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THE IMPACTS OF BUS LANES ON URBAN TRAFFIC ENVIRONMENT

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Licenciado em Engenharia Civil pela Faculdade de Engenharia da Universidade do Porto

DISSERTAÇÃO SUBMETIDA PARA SATISFAÇÃO PARCIAL DOS
REQUISITOS DE GRAU DE MESTRE EM

TRANSPORTES

Dissertação realizada sob a supervisão do

Professor Doutor José Pedro Tavares do Departamento de Engenharia Civil da Faculdade de Engenharia da Universidade do Porto

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RESUMO

A melhoria das condições operacionais do Transporte Público é um dos principais vectores a considerar no combate aos efeitos negativos associados ao congestionamento rodoviário em meio urbano. A implementação de corredores exclusivos para o transporte colectivo (corredores BUS) e a aplicação de medidas de prioridade junto das intersecções controladas por sinais luminosos constituem as abordagens mais testadas com vista a materialização desse objectivo (Waterson *et al.*, 2004; Jepson e Ferreira, 1999; Hounsell e McDonald, 1988).

A correcta avaliação dos impactes decorrentes da introdução de um corredor BUS deve considerar as alterações às condições operacionais de todos os modos de transporte considerando a área de influência do novo esquema. As diferentes metodologias para avaliação dos impactes assentam em comparações entre as condições operacionais para as situações “antes” e “depois”, variando os métodos para a quantificação dos mesmos. A selecção da metodologia está relacionada com o nível de fiabilidade e detalhe pretendidos, embora na sua maioria a aplicação seja restrita ao estudo do corredor.

Esta dissertação propõe uma metodologia geral para a avaliação dos impactes operacionais associados a esquemas rodoviários que consideram corredores BUS. A sua aplicação assenta na utilização de modelos de tráfego que permitirão a definição de uma área de influência relativa às áreas onde as principais alterações se farão sentir. O posterior processamento da informação para os cenários considerados permitirá agilizar o processo de tratamento das varáveis operacionais indispensáveis à avaliação final.

A metodologia proposta foi testada no estudo de um corredor BUS a implementar na Rua da Constituição na cidade do Porto. A avaliação pressupôs a modelação dos cenários relativos às situações “antes” (sem corredor) e “depois” (com corredor), sendo utilizados dois modelos de tráfego de características distintas: SATURN (modelo de afectação/simulação de tráfego) e DRACULA (modelo de microsimulação).

Os resultados permitiram salientar a importância da consideração de uma área de influência para a análise dos impactes operacionais em detrimento de uma avaliação apenas centrada nos resultados registados junto ao corredor BUS. Neste ponto, a consideração dos efeitos do redireccionamento de tráfego provocado pelo corredor BUS foram avaliados como determinantes nos resultados operacionais obtidos. Tal facto enalteceu a necessidade de utilização de modelos de tráfego na avaliação operacional de esquemas que consideram corredores BUS em ambiente rodoviário urbano, tal como previsto na metodologia proposta.

ABSTRACT

Improving the operational conditions for Public Transport appears to be one of the key aspects regarding the decrease in urban traffic congestion. The implementation of bus lane schemes and traffic signal priority are the most used solutions on this field (Waterson *et al.*, 2004; Jepson and Ferreira, 1999; Hounsell and McDonald, 1988).

For the bus lane case, a variety of methods can be used to assess the impacts and evaluate if the previewed benefits can overcome the expected disbenefits. They are based on the quantification of changes in operational indicators between the "before" and "after" scenarios. The application of these approaches is often limited to the analysis of the tested corridor, neglecting potentially important operational impacts on vehicles that circulate on the surroundings.

This dissertation proposes a general methodology for assessing the operational impacts caused by a bus lane scheme. The framework is based on traffic modelling tools and contemplates the definition of a study area for witch overall operational net changes should be quantified. Decision making regarding the operational feasibility of the tested scheme will be based on the comparison between the proposed operational indicators for the considered scenarios.

The proposed methodology was tested by modelling a hypothetical bus lane introduction in a major arterial street located in Porto (Rua da Constituição). Two scenarios, "without" and "with" bus lane, were developed and their operational results compared. The work considered two different traffic models, namely SATURN (assignment/simulation model) and DRACULA (microsimulation model).

The generalization of results highlighted the importance of considering a study area of analysis instead of the typical corridor approach. In this matter the traffic reassignment aspects were confirmed as a key aspect to be considered within the evaluation process. This fact enhanced the complexity of assessing bus lanes impacts on the urban traffic environment, reinforcing the importance of considering traffic modelling in the evaluation process.

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CHAPTER 1 – INTRODUCTION

1.1. BACKGROUND

The continuous increase in car travel over the past decades has been leading to the development of road congestion especially in the urban areas where the competition for road space is higher. The phenomenon is closely related with the changes in the urban land use and economic development, witch contribute to the raising car usage over the public transport.

In fact, over the last decades the urban mobility patterns are becoming less centrally orientated and the choice for a more flexible and reliable transport mode such as the private car has been gaining way. This situation leads to severe economic, environmental and social impacts, witch end up having direct influence on the deterioration on the community's life standards.

The public awareness on the effects of traffic congestion is pressuring the Transportation Local Authorities for ways to deal with the problem. Two main sorts of solutions have arisen:

- Expansion of road capacity through new construction;
- Promotion of public transport for enhancing modal change.

The first solution can solve congestion on a short/medium term horizon but heavily depends on the available financial resources as also on the physical possibilities for its implementation. Additionally, long term effects seem to favour the increase of car usage because if the operational conditions become more attractive the more traffic is likely to be generated, witch is clearly ineffective for breaking the congestion cycle.

The awareness of these limitations has centralized the role of public transport as a key factor to account when dealing with traffic congestion problems. The objective is to improve its attractiveness to consolidate a long term solution aiming modal shifting. Such improvements may contemplate new construction to improve the public transport network capacity to measures that enhance their operational conditions in comparison with the general traffic.

