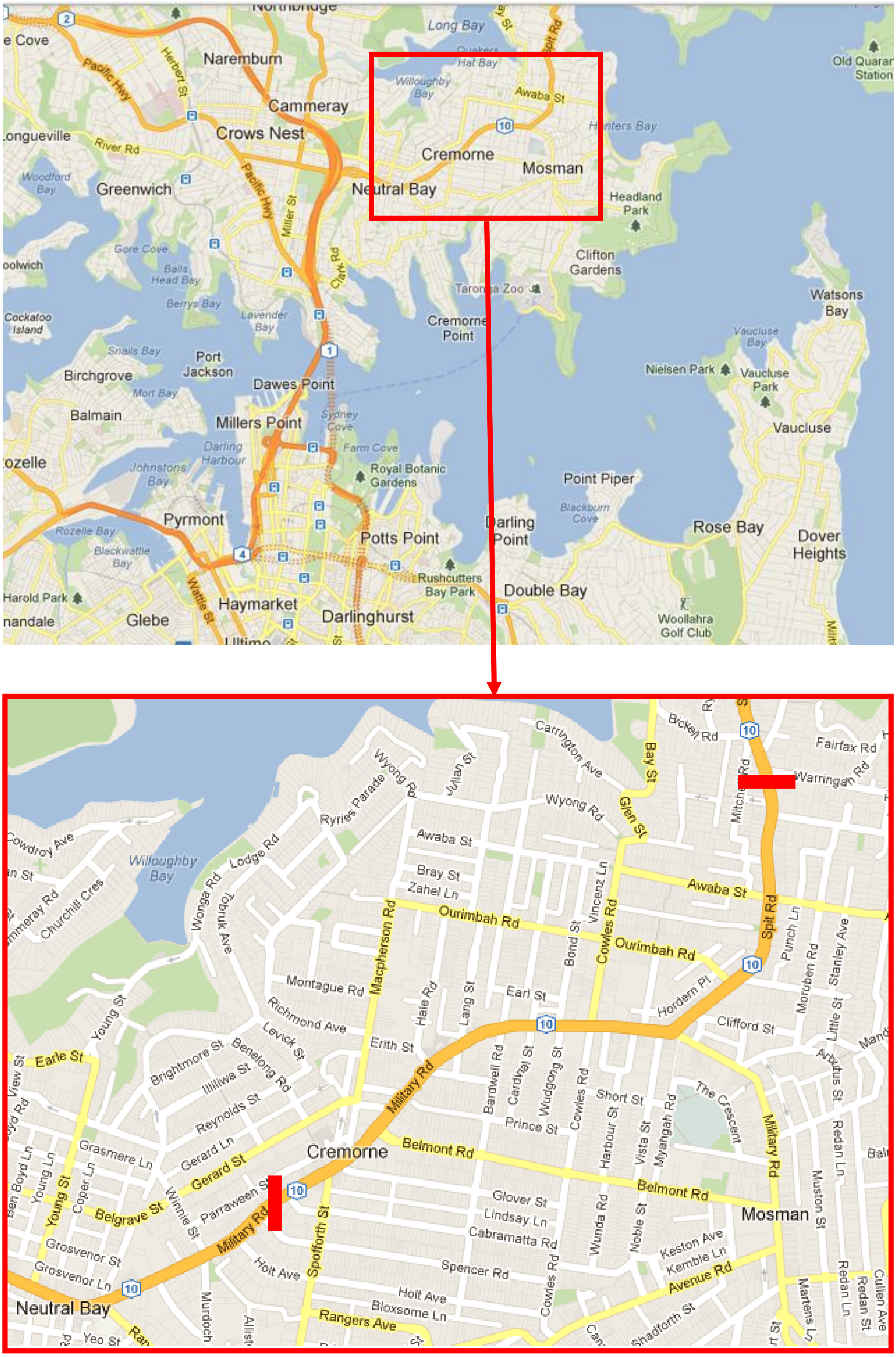

Figure 16: Location of the Military road in Sydney, and Zoom on the studied stretch

Once modelled using Commuter, this stretch looks like the following:

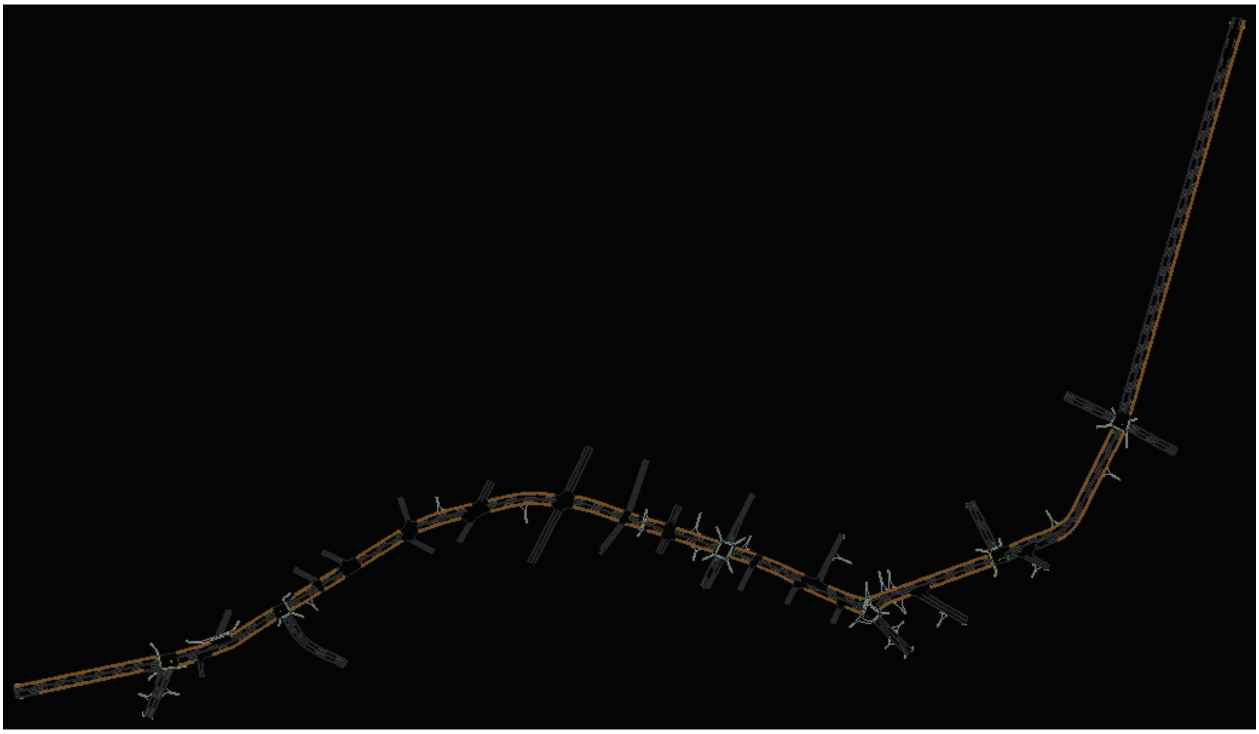

Figure 17: Overview of the network of the Military Road model

This road is characterized by a great amount of public transport traffic. Indeed there are more than fifty bus lines that take this road.

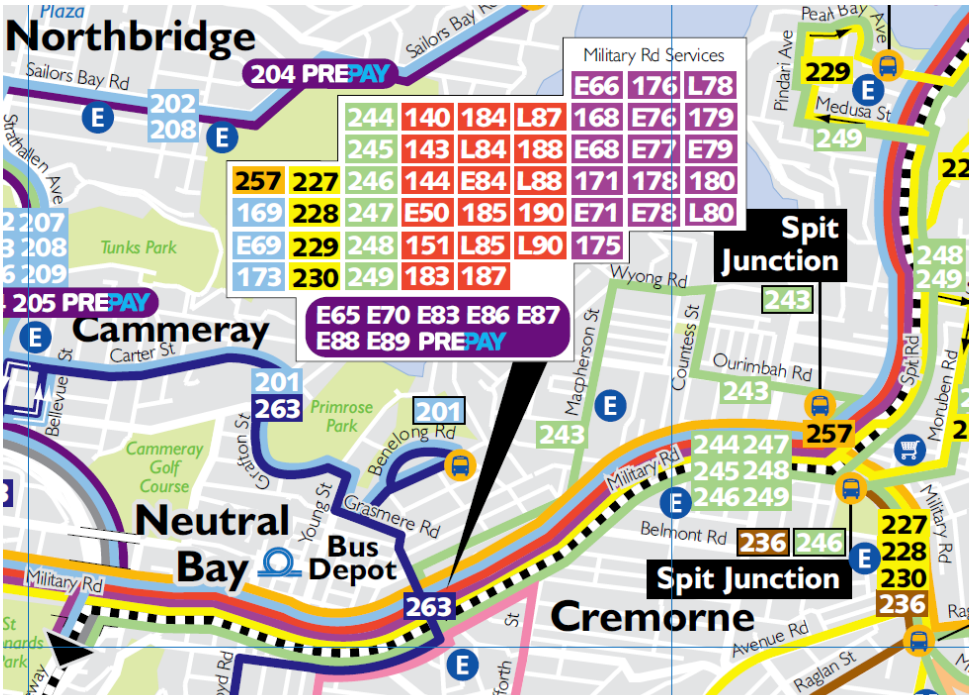

Figure 18: Map of Sydney buses within the Northern Region, *Transport for New South Wales*

Figure 18 indicates the different bus services that follow the Military Road. Some of them, like 178, 244 or L85 lines, deliver services for the whole day, whereas others, *e.g.* 173 or 249, deliver services only during rush hours. However, the frequency of two services varies considerably from about ten minute frequency for services operating during peak hours to hourly for some operating during off-peak periods.

Reasoning and methods

Simulation terms

In order to discover and analyse the parameters that play an important role in BRT systems, two different periods have been chosen and tested through Commuter: one during the morning peak hours, between 7 and 9 am, and another one during off-peak hours, between 1 and 3 pm. Thus, using the comparison of these two terms, it is possible to see the influence of congestion on the parameters and on the overall network.

The afternoon peak has not been considered in the simulations because of its similarity to the morning peak. This phenomenon can be noticed using the following graph, which indicates the distribution of demand by time of day on the Military Road: the level of demand is approximately the same for the morning peak and the afternoon peak, so it does not seem necessary to study both.

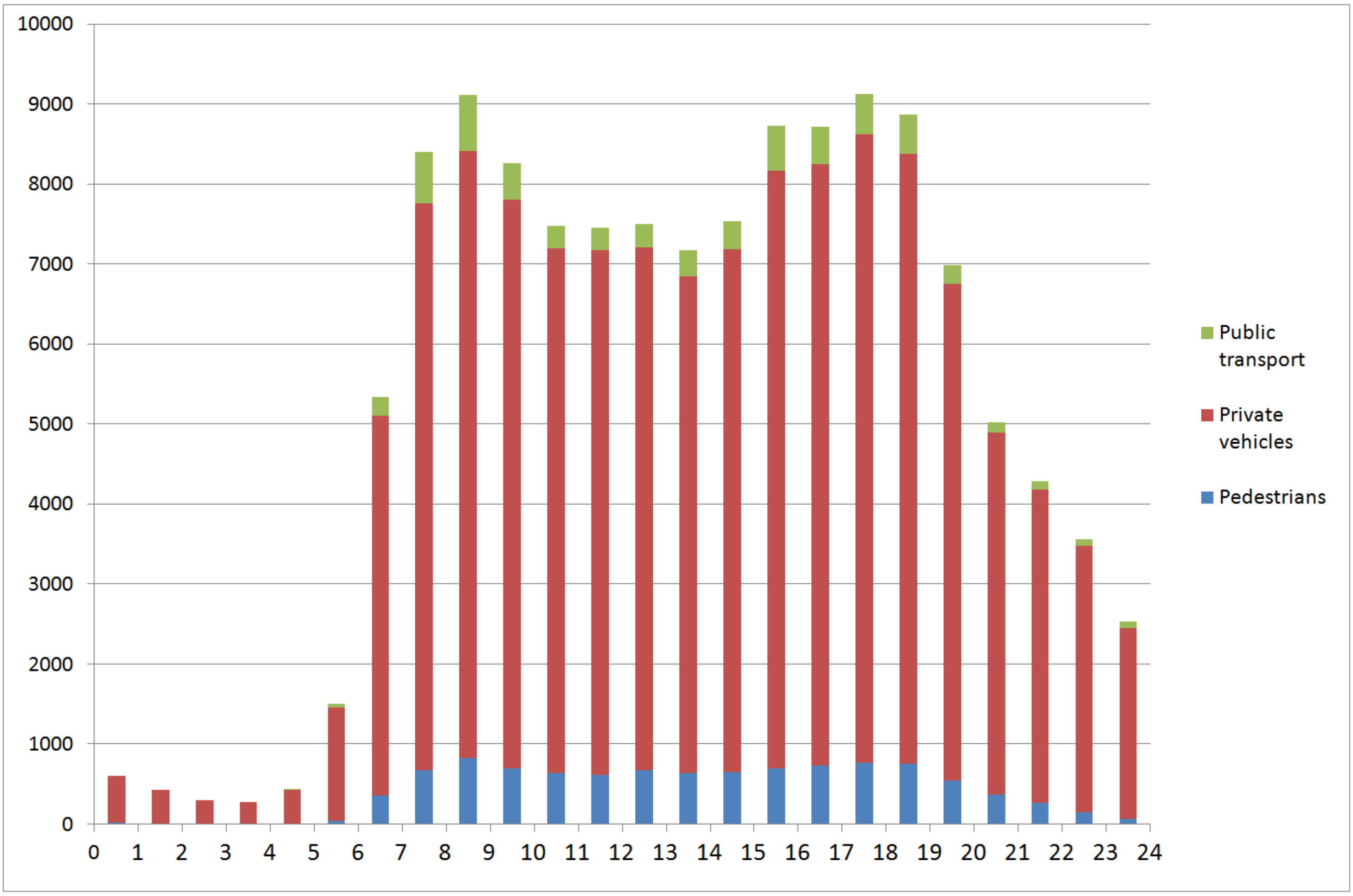

Figure 19: Calibrated distribution of demand by time of day on the Military Road in Sydney, Australia

Chosen criteria

There are different modes of transport within the Military Road model, such as people walking, people driving, people in taxis, and people in buses (and, whilst there are no people cycling in the model, cycling has only a small percentage take-up in Sydney). The pre-calibrated model contains three distinct kinds of trips in the network, namely Person Trips (for people walking only, or people walking and then riding buses), Public Transport Trips (people on public transport trips), and Private Vehicle Trips (for private vehicles, such as cars, trucks, taxis). As this study was concerned with the impact of changing various parameters on BRT, the pedestrian demand (people making only walking trips with no interchange to another mode) was set to zero since Commuter v3.50 provides results for Person Trips as the combined pedestrian and bus passenger trips.

The network changes proposed for the simulation were chosen because of their potential impact on all three types of trips (Person Trips (PT), Public Transport Trips (PTT) and Private Vehicle Trips (PVT)) as the objective was to examine how all three classes of trip interact. In measuring this interaction, the measures shown in Figure 20 were extracted from the Commuter output.