Buses play a very important role in public transport context once they can make excellent use of limited road space, carrying many more passengers than a private car for a given amount of road space. The main problem is that they usually share the road infrastructure with general traffic, getting equally affected by congestion.

On the other hand, the potential improvement of their operational conditions might be economically viable once it is most likely to induce savings in the system overall costs and passenger times. It is based on this principle that traffic planners study the implementation of bus priority measures, defined in the *Transit Capacity and Quality of Service Manual* (TRB, 2003) as: “a range of techniques designed to speed up transit vehicles and improve overall systems efficiency”. Examples of these measures are:

- Busways and freeways HOV lanes;
- Arterial streets bus lanes;
- Traffic signal priority;
- Site specific priority treatments (queue jumps, boarding islands, curb extensions, parking restrictions, turn restrictions exemptions, etc.);
- Transit operating measures (bus stop relocation, bus stop consolidation, skip-stop operation, platooning, design standards, etc.);

Along with the implementation of traffic signal priority, bus lane schemes are the most used solutions on this field (Waterson *et al.*, 2004; Jepson and Ferreira, 1999; Hounsell and McDonald, 1988). They consist in especial lanes dedicated to buses working as a queued jump device in congested road sections. The main objective is to improve operational performance of buses (travel time, speed and reliability) by providing congestion-free conditions to buses

Although the main potential advantages are identified, the fact is that is the bus lane scheme, as any other form of road space allocation usually implies tradeoffs among the road users. In road congested environments it is most likely that the possible impacts for buses will negatively affect general traffic. Thus, a bus lane scheme must be evaluated to assess if the predicted overall benefits exceed the disbenefits.

This research is focused on the evaluation of operational impacts induced by bus lane schemes and aims to contribute to the discussion regarding this subject.

1.2. OBJECTIVES

The main objective of this dissertation is to propose and test the applicability of a general framework based on traffic modelling to assess the time impacts caused by the bus lane schemes on an urban traffic environment. The methodology is based on two basic principals:

- The evaluation is made based on the comparison of time aggregated operational changes (provided by the model) between the “before” and “after” bus lane introduction scenarios;
- The size of study area must allow the quantification of time impacts for all traffic significantly affected (surrounding traffic) by the bus lane introduction.

Being a general framework it is expected that the range of applicability can be extended to a diversity of real-life schemes for the study of both contra and with flow bus lanes as well as for the operational evaluation and optimization of already implemented ones.

In order to pursue with the main objective some steps were followed enabling secondary objectives to be accomplished such as:

- Presentation of bus lanes as bus priority measure enhancing the main benefits and disbenefits, as well as the main influential factors for the evaluation process;
- Compilation of some documented studies regarding the evaluation of bus lanes in a urban environment;
- Definition of a methodology for the evaluation of bus lanes schemes;
- Application of the proposed methodology to the reality of an urban arterial street located in Porto, enabling conclusions based on operational changes to be drawn for an hypothetical implementation of a bus lane.

1.3. STRUCTURE OF THE DISSERTATION

This dissertation is organized six chapters in addition to this introductory one. The second chapter presents an overview of the main characteristics of the bus lanes (with and contra flow), enhancing their main advantages and disadvantages along with some important operational issues that can influence their applicability.

Chapter 3 summarizes the bibliographic review made on the bus lane evaluation approaches. A classification is proposed based on the main characteristics of the reported experiences. The section ends with a close up of the main advantages and disadvantages of each type of approach.

Based on those conclusions, Chapter 4 describes and justifies each phase of the general modelling methodology proposed for the evaluation of the bus lanes schemes. The methodology was based on the previous analysed methodologies and aims to overcome their main limitations.

Chapter 5 resumes the application of the proposed methodology to a real life scheme on an arterial street located in the city of Porto. Detailed results are presented and commented allowing conclusions to be drawn regarding the site specific conditions for the proposed bus lane scheme.

The main conclusions of the developed work are presented in Chapter 6, where especial emphasis is given to the capacities of tested framework for the study of bus lanes schemes.

Additionally, the relevant issues that were not assessed were pointed out once they might be relevant for the development of future studies regarding the subject.

CHAPTER 2 - BUS LANES CHARACTERIZATION

2.1. INTRODUCTION

This chapter is focused on the characterization of bus lanes. The presentation outlines the main objectives and applicability conditions of this bus priority treatment providing additional attention to some operational aspects that can be important to the overall performance of the scheme. The potential advantages and disadvantages provided by the with-flow and the contra-flow will be described enforcing the need for the application of an evaluation framework to quantify the main impacts regarding their implementation.

2.2. SCOPE

The previous chapter introduced bus priority measures as an important concept to consider for the improvement of operational conditions for buses. According to a bus lane study (Lunes and Willumsen, 1988) the Brazilian guidelines (EBTU, 1982) set the application range of these measures to whenever one of the following cases occurs:

- Average bus journey time, inclusive of delay and stops, is less than 20 Km/h;
- Average bus speed while vehicle moving is less than 30 km/h;
- Average bus delay at traffic signals or bus-stops is greater than 15 seconds;
- There is more than 20 percent difference between travel time at peak and at off-peak.

Note that these conditions relate to a reality where bus has a very strong importance in the transport system witch may implicate the difficulty of transposing these requirements to different operational standards.

The applicability of the each priority measure is related with the site operational and physical conditions as also with the characteristics of each measure. Table 2.1 shows the main characteristics present by the *Highway Capacity Manual* (TRB, 2000) for the most used bus priority treatments in the United States.