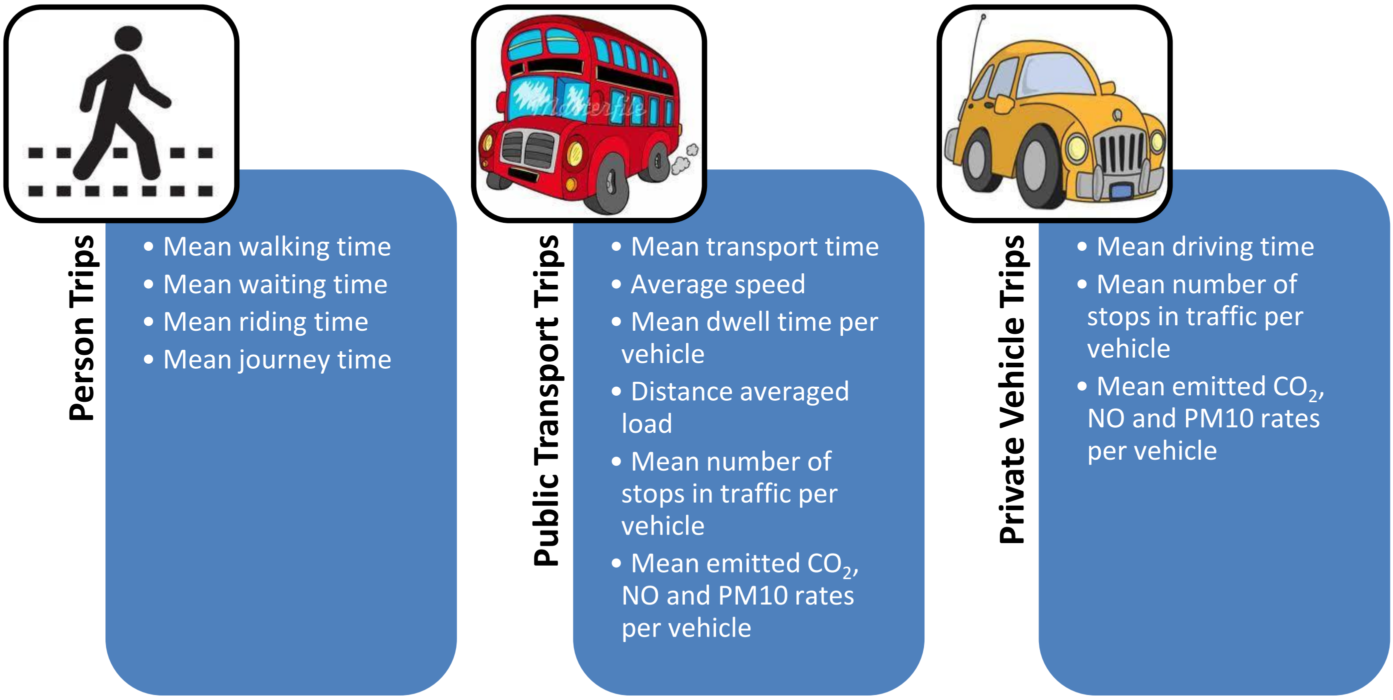

Figure 20: Measures extracted from Commuter output

Some of these measures do not have obvious definitions and are clarified next. For PT, waiting time refers to public transport users who wait at traffic lights or at a bus stop before boarding a vehicle. The journey time is the sum of walking, waiting and riding times.

In PTTs, transport time is the journey time of a vehicle in service. Dwell time is the stationary time of the vehicle at a bus stop (*i.e.* from stop to start time, including doors opening and closing and passengers boarding and alighting). Commuter presents dwell time as boarding or alighting time multiplied by the number of passengers. As the number of doors of the vehicles affects how quickly passengers board or alight services, this is a variable which is definable in the Commuter software either directly for vehicles (the number of doors) or indirectly at the bus stop where the number of doors can be set to alter the expectation of passengers as to how many doors will be available for boarding process on the next service to arrive. Changing the number of doors affects the alighting process whereas changing the number of doors at bus stops affects the boarding process.

The distance averaged load is the distance of the whole route of a service divided by the capacity of the vehicle. For instance, if the capacity of a bus is 50, and if there are 50 people on this bus from the start to the end of the route, then the distance averaged load is equal to 100%. However, if these 50 people ride the bus for half the distance travelled by the vehicle (thus making the bus empty for the other half of the journey), then the distance averaged load will be 50%.

These measures are concerned primarily with the performance of the system, and environmental concerns for the interactions that exist between the three kinds of trips. This allows modification of elements of design to be examined within the system, which is the main goal of this study.

Designed scenarios

The simulation experiments are scenario based where each scenario, compared to a baseline, introduces one or more elements identified as important in the literature. In total, twelve different scenarios have been investigated, leading to twelve simulations for each of morning peak and off-peak periods. Comparison is made through comparing each scenario with a baseline as discussed below.

Scenario 1 represents the baseline scenario. Nothing has been changed within the Military Road model. This scenario is used as a reference.

Scenario 2 incorporates a boost of bus capacity into the model. It has gone up from 80 to 130 pax/bus, corresponding to the capacities of some typical U.S. and Canadian BRT vehicles (Zimmerman and Levinson 2004). In order to remain coherent, the dimensions and some key features of the vehicles had to be adapted to meet this new rise in capacity: the length and width of vehicles, but also the number of doors and standings have thus been increased. By way of an example, length of buses has gone up from 12.2 meters to 24 meters. The number of doors has been changed for vehicles (and not for bus stands), so it is mainly the alighting process that is affected by this change.

Scenario 3 includes a rise in the number of stops served by bus services. Eight new stops have been created and added to the network. For all these new stops, if a stop is on the route of a bus service, then all the vehicles of this service have to serve this stop.

Scenario 4 integrates a change in traffic light phasing. The idea is to give more time to pedestrians accessing public transport to cross the roads, and to see the influence that this has on traffic. In order to do so, 20% of the time that public transport users have to wait at intersections before being able to cross the roads have been removed and put within the crossing time (thus it increases the proportion of crossing time for pedestrians accessing public transport, but the overall length of traffic light phase is held constant).

Scenario 5 incorporates the implementation of bus lanes on each side of the Military road. As their names indicate, these are lanes reserved for public transport, and are barred for all private vehicles. Since there are no bus lanes at intersections (bus lanes are implemented in a broken manner), there is no problem with cars willing to turn at intersections. They can just do so, after giving way to buses that keep going straight ahead.

Scenario 6 includes a drop in the headway between buses. The schedules of the different services have been changed in order to divide headways by approximately 2, thus increasing bus frequency.

Scenario 7 combines the drop in headways and the implementation of bus lanes, and is in fact a mixture of Scenario 5 and Scenario 6.

In Scenario 8, the demand for buses is much increased (it is multiplied by 4) with corresponding decrease in car demand so that the total demand applied on the network is held constant. Scenario 8 introduces in fact modal switch from private car to public transport.

Scenario 9 combines the previous changes in the demand (increase of bus demand and decrease of car demand), and a rise in bus frequency (like it is done in Scenario 6).

Scenario 10 is almost identical to Scenario 9, but instead of a rise in bus frequency, it is this time a rise in bus capacity, up to 130 like in Scenario 2.

Scenario 11 is again very similar to the two previous scenarios. It combines an increase of bus demand, a decrease of car demand and the implementation of bus lanes.

In the end, Scenario 12 is a mixture of several of the previous scenarios. It combines an increase of bus demand, a decrease of car demand, the implementation of bus lanes, and a boost in bus frequency and capacity. It enables a testing of the overall influence of some of the features that have just been tested separately

The following table recaps what the main changes are between the twelve investigated scenarios.

		Investigated Scenarios											
		1	2	3	4	5	6	7	8	9	10	11	12
Changed parameters	Number of stands			✱									
	Traffic lights				✱								
	Status of the lanes					✱		✱				✱	✱
	Demand								✱	✱	✱	✱	✱
	Bus Capacity		✱								✱		✱
	Bus Frequency						✱	✱		✱			✱

Table 3: Overview of the changes between the twelve investigated scenarios

As it can be noticed, Scenarios 8 to 12 introduce modal switch from private car to public transport and, as a result, the findings and analysis are divided into two parts: those which use the existing demand as shown by Scenario 1 as the baseline (Scenarios 2-8) and those which use Scenario 8 with the increase in public transport demand as the baseline (Scenarios 9-12).

Each of the scenarios considered here is linked to the dimensions of BRT systems identified by the literature as shown in Table 4 below.

Scenario	Dimension(s) investigated
1	-
2	Vehicles
3	Stations
4	ITS technologies
5	Running Ways
6	Service and Operating Plans
7	Running Ways, Service and Operating Plans
8	Network
9	Network, Service and Operating Plans
10	Network, Vehicles
11	Network, Running Ways
12	Network, Running Ways, Vehicles, Service and Operating Plans

Table 4: Dimensions studied in the different scenarios

Findings

The results are presented here for both time periods – the morning peak and the off-peak period. They are based on ten runs of the simulation program with half-hour lead in before collecting the results for the specified time periods.

ANOVA tests have been undertaken for a number of the outputs as discussed below. This is primarily as a number of the outputs described in Table 1 are composite measures. For Person Trips (PT), journey time is the sum of walking time, waiting time and riding time. For Public Transport Trips (PTT), transport time is a combined measure of moving time for buses and dwell time. Other measures such average speeds were noted but not tested as these are highly correlated with transport times as were mean emitted CO_2, NO and PM10 rates per vehicle with the number of stops in traffic per vehicle because the more a vehicle has to stop, the more it has to accelerate and brake, and subsequently the more CO_2 is emitted. For Private Vehicle Trips (PVT), the mean driving time and mean number of stops in traffic per vehicle were analysed as the emissions (CO_2, NO and PM10 rates per vehicle) are highly correlated with the number of stops in traffic per vehicle.

First simulation term: the morning peak (7 am – 9 am)

For each scenario, the measure from the Commuter output was compared with the appropriate baseline. For the ANOVA, a first consideration was whether a one-tailed or two-tailed test should be undertaken and this depended on whether there was an a priori view as to the direction of change. Table 5 shows the determination of the alternative hypotheses for Scenario 2, relative to the baseline of Scenario 1 for the selected measures, together with the p-values of the test.

	Measure	Determination of the alternative hypothesis	Alternative hypothesis H_1	p-value
PT	Mean journey time	Many interactions, hard to say whether it should decrease or increase	$\mu_1 \neq \mu_2$	0.1982
PTT	Mean transport time	Moving time should increase, bigger buses mean more interactions with the surrounding traffic	$\mu_1 < \mu_2$	8.55E-04**
	Mean dwell time per vehicle	Should decrease, bigger buses with more doors available for boarding/alighting mean reduced dwell time	$\mu_1 > \mu_2$	0.2970
	Mean number of stops in traffic per vehicle	Should increase, bigger buses mean more interactions with the surrounding traffic	$\mu_1 < \mu_2$	0.02541*
PVT	Mean driving time	Should increase, bigger buses mean more interactions with the surrounding traffic	$\mu_1 < \mu_2$	1.55E-06**
	Mean number of stops in traffic per vehicle	Should increase, bigger buses mean more interactions with the surrounding traffic	$\mu_1 < \mu_2$	8.05E-07**
*** significant at a 5% level, ** significant at a 1% level**				

Table 5: Statistical comparison of the scenarios 1 and 2 (Scenario 2: increasing bus capacity)

The mean transport time, the mean driving time and the mean number of stops in traffic per vehicle for both public transport and private vehicles rise significantly as a result of increasing the size of the buses which brings about more interactions between buses and private vehicles in comparison to the baseline of Scenario 1. The mean journey time does not change significantly suggesting that increasing the capacity of buses by itself is not beneficial to passengers.

	Measure	Determination of the alternative hypothesis	Alternative hypothesis H_1	p-value
PT	Mean journey time	More stops for buses mean longer in-vehicle time for passengers, but at the same time, more stops in the network may lead to shorter walking time for people. Outcome uncertain	$\mu_1 \neq \mu_3$	2.75E-11**
PTT	Mean transport time	Should increase, more stops for buses mean longer time spent at stops during the trip	$\mu_1 < \mu_3$	1.24E-10**
	Mean dwell time per vehicle	Should increase, more stops for buses mean more time in stopping, opening doors and starting to move, and thus longer dwell time	$\mu_1 < \mu_3$	7.99E-36**
	Mean number of stops in traffic per vehicle	Should increase, buses have to stop more often and thus more interactions with the surrounding traffic	$\mu_1 < \mu_3$	3.86E-27**
PVT	Mean driving time	Should increase, buses have to stop more often and thus disturb more the surrounding traffic	$\mu_1 < \mu_3$	1.50E-06**
	Mean number of stops in traffic per vehicle	Should increase, buses have to stop more often and thus disturb more the surrounding traffic	$\mu_1 < \mu_3$	2.11E-10**
* significant at a 5% level, ** significant at a 1% level				

Table 6: Statistical comparison of the scenarios 1 and 3 (Scenario 3: adding bus stops)

For Scenario 3, compared to the baseline, all the measures are statistically significant showing that the number of bus stops is an important parameter in the network. Indeed, the more bus stops there are, the longer the dwell times, leading to longer transport times and thus longer journey times for bus passengers. Moreover, the more bus stops there are, the more often buses have to stop during their trips, disturbing the surrounding traffic more as they do so leading to an increase in the mean number of stops in traffic per vehicle for both public transport and private vehicles as shown in Table 7. Along with this mean emissions rise sharply, highlighting how the number of stops of public transport services has to be well chosen for environmental reasons.

	Measure	Scenario 1	Scenario 3
PTT	Mean number of stops in traffic per vehicle	6.39	10.47
	Mean emitted CO_2 rate per vehicle (kg)	1.141	1.392
PVT	Mean number of stops in traffic per vehicle	2.77	3.00
	Mean emitted CO_2 rate per vehicle (kg)	0.369	0.374

Table 7: Comparison of some results obtained for the scenarios 1 and 3

Based on the results obtained for Scenario 3 and using SPSS software, correlations have been calculated for PVT between the mean number of stops in traffic per vehicle and the mean emissions. Table 8 shows these results.

		Mean number of stops in traffic per vehicle	Mean emitted CO_2 rate per vehicle (kg)	Mean emitted NO rate per vehicle (g)	Mean emitted PM10 rate per vehicle (g)
Mean number of stops in traffic per vehicle	Correlation coefficient (p-value)	1	0.736 (0.008**)	0.440 (0.102)	0.427 (0.109)
Mean emitted CO_2 rate per vehicle (kg)	Correlation coefficient (p-value)	0.736 (0.008**)	1	0.796 (0.003**)	0.545 (0.052)
Mean emitted NO rate per vehicle (g)	Correlation coefficient (p-value)	0.440 (0.102)	0.796 (0.003**)	1	0.704 (0.012*)
Mean emitted PM10 rate per vehicle (g)	Correlation coefficient (p-value)	0.427 (0.109)	0.545 (0.052)	0.704 (0.012*)	1
*** significant at a 5% level, ** significant at a 1% level**					

Table 8: Correlations between several outputs of Scenario 3 (PVT)

The mean number of stops in traffic per vehicle is correlated to the mean emitted CO_2 rate per vehicle at a 1% level of significance. Moreover, the mean emitted NO rate per vehicle is statistically linked to the two other mean emitted rates, either at a 1% level for CO_2 or at a 5% level for PM10. Thus, increasing the number of vehicle stops will also increase emissions and this is the reason why looking at the mean number of stops was chosen as a variable to monitor between Scenarios.

	Measure	Determination of the alternative hypothesis	Alternative hypothesis H_1	p-value
PT	Mean journey time	More time for pedestrians to cross the streets should lead to shorter waiting time, but at the same time it means that buses have to wait more time at intersections (longer in-vehicle time)	$\mu_1 \neq \mu_4$	0.4119
PTT	Mean transport time	Should increase, buses have to wait more time at intersections	$\mu_1 < \mu_4$	0.8011
	Mean dwell time per vehicle	Should not change	$\mu_1 \neq \mu_4$	0.7010
	Mean number of stops in traffic per vehicle	Should not change	$\mu_1 \neq \mu_4$	0.4866
PVT	Mean driving time	Should increase, cars have to wait more time at intersections	$\mu_1 < \mu_4$	0.8604
	Mean number of stops in traffic per vehicle	Should not change	$\mu_1 \neq \mu_4$	0.5298
*** significant at a 5% level, ** significant at a 1% level**				

Table 9: Statistical comparison of the scenarios 1 and 4 (Scenario 4: changing traffic lights)

In Scenario 4 where the traffic light phasing is changed to give more time to passengers walking to bus stops, the results suggest this does not lead to statistically significant changes with all measures unaffected by the change.

	Measure	Determination of the alternative hypothesis	Alternative hypothesis H_1	p-value
PT	Mean journey time	Should decrease because of shorter riding time (walk and wait time unchanged)	$\mu_1 > \mu_5$	0.0466*
PTT	Mean transport time	Should decrease, fewer interactions between buses and cars	$\mu_1 > \mu_5$	9.22E-08**
	Mean dwell time per vehicle	Should not change	$\mu_1 \neq \mu_5$	4.19E-04**
	Mean number of stops in traffic per vehicle	Should decrease, fewer interactions between buses and cars	$\mu_1 > \mu_5$	5.27E-05**
PVT	Mean driving time	Fewer interactions between buses and cars, but at the same time one lane is no longer available for cars to use	$\mu_1 \neq \mu_5$	2.13E-14**
	Mean number of stops in traffic per vehicle	Fewer interactions between buses and cars, but at the same time one lane is no longer available for cars to use (so perhaps more interactions between cars)	$\mu_1 \neq \mu_5$	1.82E-24**
*** significant at a 5% level, ** significant at a 1% level**				

Table 10: Statistical comparison of the scenarios 1 and 5 (Scenario 5: implementing bus lanes)

In contrast, the introduction of bus lanes on each side of the road in Scenario 5 brings about statistically significant changes in all measures, indicating the importance of this parameter. It makes mean transport time for public transport decrease, because buses are no longer in mixed traffic. The mean number of stops in traffic per bus is statistically significantly smaller. The lower interaction between public transport vehicles and private vehicles leads to an increase in the average speed of buses in comparison to the baseline which gives lower average journey times for bus passengers as shown in Table 11. Therefore, from customer and operator points of view, bus lanes are beneficial. Balancing this is the way in which private vehicle mean driving time is increased (as shown in Table 11) through losing one lane of road space.