Table 2.1: Bus preferential treatments (TRB, 2000)

Treatment	Advantages	Disadvantages
Signal Priority	▪ Reduces delay; ▪ Improves reliability.	▪ Risks interrupting coordinated traffic signal operation; ▪ Risks lowering intersection LOS if intersection is close to capacity; ▪ Requires ongoing interjurisdiction coordination; ▪ Buses on cross streets may incur added delay greater than the time saved by the favoured route.
Queue Bypass	▪ Reduces delay from queues at ramp meters or other locations	▪ Bus lane must be available and longer than the back of the queue
Queue Jump	▪ Reduces delay to queues at signals; ▪ Buses can leapfrog stopped traffic.	▪ Bus lane must be available and longer than the back of the queue; ▪ Right-turn or special transit signal required; ▪ Reduces green time available to other intersection traffic; ▪ Bus drivers must be alert for the short period of available green time.
Curb Extensions	▪ Reduces delay due to merging back into traffic; ▪ Increases ridding comfort because buses don't need to pull in and out of stops; ▪ Increases on-street parking by eliminating need for taper associated with bus pullouts; ▪ Increases space for bus stop amenities ▪ Reduces pedestrian street crossing distances	▪ Requires at least two travel lanes in bus direction of travel to avoid blocking traffic while passengers board and alight; ▪ Bicycle lanes require special consideration.
Boarding Islands	▪ Increases bus speed by allowing buses to use faster-moving left lane.	▪ Requires at least two travel lanes in bus direction and significant speed difference between the two lanes; ▪ Requires more right-of-way than other treatments; ▪ Pedestrian and ADA accessibility, comfort and safety issues must be carefully considered.
Parking Restrictions	▪ Increases bus and auto speeds by removing delays caused by automobile parking manoeuvres.	▪ May significantly impact adjacent land uses (both business and residential); ▪ Requires ongoing enforcement.
Bus-Stop Relocation	▪ Uses existing signal progression to bus advantage	▪ May increase walking distance for passengers transferring to a cross street bus
Turn Restriction Exemption	▪ Increases bus speed by eliminating need for detours to avoid turn restrictions	▪ Potentially lowers intersection LOS; ▪ Safety issues must be carefully considered.
Exclusive Bus Lanes	▪ Increase bus speed by reducing sources of delay; ▪ Improves reliability; ▪ Increases transit visibility,	▪ Traffic and parking effects if eliminating a travel or parking lane must be carefully considered; ▪ Requires ongoing enforcement.

Note that each measure is associated both with possible advantages and disadvantages. This fact reinforces the need for a careful evaluation procedure to select the most adequate treatment for the local operational characteristics.

The correct evaluation of the base situation should be obtained as possible through direct data collection. This procedure should enclose the collection of geometric data (lengths, number of lanes, widths, etc.), as well as traffic data (traffic flows for buses and general vehicles, journey times, maximum queues lengths, diversion possibilities, etc). Additionally, and depending on the detail of the evaluation procedure to be used, some other type of information (e.g.: accident rates, information on pedestrians, etc.) may be requested.

Bus lanes represent a perfect example of a bus preferential treatment. According to Martins (1975) the main objectives of their implementation are:

- Reduction in bus travel times;
- Improvement of bus service reliability;
- Increase in passenger safety;
- Increase in bus service visibility;
- Reduction of the operating costs.

While the advantages of the bus lanes seem clear, the choice for their implementation among others bus priority measures is not such a well discussed question in the consulted bibliography. In fact, the specificity of each case does not facilitate the establishment of general standards for guidance on the subject. In order to restraint this difficultly it is essential for planners to perform a good evaluation of the existing operational conditions and also be fully aware of the characteristics of the available bus priority measures.

In a work for applying bus priority in the city of London, Allen (1973) refers that the implementation of bus lanes should acknowledge the following points:

- Give significant advantage to buses;
- Not seriously reduce traffic capacity or cause secondary congestion by developing excessive queues;
- Give a net benefit to the community and should have a reasonable cost/benefit ratio;
- Be easy to enforce;
- Frequency and occupancy of buses should be high enough to encourage compliance by other drivers;
- Practicable to prohibit waiting and loading during the hours of operation of the bus lane;
- Not increase accident potential;
- Minimise any detriment to environment;
- Have sufficient life prior to being superseded by redevelopment or other changes in the situation.

These criteria reflect a clear concern that the main objectives of the bus lanes are accomplished with a maximum overall benefit, i.e., minimizing the impact on the surrounding traffic environment. The knowledge of the main characteristics of each type of bus lanes is essential to the pursuing this goal and will be related in the next sections.

2.2. TYPES OF BUS LANES

2.2.1. WITH FLOW

With flow bus lanes are reserved facilities for buses travelling in the same direction as the normal traffic (Figure 2.1). Occasionally, other vehicles, usually taxis and emergency vehicles are allowed to use this facility.

They work essentially as queue jump devices and should allow buses to bypass queues formed by traffic bottlenecks responsible for the congestion.

As shown in Figure 2.2 three major design features have to be accounted in the with-flow bus lanes:

- A tapered entry to the bus lane to provide a smooth transition in the number of available lanes for the general traffic;
- Physical separation, normally a continuous white lane or raised kerb separation, between the bus lane and the other lanes;
- The bus lane might be interrupted some distance from the stopline of the downstream junction providing a setback. This element may be used also by general traffic and as the double function of allowing right turn movements and avoiding capacity lost on the downstream signalized junction.

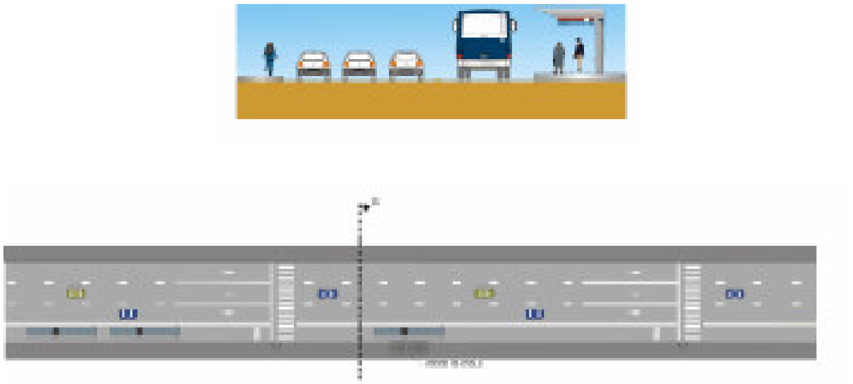


Figure 2.1: With-flow bus lanes (SEDU/PR and NTU, 2002)

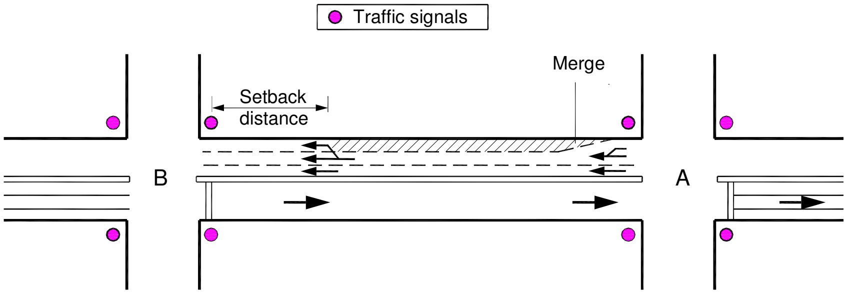


Figure 2.2: With-flow bus lanes major design features

2.2.1.1. Potential advantages

As bus lanes represent a classic example of a bus priority measure, the main resulting benefits from the scheme implementation will reflect on improvements of their operational conditions. The most expected changes are engaged with the following items:

- Travel time reductions: bus lanes work as “queue jump” device that allows buses to pass other queuing vehicles travelling in the same congested road. Along with this feature, the “free running” conditions provided by the vehicle segregation may allow buses to increase their average speed and consequently reduce travel times. For the general traffic some travel time benefits may also occur although these are normally lower when compared with effects for buses. The less friction between vehicles and the needless to stop or overtake buses at bus stops is among the most influent factors regarding this advantage;

- Gain in reliability: the existence of an exclusive lane makes bus travel times less depend on local congestion, allowing decreases in the variation of travel times and by that an improvement in bus reliability. This fact will directly improve the bus quality of service, materialized on the level of comfort felt by bus passengers at bus stops (less uncertainty on the arrival time) and inside the bus (less need of high accelerations and decelerations). Additionally, the bus operator can also benefit directly once more reliable bus travel times may help improve the fleet management and operations, allowing fewer buses needed to provide the same service;

- Energetic and environmental gains: the improvements in travel time may lead to lower operating times for buses and consequently to a decrease in fuel consumptions. The contribution free-of-congestion conditions for buses may also be significant on this matter, once the constant stop-and-go operations are the most penalizing. The environmental aspect is directly connected with this fact once the main impacts are related with pollutant emissions that potentially will decrease with the bus lane introduction;

- Modal shift: the better operational conditions predicted to buses will hopefully make them a more attractive mode to the road users and so modal shift is more likely to occur. The possible reduction in traffic congestion and the increase of revenues by the bus operator will be the direct benefits of this change. The visibility of a bus lane may also have significant promotional effect on the passenger's perception for the advantages of buses when compared with the private car and positively contribute to the desired modal shift.

2.2.1.2. Potential disadvantages

In opposition to the previous point the potential disadvantages are clearly more severe to the general traffic operational conditions. The negative impacts for buses are, at least in the section of the bus lane, minimal. Nevertheless, it must be remarked that the level of congestion caused by the bus lane, may deteriorate the operational conditions for buses in the surroundings. The remaining most pointed disadvantages are:

- Travel times increases: the bus lane schemes usually impose the reduction of the stacking capacity witch will lead to an increase of average queue lengths and car delays near signalized intersections. The consequences may be more severe if there if the queue passes the upstream junction of the road once this will be reflected in the increase of travel times for general traffic and well as buses operating in the affected area. The level of these impacts will depend on the traffic demand as also on some other operational aspect that can be considered to attenuate the negative impacts;

- Deterioration of operating conditions in the surrounding area: traffic re-assignment that might occur in response to the operating changes may lead to increasing delays on the competing roads. The magnitude of this phenomenon varies with the existing possibilities for diversion witch make it very much site specific;

- Safety: in the case of with flow bus lanes, this factor is more connected with the existence of boarding island for the medium bus lanes or the level of information (especially at an early stage) that drivers and pedestrians have of the new scheme.

- Logistical changes: as most frequent type of bus lanes are right sided, they are often implemented by converting previous parking lanes. If so, there is an effective lost in parking provision. Another problem to be accounted might be the loading and unloading that supports the commercial activity and the access provision to properties.

- Implementation costs: Costs involving the studies, the construction works and the operation (e.g.: illegal use reinforcement) of the bus lane have to be considered, however their importance is again very much depend of the scheme and the type of bus lane to be introduced. Note that the implementation costs can be relatively low when compared with some other bus priority measures (e.g.

2.2.2. CONTRA-FLOW

Contra flow bus lanes are reserved facilities for buses in the opposite direction of the normal traffic flow (Figure 2.3).

The main objective of this type of lanes is to avoid diversions caused normally imposed by one-way systems. They both (with and contra) potentially provide bus journey time improvements but the contra flow bus lane adds the advantage of shorter distances to buses when compared with the general traffic.

Similarly to the design of the with flow lanes, the contra flow bus lanes must be segregated from the remaining traffic by means continuous (single or double) line painted or raised kerb solution. The remaining design features are mainly related are related with the necessary junction's re-arrangements (Figure 2.4).