	Measure	Scenario 1	Scenario 5
PTT	Average speed (km/h)	21.96	23.22
PVT	Mean driving time (h:mm:ss)	0:05:09	0:06:01

Table 11: Comparison of some results obtained for the scenarios 1 and 5

	Measure	Determination of the alternative hypothesis	Alternative hypothesis H_1	p-value
PT	Mean journey time	Passengers should wait less time at stops because of more frequent services, but at the same time it means more buses on the road and thus longer in-vehicle time (the more buses there are on the road, the more they disturb each other)	$\mu_1 \neq \mu_6$	0.0575
PTT	Mean transport time	Should increase (bus on bus congestion phenomenon), the more buses there are on the road, the more they disturb each other	$\mu_1 < \mu_6$	1.29E-09**
	Mean dwell time per vehicle	Should decrease, the more frequent buses are, the fewer people waiting to board at bus stops there are, and thus the shorter dwell times	$\mu_1 > \mu_6$	3.23E-28**
	Mean number of stops in traffic per vehicle	Should increase (bus on bus congestion phenomenon), the more buses there are on the road, the more they disturb each other	$\mu_1 < \mu_6$	0.3945
PVT	Mean driving time	Should increase, there are more buses likely to disturb car flows	$\mu_1 < \mu_6$	4.68E-07**
	Mean number of stops in traffic per vehicle	Should increase, there are more buses likely to disturb car flows	$\mu_1 < \mu_6$	1.11E-20**
*** significant at a 5% level, ** significant at a 1% level**				

Table 12: Statistical comparison of the scenarios 1 and 6 (Scenario 6: increasing bus frequency)

In Scenario 6, the increase in frequency of bus services gives rise to bus on bus congestion. The number of buses on the road is such that they are on each other's way, and the mean transport time rises. As there is no bus lane in this scenario to separate cars and buses flows, buses also disturb the surrounding traffic, and the mean number of stops in traffic for private vehicles increases too. But the mean journey time for bus passengers is not statistically different from the baseline value although the p-value at 0.057 is close to there being a statistically significant difference for the mean journey time at the 5% level.

	Measure	Determination of the alternative hypothesis	Alternative hypothesis H_1	p-value
PT	Mean journey time	Many interactions, hard to say whether it should decrease or increase	$\mu_1 \neq \mu_7$	0.00166**
PTT	Mean transport time	More buses on the road, so normally more disturbance in traffic flows, but at the same time implementation of bus lanes (so buses are no longer in mixed traffic)	$\mu_1 \neq \mu_7$	2.59E-04**
	Mean dwell time per vehicle	Should decrease, the more frequent buses are, the fewer people waiting to board at bus stops there are, and thus the shorter dwell times	$\mu_1 > \mu_7$	2.49E-29**
	Mean number of stops in traffic per vehicle	More buses on the road, so normally more disturbance in traffic flows, but at the same time implementation of bus lanes (so buses are no longer in mixed traffic)	$\mu_1 \neq \mu_7$	3.67E-06**
PVT	Mean driving time	More buses on the road, so normally more disturbance in traffic flows, but at the same time implementation of bus lanes (buses are no longer disturbing car flows)	$\mu_1 \neq \mu_7$	2.13E-14**
	Mean number of stops in traffic per vehicle	Should decrease, buses are no longer disturbing cars because of the bus lanes (and the increase in bus frequency should not have consequences on cars)	$\mu_1 > \mu_7$	9E-08**
*** significant at a 5% level, ** significant at a 1% level**				

Table 13: Statistical comparison of the scenarios 1 and 7 (Scenario 7: increasing bus frequency + implementing bus lanes)

Scenario 7, by including both bus lanes and increased frequency, shows all the measures are statistically significantly different from the baseline values. The mean transport time increases for scenario 7 in comparison to the baseline (which is not the case for Scenario 5), suggesting that the introduction of bus lanes is not sufficient to offset the disturbance created by the high number of buses.

	Measure	Scenario 1	Scenario 5	Scenario 7
PTT	Mean transport time (h:mm:ss)	0:04:25	0:03:39	0:04:51

Table 14: Comparison of mean transport time for the scenarios 1, 5 and 7

	Measure	Determination of the alternative hypothesis	Alternative hypothesis H_1	p-value
PT	Mean journey time	Should increase, because the number of passengers is multiplied by 4 (increased walking time: more on each other's way when they walk; increased riding time: increased dwell time because of the high demand)	$\mu_1 < \mu_8$	1.29E-22**
PTT	Mean transport time	Dwell time is much higher, but at the same time the car demand is reduced (so less disturbance between cars and buses)	$\mu_1 \neq \mu_8$	8.37E-21**
	Mean dwell time per vehicle	Should increase, because there are much more people willing to board or alight	$\mu_1 < \mu_8$	1.84E-21**
	Mean number of stops in traffic per vehicle	Should decrease, because car demand is reduced	$\mu_1 > \mu_8$	1.77E-12**
PVT	Mean driving time	Should decrease, because car demand is reduced	$\mu_1 > \mu_8$	1.14E-14**
	Mean number of stops in traffic per vehicle	Should decrease, because car demand is reduced	$\mu_1 > \mu_8$	0.05837
* significant at a 5% level, ** significant at a 1% level				

Table 15: Statistical comparison of the scenarios 1 and 8 (Scenario 8: increasing bus demand + decreasing car demand)

In Scenario 8, the demand for buses is much increased with corresponding decrease in car demand so that the total demand is held constant. For PTT this leads to a statistically significant increase in mean dwell time per vehicle, an increase in mean in-vehicle time and a statistically significant increase in mean journey time. Conversely, the mean driving time decreases significantly because of the number of private vehicles which is reduced in comparison to the baseline.

For Scenarios 9-12, Scenario 8 is treated as the new baseline reference point.

	Measure	Determination of the alternative hypothesis	Alternative hypothesis H_1	p-value
PT	Mean journey time	Many interactions, hard to say whether it should decrease or increase	$\mu_8 \neq \mu_9$	0.0706
PTT	Mean transport time	Should increase (bus on bus congestion phenomenon), the more buses there are on the road, the more they disturb each other	$\mu_8 < \mu_9$	0.03944*
	Mean dwell time per vehicle	Should decrease, the more frequent buses are, the fewer people waiting to board at bus stops there are, and thus the shorter dwell times	$\mu_8 > \mu_9$	5.84E-15**
	Mean number of stops in traffic per vehicle	Should increase (bus on bus congestion phenomenon), the more buses there are on the road, the more they disturb each other	$\mu_8 < \mu_9$	1.79E-10**
PVT	Mean driving time	Should increase, there are more buses likely to disturb car flows	$\mu_8 < \mu_9$	5.10E-04**
	Mean number of stops in traffic per vehicle	Should increase, there are more buses likely to disturb car flows	$\mu_8 < \mu_9$	0.02658*
* significant at a 5% level, ** significant at a 1% level				

Table 16: Statistical comparison of the scenarios 8 and 9
(Scenario 9: increasing bus demand + decreasing car demand + increasing bus frequency)

For Scenario 9, the results are similar to the comparison of Scenarios 1 and 6, with the exception of the mean number of stops in traffic per bus, which is now significant.

	Measure	Determination of the alternative hypothesis	Alternative hypothesis H_1	p-value
PT	Mean journey time	Many interactions, hard to say whether it should decrease or increase	$\mu_8 \neq \mu_{10}$	2.79E-08**
PTT	Mean transport time	Should increase, bigger buses mean more interactions with the surrounding traffic	$\mu_8 < \mu_{10}$	4.27E-08**
	Mean dwell time per vehicle	Should decrease, bigger buses with more doors available for boarding/alighting mean reduced dwell time	$\mu_8 > \mu_{10}$	0.1593
	Mean number of stops in traffic per vehicle	Should increase, bigger buses mean more interactions with the surrounding traffic	$\mu_8 < \mu_{10}$	2.72E-12**
PVT	Mean driving time	Should increase, bigger buses mean more interactions with the surrounding traffic	$\mu_8 < \mu_{10}$	6.42E-04**
	Mean number of stops in traffic per vehicle	Should increase, bigger buses mean more interactions with the surrounding traffic	$\mu_8 < \mu_{10}$	0.001052**
* significant at a 5% level, ** significant at a 1% level				

Table 17: Statistical comparison of the scenarios 8 and 10
(Scenario 10: increasing bus demand + decreasing car demand + increasing bus capacity)

Similarly for Scenario 10 where the increased capacity of vehicles does not appear to cope with the increase in demand so the mean journey time for passengers is, as compared to the comparison between Scenarios 1 and 2, statistically different from the baseline of Scenario 8.

	Measure	Determination of the alternative hypothesis	Alternative hypothesis H_1	p-value
PT	Mean journey time	Should decrease because of shorter riding time (walk and wait time unchanged)	$\mu_8 > \mu_{11}$	0.4441
PTT	Mean transport time	Should decrease, fewer interactions between buses and cars	$\mu_8 > \mu_{11}$	0.8905
	Mean dwell time per vehicle	Should not change	$\mu_8 \neq \mu_{11}$	0.04520*
	Mean number of stops in traffic per vehicle	Should decrease, fewer interactions between buses and cars	$\mu_8 > \mu_{11}$	9.2E-05**
PVT	Mean driving time	Fewer interactions between buses and cars, but at the same time one lane is no longer available for cars to use	$\mu_8 \neq \mu_{11}$	1.17E-05**
	Mean number of stops in traffic per vehicle	Fewer interactions between buses and cars, but at the same time one lane is no longer available for cars to use (so perhaps more interactions between cars)	$\mu_8 \neq \mu_{11}$	6.95E-10**
* significant at a 5% level, ** significant at a 1% level				

Table 18: Statistical comparison of the scenarios 8 and 11
(Scenario 11: increasing bus demand + decreasing car demand + implementing bus lanes)

The introduction of bus lanes in Scenario 11 gives statistically insignificant changes to mean journey time and mean transport time, as compared to the Scenario 8 reference point. This suggests that the introduction of bus lanes is not sufficient to reduce these measures, in the presence of higher demand.

	Measure	Determination of the alternative hypothesis	Alternative hypothesis H_1	p-value
PT	Mean journey time	Many interactions, hard to say whether the parameters should increase or decrease	$\mu_8 \neq \mu_{12}$	1.56E-04**
PTT	Mean transport time	Many interactions, hard to say whether the parameters should increase or decrease	$\mu_8 \neq \mu_{12}$	0.05705
	Mean dwell time per vehicle	Should decrease	$\mu_8 > \mu_{12}$	1.19E-15**
	Mean number of stops in traffic per vehicle	Many interactions, hard to say whether the parameters should increase or decrease	$\mu_8 \neq \mu_{12}$	4.44E-13**
PVT	Mean driving time	Many interactions, hard to say whether the parameters should increase or decrease	$\mu_8 \neq \mu_{12}$	2.40E-05**
	Mean number of stops in traffic per vehicle	Many interactions, hard to say whether the parameters should increase or decrease	$\mu_8 \neq \mu_{12}$	0.01109*
*** significant at a 5% level, ** significant at a 1% level**				

Table 19: Statistical comparison of the scenarios 8 and 12
(Scenario 12: increasing bus demand + decreasing car demand + increasing bus frequency and capacity + implementing bus lanes)

Scenario 12 includes modal shift to bus, increased bus frequency and capacity with bus lanes. All the measures, except mean transport time (although the p-value is close at 0.057), are statistically different from the values of the Scenario 8 baseline. As expected, the mean dwell time per vehicle decreases in a statistically significant way.

Table 20 recaps the full results for the morning peak.

	Person Trips		Public Transport Trips						Private Vehicle Trips			
	Mean journey time		Mean transport time		Mean dwell time per vehicle		Mean number of stops in traffic per vehicle		Mean driving time		Mean number of stops in traffic per vehicle	
	Hypothesis H_1	Value (p-value)	Hypothesis H_1	Value (p-value)	Hypothesis H_1	Value (p-value)	Hypothesis H_1	Value (p-value)	Hypothesis H_1	Value (p-value)	Hypothesis H_1	Value (p-value)
Scenario 1 (1st reference)	-	0:05:48	-	0:04:25	-	0:00:36	-	6.39	-	0:05:09	-	2.77
Scenarios 1-2	$\mu_1 \neq \mu_2$	0:05:58 (0.1982)	$\mu_1 < \mu_2$	0:05:02 (8.55E-04**)	$\mu_1 > \mu_2$	(0:00:36) 0.2970	$\mu_1 < \mu_2$	6.51 (0.02541*)	$\mu_1 < \mu_2$	0:05:27 (1.55E-06**)	$\mu_1 < \mu_2$	2.93 (8.05E-07**)
Scenarios 1-3	$\mu_1 \neq \mu_3$	0:06:44 (2.75E-11**)	$\mu_1 < \mu_3$	0:05:44 (1.24E-10**)	$\mu_1 < \mu_3$	0:01:24 (7.99E-36**)	$\mu_1 < \mu_3$	10.47 (3.86E-27**)	$\mu_1 < \mu_3$	0:05:36 (1.50E-06**)	$\mu_1 < \mu_3$	3.00 (2.11E-10**)
Scenarios 1-4	$\mu_1 \neq \mu_4$	0:05:44 (0.4119)	$\mu_1 < \mu_4$	0:04:27 (0.8011)	$\mu_1 \neq \mu_4$	0:00:36 (0.7010)	$\mu_1 \neq \mu_4$	6.37 (0.4866)	$\mu_1 < \mu_4$	0:05:10 (0.8604)	$\mu_1 \neq \mu_4$	2.78 (0.5298)
Scenarios 1-5	$\mu_1 > \mu_5$	0:05:40 (0.0466*)	$\mu_1 > \mu_5$	0:03:39 (9.22E-08**)	$\mu_1 \neq \mu_5$	0:00:35 (4.19E-04**)	$\mu_1 > \mu_5$	6.21 (5.27E-05**)	$\mu_1 \neq \mu_5$	0:06:01 (2.13E-14**)	$\mu_1 \neq \mu_5$	1.85 (1.82E-24**)
Scenarios 1-6	$\mu_1 \neq \mu_6$	0:06:00 (0.0575)	$\mu_1 < \mu_6$	0:05:50 (1.29E-09**)	$\mu_1 > \mu_6$	0:00:24 (3.23E-28**)	$\mu_1 < \mu_6$	6.45 (0.3945)	$\mu_1 < \mu_6$	0:05:53 (4.68E-07**)	$\mu_1 < \mu_6$	4.46 (1.11E-20**)
Scenarios 1-7	$\mu_1 \neq \mu_7$	0:06:04 (0.00166**)	$\mu_1 \neq \mu_7$	0:04:51 (2.59E-04**)	$\mu_1 > \mu_7$	0:00:24 (2.49E-29**)	$\mu_1 \neq \mu_7$	6.17 (3.67E-06**)	$\mu_1 \neq \mu_7$	0:05:54 (2.13E-14**)	$\mu_1 > \mu_7$	2.65 (9E-08**)
Scenarios 1-8	$\mu_1 < \mu_8$	0:17:22 (1.29E-22**)	$\mu_1 \neq \mu_8$	0:13:20 (8.37E-21**)	$\mu_1 < \mu_8$	0:01:52 (1.84E-21**)	$\mu_1 > \mu_8$	7.45 (1.77E-12**)	$\mu_1 > \mu_8$	0:03:25 (1.14E-14**)	$\mu_1 > \mu_8$	2.92 (0.05837)
Scenario 8 (2nd reference)	-	0:17:22	-	0:13:20	-	0:01:52	-	7.45	-	0:03:25	-	2.92
Scenarios 8-9	$\mu_8 \neq \mu_9$	0:16:57 (0.0706)	$\mu_8 < \mu_9$	0:14:25 (0.03944*)	$\mu_8 > \mu_9$	0:01:12 (5.84E-15**)	$\mu_8 < \mu_9$	8.69 (1.79E-10**)	$\mu_8 < \mu_9$	0:03:47 (5.10E-04**)	$\mu_8 < \mu_9$	3.22 (0.02658*)
Scenarios 8-10	$\mu_8 \neq \mu_{10}$	0:21:01 (2.79E-08**)	$\mu_8 < \mu_{10}$	0:16:52 (4.27E-08**)	$\mu_8 > \mu_{10}$	0:01:54 (0.1593)	$\mu_8 < \mu_{10}$	8.89 (2.72E-12**)	$\mu_8 < \mu_{10}$	0:03:53 (6.42E-04**)	$\mu_8 < \mu_{10}$	3.45 (0.001052**)
Scenarios 8-11	$\mu_8 > \mu_{11}$	0:17:41 (0.4441)	$\mu_8 > \mu_{11}$	0:13:22 (0.8905)	$\mu_8 \neq \mu_{11}$	0:01:55 (0.04520*)	$\mu_8 > \mu_{11}$	7.13 (9.2E-05**)	$\mu_8 \neq \mu_{11}$	0:02:56 (1.17E-05**)	$\mu_8 \neq \mu_{11}$	1.87 (6.95E-10**)
Scenarios 8-12	$\mu_8 \neq \mu_{12}$	0:19:02 (1.56E-04**)	$\mu_8 \neq \mu_{12}$	0:12:46 (0.05705)	$\mu_8 > \mu_{12}$	0:01:13 (1.19E-15**)	$\mu_8 \neq \mu_{12}$	9.10 (4.44E-13**)	$\mu_8 \neq \mu_{12}$	0:04:12 (2.40E-05**)	$\mu_8 \neq \mu_{12}$	3.23 (0.01109*)
*** significant at a 5% level, ** significant at a 1% level**												