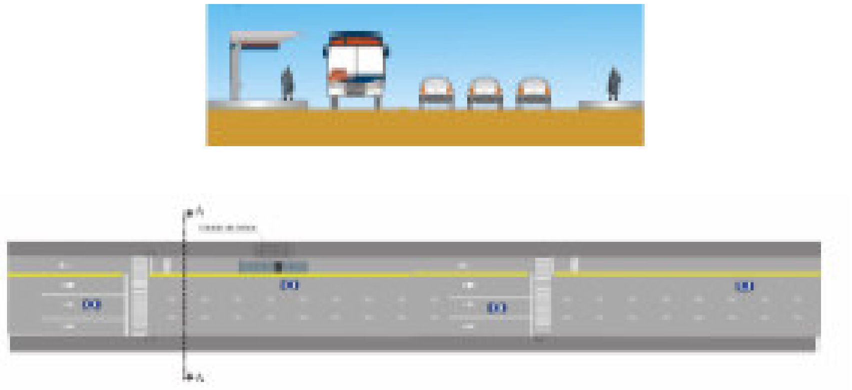
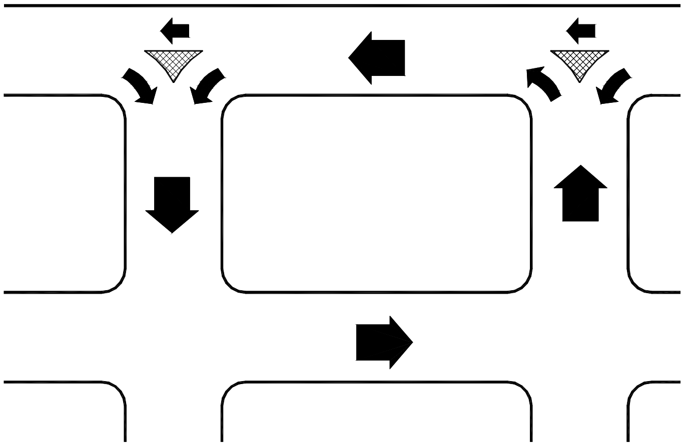
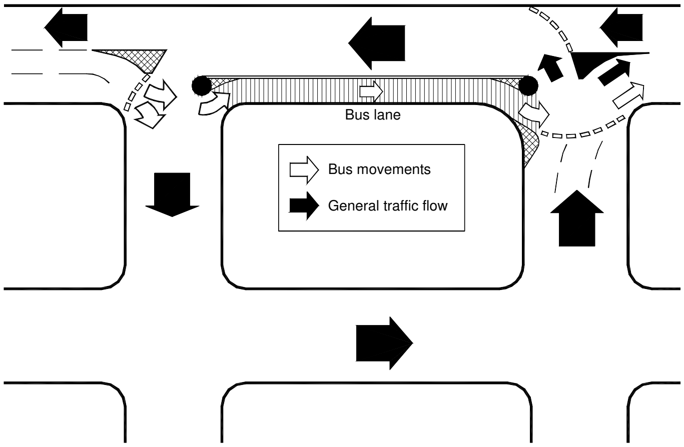


Figure 2.3: Contra-flow bus lane (SEDU/PR and NTU, 2002).



a) one-way system without bus lane



b) One-way system with contra-flow bus lane

Figure 2.4: Example of a contra-flow bus lane scheme (OTAN, 1976).

2.2.2.1. Potential Advantages

The potential advantages of the contra-flow bus lanes are similar to the ones already identified for the with-flow ones. The following aspects represent the more specific advantages:

- Travel times reductions: this type of advantage is theoretically more evident in the case of contra bus lanes because they allow buses to skip lengthily diversions. As normally contra bus lanes are implemented in one-way schemes the differences between bus and general travel times tend to be more accentuated especially because is the route length is shorten. Some time gaining for general traffic might also be reported due to the less interference by buses (bus stops, lower speeds, etc.) in their routes. The possible reduction in passenger walking time to the bus stop might also be achieved.

- Service perception: the majority of contra flow bus lane is introduced along with the conversion of general traffic schemes into one-way ones. In these cases, the bus lane allows the maintenance of both direction of the street on a bus route, enhancing a simpler comprehension of the bus service by users. Additionally, the fact of operating 24h a day can be seen as an extra promotional factor regarding the enhancement of the advantages of public transport use.

- Lower level of enforcement: the danger of using the contra bus lanes as an alternative route or as an (illegal) parking option more evident, witch may imply less level of enforcement needed.

2.2.2.2. Potential Disadvantages

The main disadvantages of the contra flow bus lanes are mainly due to changes in the junctions that may deteriorate the circulating conditions for the traffic running in the opposing direction of the new scheme. The most important aspects to consider might be:

- Travel time increases: the implementation of contra bus lanes usually require structural (lane conversion, introduction of traffic lights, etc,) and operational (retiming and phase changes, permitted turns, etc.) changes at the intersections. These requirements often result in extra delays for the general traffic (or buses travelling in the same direction) because the junction capacity is influenced. This negative effect is obviously extensive to the buses operating in the same way of the general traffic. Although a lower extent, the lost of effective “width” in the general traffic lane next to the bus lane might also have a residual impact on the operating speeds.

- Safety issue: again the safety issue is again mostly related with the knowledge of the network by the different road users. Pedestrians are the most vulnerable group and special measures regarding information and physical arrangements (e.g. introduction of traffic signals for pedestrian crossing, crossing islands, etc.) must be a part of the implementation scheme. As for buses and general traffic, rearrangements (traffic signal, extra signalization, horizontal marks, etc.) near intersections should minimize the risk of accident caused by the introduction of new conflicts.

- Costs: the possible reappearance of conflicting movements previously abolished with the introduction of the one-way scheme may require some level of rearrangements especially in the junctions. These changes usually concern introduction of traffic lights, channelling works, re-signing and road painting works that will certainly increase the implementation costs.

- Loading/Unloading operations: these operations are more difficult in the case of a contra flow bus lane. This fact is highlighted by the difficulty of considering a peak hour schedule for this type of lanes witch enables delivery vehicles to operate. This problem might be abbreviated if the possibility transferring deliveries to adjacent streets or even accounting special parking places for these vehicles on the kerbside of the general traffic lanes is viable.

2.2.3. DESIGN AND OPERATION

The introduction of a bus lane implicates tradeoffs between all the road users. Their implementation depends on rearrangements made on the road system that might be:

- Re-designating an existing travel lane as a bus lane;
- Narrowing existing lanes to provide an additional lanes;
- Widening the street to add a new lane;
- Restricting on-street parking (part-time) or full-time) to provide a bus lane.