Table 20: Statistical comparison of all the scenarios for the morning peak hours (first simulation term)

Journey time for passengers is a composite measure of walking time, waiting time and in-vehicle time. In order to have a clear insight into the point of view of customers, the mean journey time has been valued using the monetary values appropriate to the morning peak, as identified by the *National Guidelines for Transport System Management in Australia*, Australian Transport Council (Ockwell *et al.* 2006). These guidelines include a penalty for crowding with journey times for passengers with seats being multiplied by 1.3 and those without a seat by 2.0, thus recognising that crowded services 'cost' even seated passengers more. This penalty has the same value for all the scenarios, with the exception of Scenarios 2, 10 and 12, where the capacity of buses has been increased and the value of the penalty is therefore different. Table 21 presents the results.

Scenario	Mean journey time (h)	Mean journey time ($\$_{2006}$)	Mean weighted journey time ($\$_{2006}$)
1	0.0967	1.3878	1.3692
2	0.0994	1.5566	1.4877
3	0.1125	1.6151	1.5954
4	0.0956	1.3719	1.3531
5	0.0942	1.3519	1.3342
6	0.1003	1.4397	1.4191
7	0.1011	1.4516	1.4314
8	0.2894	4.1555	4.1075
9	0.2825	4.0558	4.0189
10	0.3503	5.4829	5.3518
11	0.2947	4.2313	4.1852
12	0.3172	4.9654	4.8472

* In-Vehicle Time (IVT) Valuation ($\$_{2006}$/h) = 9.97;
Crowded period valuation = x 1.44 IVT for all the scenarios (except for Scenarios 2, 10 and 12, valuation = x 1.57 IVT);
Walking time valuation = x 1.36 IVT and Waiting time valuation = x 1.41 IVT

Table 21: Weighted journey time for bus passengers trips in the morning peak ($\$_{2006}$)*

Table 21 shows that mean journey time and mean weighted journey time escalate for Scenario 8, revealing that bus passengers are really penalized by modal shift and the consequential increase in demand. However, passengers appear to benefit from bus lanes with the weighted value for the mean journey time for Scenario 5 is a minimum.

Second simulation term: the afternoon off-peak period (1 pm – 3 pm)

The results for the off-peak period are given in Table 22. These simulations relate to a time period where there is no congestion and the discussion of this section is both relative to the Scenario 1 and 8 baselines as in the previous section but also comparative between the peak and off-peak periods.

Increasing the capacity of buses (Scenario 2) has poor influence on the network during the off-peak period with no measure being statistically different from the baseline of Scenario 1. In contrast, adding new bus stops to the network remains an important parameter as almost all the criteria are significant for the comparison of the scenarios 1 and 3, except the measures for car drivers with the mean driving time and mean number of stops in traffic for private vehicles being not statistically significantly different from the baseline suggesting that on uncongested roads, private vehicles are less affected by public transport traffic.

	Person Trips		**Public Transport Trips**						**Private Vehicle Trips**			
	Mean journey time		**Mean transport time**		**Mean dwell time per vehicle**		**Mean number of stops in traffic per vehicle**		**Mean driving time**		**Mean number of stops in traffic per vehicle**	
	Hypothesis H_1	Value (p-value)	Hypothesis H_1	Value (p-value)	Hypothesis H_1	Value (p-value)	Hypothesis H_1	Value (p-value)	Hypothesis H_1	Value (p-value)	Hypothesis H_1	Value (p-value)
Scenario 1 (1st reference)	-	0:06:34	-	0:03:39	-	0:00:36	-	5.95	-	0:03:57	-	2.57
Scenarios 1-2	$\mu_1 \neq \mu_2$	0:06:34 (0.9656)	$\mu_1 < \mu_2$	0:03:40 (0.7868)	$\mu_1 > \mu_2$	0:00:36 (0.5375)	$\mu_1 < \mu_2$	5.90 (0.4202)	$\mu_1 < \mu_2$	0:04:01 (0.3912)	$\mu_1 < \mu_2$	2.57 (0.8887)
Scenarios 1-3	$\mu_1 \neq \mu_3$	0:06:51 (1.22E-05**)	$\mu_1 < \mu_3$	0:03:56 (3.56E-08**)	$\mu_1 < \mu_3$	0:00:41 (3.31E-18**)	$\mu_1 < \mu_3$	8.57 (7.94E-20**)	$\mu_1 < \mu_3$	0:03:52 (0.3311)	$\mu_1 < \mu_3$	2.57 (0.7551)
Scenarios 1-4	$\mu_1 \neq \mu_4$	0:06:33 (0.9770)	$\mu_1 < \mu_4$	0:03:40 (0.7975)	$\mu_1 \neq \mu_4$	0:00:36 (0.9840)	$\mu_1 \neq \mu_4$	6.01 (0.3133)	$\mu_1 < \mu_4$	0:03:56 (0.8427)	$\mu_1 \neq \mu_4$	2.57 (0.8506)
Scenarios 1-5	$\mu_1 > \mu_5$	0:06:29 (0.1059)	$\mu_1 > \mu_5$	0:03:18 (3.77E-09**)	$\mu_1 \neq \mu_5$	0:00:36 (0.5241)	$\mu_1 > \mu_5$	5.18 (6.33E-11**)	$\mu_1 \neq \mu_5$	0:02:51 (2.69E-11**)	$\mu_1 \neq \mu_5$	1.83 (1.02E-19**)
Scenarios 1-6	$\mu_1 \neq \mu_6$	**0:06:12 (1.67E-04**)**	$\mu_1 < \mu_6$	0:03:54 (5.24E-05**)	$\mu_1 > \mu_6$	0:00:23 (1.15E-26**)	$\mu_1 < \mu_6$	**6.23 (8.06E-05**)**	$\mu_1 < \mu_6$	0:04:05 (0.1213)	$\mu_1 < \mu_6$	2.64 (9.77E-04**)
Scenarios 1-7	$\mu_1 \neq \mu_7$	0:06:09 (3.70E-05**)	$\mu_1 \neq \mu_7$	0:03:30 (0.009056**)	$\mu_1 > \mu_7$	0:00:23 (9.11E-27**)	$\mu_1 \neq \mu_7$	5.54 (4.71E-06**)	$\mu_1 \neq \mu_7$	0:02:55 (4.77E-11**)	$\mu_1 > \mu_7$	1.94 (1.42E-18**)
Scenarios 1-8	$\mu_1 < \mu_8$	0:09:20 (3.18E-17**)	$\mu_1 \neq \mu_8$	0:05:34 (4.42E-19**)	$\mu_1 < \mu_8$	0:01:47 (2.09E-35**)	$\mu_1 > \mu_8$	6.38 (5.47E-07**)	$\mu_1 > \mu_8$	0:03:07 (1.86E-09**)	$\mu_1 > \mu_8$	**2.50 (0.002447**)**
Scenario 8 (2nd reference)	-	0:09:20	-	0:05:34	-	0:01:47	-	6.38	-	0:03:07	-	2.50
Scenarios 8-9	$\mu_8 \neq \mu_9$	**0:07:54 (7.42E-10**)**	$\mu_8 < \mu_9$	0:05:18 (2.52E-04**)	$\mu_8 > \mu_9$	0:01:02 (4.61E-31**)	$\mu_8 < \mu_9$	6.70 (1.22E-05**)	$\mu_8 < \mu_9$	0:03:31 (7.68E-10**)	$\mu_8 < \mu_9$	2.77 (3.40E-10**)
Scenarios 8-10	$\mu_8 \neq \mu_{10}$	0:09:25 (0.4863)	$\mu_8 < \mu_{10}$	0:05:39 (0.2166)	$\mu_8 > \mu_{10}$	0:01:47 (0.9377)	$\mu_8 < \mu_{10}$	6.46 (0.1693)	$\mu_8 < \mu_{10}$	0:03:12 (5.60E-05**)	$\mu_8 < \mu_{10}$	2.61 (4.09E-04**)
Scenarios 8-11	$\mu_8 > \mu_{11}$	0:09:22 (0.7591)	$\mu_8 > \mu_{11}$	**0:05:14 (2.22E-06**)**	$\mu_8 \neq \mu_{11}$	0:01:47 (0.7034)	$\mu_8 > \mu_{11}$	5.67 (3.69E-13**)	$\mu_8 \neq \mu_{11}$	0:02:39 (1.76E-20**)	$\mu_8 \neq \mu_{11}$	1.55 (1.38E-21**)
Scenarios 8-12	$\mu_8 \neq \mu_{12}$	0:07:50 (5.75E-09**)	$\mu_8 \neq \mu_{12}$	**0:05:04 (7.22E-07**)**	$\mu_8 > \mu_{12}$	0:01:02 (1.23E-31**)	$\mu_8 \neq \mu_{12}$	6.48 (0.1655)	$\mu_8 \neq \mu_{12}$	0:02:38 (1.65E-20**)	$\mu_8 \neq \mu_{12}$	1.56 (6.22E-21**)
*** significant at a 5% level, ** significant at a 1% level, in bold: values that are not significant for the first simulation term but that are significant here**												