The resulting effects will hopefully help the buses travelling on the bus lane corridor to improve their operational performance (time journeys, speeds and reliability), but the remaining general traffic might experience opposite effects. To attenuate these negative impacts there are some design and operational issues that should be considered when planning a bus lane and might represent an extra characterization element. Some of these issues are:

Side of the bus lane: The most usual type of bus lanes is located on the right side (left-side in the United Kingdom) lane. Nevertheless, the use bus lanes located on the right side (medium bus lanes) might be justifiable under certain operational condition (e.g.: cases where the buses have to make a left turns) (Figure 2.5). Note that this type of bus lanes require special regards on the loading and unloading of bus passengers, and so there must be enough road space to allow the provision of boarding islands or the utilization of specially adapted buses to allow this operation to be made on the left side must be considered.

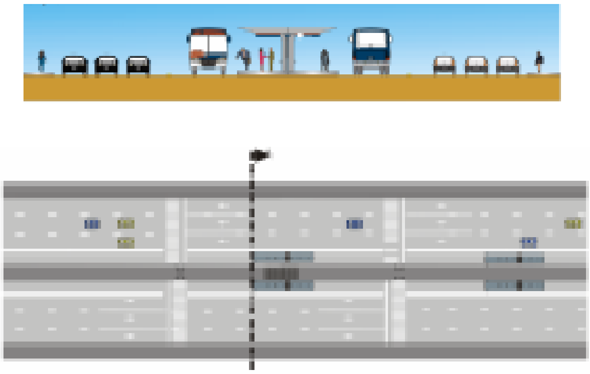


Figure 2.5: Medium bus lanes (SEDU/PR and NTU, 2002).

Provision of setback: The provision of setback is extremely important in maximising the benefits which can be achieved once it can be a key aspect prevent significant junction capacity losses and this way avoiding extra queuing. A significant number of studies (Oldfield et al, 1977; OTAN, 1976, Lunes and Willumsen, 1988; Jepson and Ferreira, 1999) have dedicated their efforts on calculating the "optimum setback" for a number of operational conditions. The length of the setback can make an appreciable difference to the benefits to be obtained from a bus lane, once if it is too short the capacity of the junction is lost and queuing is likely to appear. On the other hand, if the setback is too long no capacity is lost but buses might not pass the first green.

Figure 2.6 presents the relation between the level of saturation of the junction and the ideal setback for two packing factors considered (ratio between number vehicles using the setback and maximum number of vehicles that can do it). For practical reasons a number close to two times the effective green time (2g) might be a good approximation to the value of the "optimum setback", although close post-implantation analysis might advice later changes (OTAN, 1976).

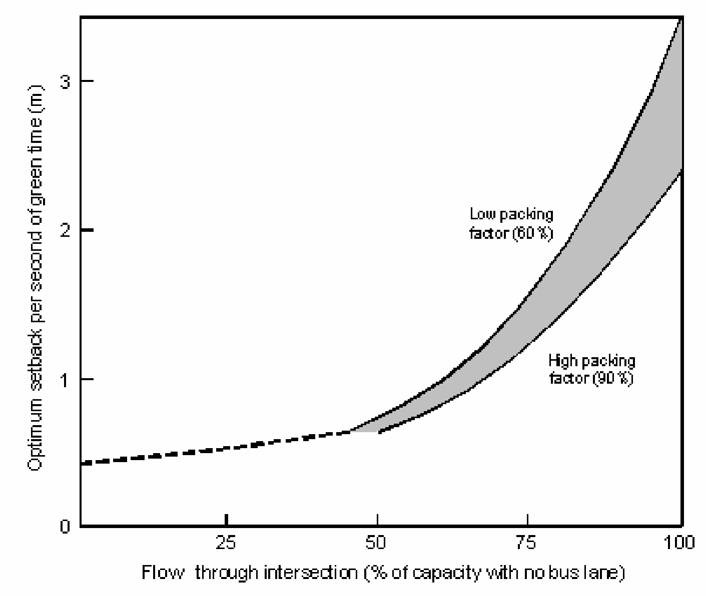


Figure 2.6: Optimal setback of a bus lane (OTAN, 1976).

Operation schedule: it as been argued that the justification of bus lanes is dependable of the level of traffic congestion as also the level of bus demand on the studied corridor. This way, some bus lanes only operate during peak-hour and work as general traffic lanes or parking lanes in the remaining time as Figure 2.4 shows. This might be seen as an advantage where operational conditions and bus demand do not justify the bus lane consideration, although most local authorities prefer to maintain the bus lane on 24h schedule. The main reasons for this option are:

- Maintain the service visibility and promote public transport;
- Avoid extra signalization and/or alteration of design features (ex: traffic lights), especially for the cases where other bus priority measurers have been implemented like bus-only turns or priority at signalized junctions;
- Avoid additional reinforcement costs especially because of the period before the operating schedule (e.g. parked cars in the bus lane).

Figure 2.7: Full time bus lane in Portland and part-time bus lane in San Francisco (TRB, 2003).

In the case of contra flows bus lanes this is particularly difficult because the safety risks are bigger and the changes in the junctions are usually not very adoptable.

To deal with the problem of possible disbenefits that traditional bus lanes schemes may bring to the general traffic some emerging new concepts, relying on the use of Intelligent Transport Systems (ITS), have arisen and are being tested.

The first one are the Intermittent Bus Lanes (IBL) (Viegas and Lu, 1997) witch are defined as: “lane witch the status of a given section changes according to the presence or not in its spatial domain”. This way the referred lane changes its status to “bus lane” only if a bus is detected using available Automatic Vehicle Detection (AVL) on the upstream section. When it occurs, the longitudinal lights on the road pavement separating the IBL from the remaining lanes turn “on” and no general traffic is not allowed to enter the IBL, promoting free of congestion conditions for the coming bus.