Table 22: Statistical comparison of all the scenarios for the afternoon off-peak hours (second simulation term)

Table 22 shows that, as for the morning peak hours, the introduction of bus lanes brings about statistically significant improvements in mean transport time because bus services are no longer operating in mixed traffic. Mean driving time decreases for Scenario 5 (this contrasts with the morning peak results) and so removing one lane on each side of the road to implement bus lanes does not seem to affect car drivers in the off-peak, even if it means fewer lanes available for them.

	Measure	Scenario 1	Scenario 5
PVT	Mean driving time (h:mm:ss)	0:03:57	0:02:51

Table 23: Comparison of some results obtained for the scenarios 1 and 5

Increasing the frequency of bus services and changing the demand that is applied on the network turn out to be important parameters, as for the morning peak (Scenarios 6 and 8).

Mean weighted journey times for bus passengers have been calculated in the same way as for the morning peak and are presented in Table 24, although no penalty for crowding was applied as the off-peak is not considered to be subject to crowding. The smallest mean weighted journey time is obtained for Scenario 7, which is the alternative that combines an increase in bus frequency and the introduction of bus lanes, highlighting once again that these two parameters are relevant when analysing the Military Road network.

Scenario	Mean journey time (h)	Mean journey time ($\$_{2006}$)	Mean weighted journey time ($\$_{2006}$)
1	0.1092	1.0884	1.3031
2	0.1092	1.0884	1.3031
3	0.1144	1.1410	1.3579
4	0.1092	1.0884	1.3031
5	0.1078	1.0745	1.2923
6	0.1033	1.0302	1.2284
7	0.1022	1.0192	1.2193
8	0.1556	1.5509	1.7617
9	0.1319	1.3155	1.5023
10	0.1569	1.5647	1.7755
11	0.1561	1.5564	1.7691
12	0.1306	1.3016	1.4883

* In-Vehicle Time (IVT) Valuation ($\$_{2006}$/h) = 9.97;
Walking time valuation = x 1.36 IVT and Waiting time valuation = x 1.41 IVT

Table 24: Weighted journey time for bus passengers trips in the off-peak ($\$_{2006}$)*

Limitations of this case study

This case study contains some limitations that are as follows.

First, and because of time issues, each of the tested scenarios has only been run ten times. For such studies, simulations are usually run several dozens of times, in order to increase the accuracy of the results. Therefore, some of the figures provided in this work must be handled with caution, especially the p-values which are close from the level of significance. Additional runs of the simulations would have been desirable to correct some possible discrepancies.

As it is said earlier in the report, the pedestrians demand is set to zero for all the simulations, meaning that this study focuses on bus passengers (which is fundamental to have a customer point of view). Since pedestrians undertaking walk only journeys have been suppressed, this will lead to a loss of interactions between these trips and walk trips to access public transport. Although this will lead to a loss of interactions between walkers, it is likely to have more of an effect when there is higher modal shift towards public transport when, for example, there could be a higher level of interactions at road junctions for pedestrian crossings.

Two simulation terms and twelve distinct scenarios have been studied through Commuter, allowing several aspects of the Military Road system to be investigated. There are still some other features that have not been tested, and thus, it is likely that some aspects may not have been taken into account, perhaps bringing about some changes to the findings of this article. Moreover, the coded and calibrated network is a single corridor: to the extent that this corridor is special, the results cannot be generalised. However, the Military Road corridor is not particularly special and has the features that might be expected of any urban corridor, and it is believed that this is not too serious a limitation to the results.

Finally, there is no denying that microsimulation can provide results in an appealing and realistic way using its high level of detail. Nevertheless, slight changes in the model in comparison to the network in the 'real life' can lead to quite high discrepancies. This explains once again why it must be reminded that the previous results should be handled with caution, and may sometimes need to be qualified.

It must also be kept in mind that if models tend to be very similar to reality, they remain models and always contain some drawbacks, slight as they might be. And this can lead to discrepancies in comparison to reality.

Conclusions

The previous study analyses the influence of various parameters within the Military Road system using microsimulation. Two simulation terms have been tested, and for each term, twelve different scenarios have been investigated. These scenarios include the modification of some features in the network or the implementation of new ones. Here are several features that were studied through Commuter: the introduction of bus lanes, the demand applied on the network, the capacity and frequency of buses, the traffic lights, *etc.* Each of these features is linked to the dimensions of BRT systems identified in the literature. Therefore, the simulations allow the contribution of these dimensions to be checked.

The strength of the results comes from the examination of the three different points of view, namely a customer point of view, an operator point of view and a car driver point of view. This allows the advantages to different stakeholders of the setting up of a new design in the network to be estimated. The results show four parameters in particular appear to be very relevant: adding bus stops in the network, introducing bus lanes on each side of the road, increasing the frequency of bus services, and changing the demand applied on the model. For the scenarios including these features, most of the measures show statistically significant differences from the reference case. The feature that appears to make the biggest difference is the implementation of bus lanes within the network. As this separates public transport from other means of transport, such as cars, it makes traffic conditions easier for buses. From an operator point of view, this feature is advantageous but it is also important for passengers, as seen from the calculations of weighted journey times. For car drivers, the results are more mixed, and are affected by whether congestion is present as during uncongested periods, car drivers also benefit from the introduction of bus lanes in the network as this gives fewer interactions between cars and buses flows.

4 Acknowledgements

The authors would like to thank the Azalient's team, and more particularly Gordon Duncan, Gareth Millar and Chao Zhu for their assistance in the handling of Commuter. They also would like to acknowledge Roads and Maritime Services in providing access to the Military Road model.
Any omissions or errors are the responsibility of the authors.

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