Another emerging concept is called BLIP – Bus Lanes with Intermittent Priority (Eichler, 2005). The solution is similar to the IBL in most of the conceptual background, although once the bus is detected the general traffic using the BLIP must leave. This way, BLIP does not have to use especial traffic signal to “flush queued vehicles from the paths of buses” and becomes a “easier and less expensive to implement”.

Allowance to use by other vehicles: the definition of the type of vehicles allowed to use the bus lane might another distinguishing factor in to their characterization. The emergency vehicles are perhaps a well accepted permission, but the use of the bus lane by taxis and High Occupancy Vehicles (HOV’s) is somewhat more doubtable and might require special evaluation. Thus if these flows are high, the primary objective of the bus lane might not be accomplishable. On the other hand, if the bus flows are to low to justify a bus lane, these permissions might help in increasing the overall benefits of the measure and public acceptance of the new scheme.

2.3. CONCLUDING REMARKS

This chapter presented the main characteristics of the bus lanes within the scope of the bus priority measures. The operational benefits of their implementation can be significant for buses especially in highly congested road environments. On the other hand, it is precisely in these conditions that the major disbenefits of this solution are more likely to occur.

In order to deal with this problem, the magnitude of these impacts should and must be assessed to correctly evaluate if the introduction of the bus lane will bring overall benefits.

The evaluation should be performed before the implementation aiming the quantification of the main advantages and disadvantages of the tested scheme based on collected data field. Note that in spite of the dominant time related aspects, and as shown in this chapter, the implementation bus lane can involve other aspects that should also be apart of the evaluation process. The consideration of some design and operational features might help minimize the disbenefits and enhance the viability of the proposed bus lane scheme.

Additionally, a monitoring procedure is essential to evaluate if the predicted results correspond to the expected ones. This procedure will allow the detection and correction of possible problems that were not predicted or misjudged in the pre-evaluation.

The methodologies available to perform the evaluation of impacts due to a bus lanes scheme will be discussed in the next chapter with especial focusing on the quantification of the operational aspects.

CHAPTER 3 – EVALUATION OF BUS LANES

3.1. INTRODUCTION

The previous chapter has shown that the problem of bus lane introduction requires an evaluation process to assess whether the scheme will guarantee overall net benefits. To reach this goal it is necessary to quantify and compare the main tradeoffs among the several road users.

This chapter is a bibliographic review of the approaches used in these cases with a deliberate emphasis on the methods to assess the travel time changes. The justification for this choice is based on the following assumptions:

- Time changes are the most direct impact on bus and car users and the most pointed aspect to justify a bus lane;
- Time changes are the monetary dominant aspect in the overall economic evaluation (Currie, 2004 and Webster and Bly, 1979).

The approaches presented were classified into different groups regarding the methodology used for the quantification of the operational indicators. The task revealed not to be a clear-cut issue, once common characteristics and complementarity's between the methods were found. Anyway it was able to identify three major classes:

- Field Studies;
- Non-modelling approach;
- Modelling approach.

Additionally, a small presentation of the main aspects regarding the economic evaluation and other additional studies is made to demonstrate that, although time related issues are the most significant aspects to the evaluation process, there other impacts that should be accounted within the evaluation of a bus lane scheme.

3.2. FIELD STUDIES

Probably the most straightforward way to evaluate the impacts of a bus lane is by using field measurements. The main objective of these studies is to compare the “before” and “after” bus lane implementation situations, by analysing the changes in key measures of performance (usually average journey times or speeds).

The application of this approach involves the risk of testing traffic schemes in a “real life” situation, witch in fact can be quite unreasonable in a highly congested traffic environment.

The awareness to this fact has assigned this method to the role of the last evaluation to be made after a rigorous pre-implementation project containing the quantification of the expected impacts. Hence, besides providing important results for the evaluation and monitoring of the bus lane scheme, these studies can also be used to evaluate the efficiency of the techniques used in the pre-implementation project.

This section will expose some studies that relied largely on field measurements and their main conclusions were obtained through the comparison of the same variables for the “before” and “after” situations. No mention is made to the methodology used for the estimation of results and selection of alternatives prior to the implementation of the bus lane scheme, although regarding the importance of their implementation area (typically central city areas), it is presumed that some sort of pre-evaluation was proceed.

The Madison Avenue Dual width-flow bus lane project held in New York in 1981 (Schwartz, S. *et al.*, 1982) is one of the most emblematic studies in the field. The project objective was the conversion of 0.85 miles of the avenue design from a 4 general traffic lanes to a 3 general traffic + 2 “right side” bus lanes as illustrated in Figure 3.1.

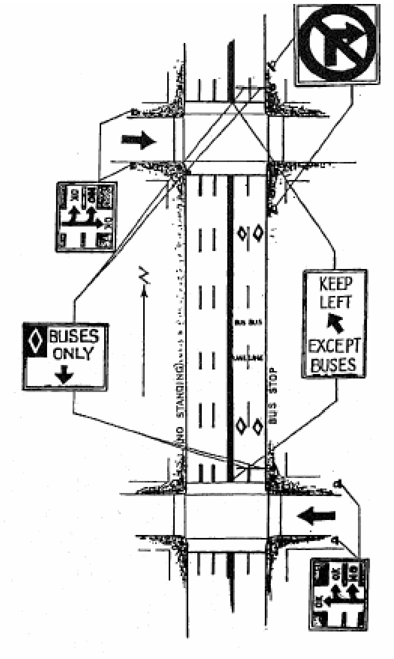


Figure 3.1: Madison Avenue dual bus lane scheme (Schwartz, S. *et al.*, 1982)

The bus lane scheme was valid for weekdays in the afternoon period (2:00 to 7:00 p.m.) and was introduced after a bus stop relocation and parking banning. A public information campaign was held along with the creation of new reinforcement teams specifically for the project.

Field surveys that were held for the "before" and "after" scenarios helped drawing some conclusions:

- the impacts on bus performance during the peak-hour were very significant, as stated in the average travel time reduction by 45% (from 18 to 10 minutes) and average speed increased by 83% (2.9 to 5.3 mph);

- Bus reliability, assumed as "an even more important effect" than the latest, was assessed by means of standard deviation of their travel times. Results showed reductions greater than 50% for both express and local buses;

- The impacts on the general traffic was assessed by measures of the speeds and volumes, witch both increased by 10% in the peak-hour. The problem of probable traffic reassignment was approached by making field measurements on the nearby parallel avenues, witch indicated insignificant changes in terms of average speed and volumes.

Another fine example of a field studies to evaluate the introduction of a bus lane was held in Bangkok (Tanaboriboon, 1983). Bus and car travel changes and their variability were surveyed for the "before" and "after" implementation periods in sections of 4 different "peak hour operating" bus lanes that represented a small part of an overall 95 km bus priority network.

Results claimed a general improvement in bus travel time (time saved varied from -0.4% to -47%) and reliability significantly decreased in the majority of the cases. Car travel times had a wider range of results: times raised in one scheme (+90%) but had opposite behaviour in the other study areas with a variable decreasing (from -3.0% to -27.6%). The unsuccessful exception was attributed to the existence of many secondary streets, site operational standards and local traffic conditions.

An impact study held in a 3 Km arterial downtown Toronto (Shalaby and Soberman, 1994) suggests that bus mean travel times "decreased significantly" with no automobile time impact, both in the arterial street and surrounding streets. The work explored the fragility of an impact study relying solely on bus total travel time and proposed an analysis segment by segment based on the variation of two components: total dwell time and total running time. The method allowed the location of the "trouble" segments and enhanced the clarification of causes for the verified delays.

In a field evaluation work done in the Greek city of Thessaloniky (TOS, 1997), the project's report pointed changes in bus speeds from 7.8 Km/h to 11.8 Km/h and a 10% and 15% improvement in the Mitoploleos (980m) and Vas Olga (3200m) bus lanes, respectively.

In a study held in Lisbon, "after" implementation surveys were conducted to measure the car and bus times along the Rossio-Entrecampos-Rossio corridor that contained bus lane facilities at around 70% of its length (Lopes, 2003).

The results demonstrated that buses were 10% and 38% quicker than cars for each considered direction of the corridor, confirming the time benefits that buses can obtain from a comprehensive bus lane scheme. Additionally, the author presented a description of some empirical results on bus lane impacts worldwide that generally pointed benefits for buses operational conditions.

The generality of studies pointed out important time savings to buses and relative low impacts to general traffic, although the comparison between them proved to be difficult, because:

- Simplifications made in the data analysis regarding the measures of performance (e.g. consideration or not of the dwell times or delays at the traffic signals, area of analysis);
- Dependence on local characteristics (e.g.: geometry, enforcement level, operational reality, etc.) for the success of the scheme.

On the other hand, the monitoring aspect of this studies was shown to be an effective way for evaluating the effectiveness of the bus lanes, as also for deeper understanding of results, especially when they are not evident by the simple analysis of the changes in the measures of performance (e.g.: increase on bus travel times as a result on increase in bus ridership).

3.3. NON-MODELLING APPROACH

A non-modelling approach to the assessment of operational impacts of a bus lane introduction lays on the use of manual techniques. Those vary from a typical operational approach, based on traffic engineering procedures, to the application of simple formulations based on passenger time variations. The mixed techniques try to embrace the best features of both and will be equally discussed.

All of these methods allow the pursuing with decision making on the feasibility of the tested bus lane based on a small amount of information.

On the other hand, by regarding on less information these studies usually are usually restricted to the corridor were the bus lane is being tested. This type of corridor analysis tends to neglect some important changes in operational conditions due to the bus lane introduction, per example: the increase in congestion by lost in road capacity for general traffic affecting the upstream roads and changes in travel demand due to traffic reassignment effects.

The limitations and advantages of this type of approach will be discussed next, along with the classification of each non-modelling approach considered as:

- Operational approach;
- Passenger based approach;
- Mixed techniques.

3.3.1. OPERATIONAL APPROACH

The application of basic traffic engineering theory can provide quick and straightforward information regarding the quantification of time effects caused by new bus lanes schemes. The methods employ some basic field data (traffic flows, travel times and average queues), and its application is only recommended for the following situations:

- As a first approach method to test if the proposed bus lane scheme is expected to produce good results;
- To help choosing, at the preliminary stage, the best bus lane scheme;
- To work as the only method of evaluation in very simple systems (Lunes and Willumsen, 1988).

A current procedure in this type of studies is the uniformization of traffic flows into passenger car unit (pcu). This can be accomplished by applying equivalence coefficients for each vehicle considered to account the differences between physical (vehicle length) and operational skills.

The approach proposed by Hounsell and McDonald (1988) formulates the problem from a purely physical point of view and assume that the introduction of a bus lane would only redistribute the delays between bus and non-bus traffic, maintaining the total delay unaltered for given time period (normally the peak hour). This is only possible by considering that the downstream junction capacity remains unaltered, witch can only be achieved by the provision of an “optimum” setback.

Thus, the formula comes as:

$$T_a.q_a = T_b.q_b + T_{nb}.q_{nb} \qquad (3.1)$$

with:

T_a[sec]: Average travel time for all vehicles without bus lane;
q_a[pcu[1]]: Total flow without bus lane;
T_b[sec]: Average travel time for buses with bus lane;
q_b[pcu]: Bus flow with bus lane;
T_{nb}[sec]: Average travel time for non-bus traffic with bus lane introduction;
q_{nb}[pcu]: Non-bus flow without bus lane introduction.

This approach is based on the assumption that the flows remain unaltered for the "with" and "without" bus lane situations. Additionally, the average travel time is considered the same for all vehicles in the "without" situation, fact that unables the dwell times and different vehicle operational conditions to be considered.

However, the application of this expression is useful to get a rough prediction on times in situations where:

- The bus lane already exists, witch implicates the estimation of T_a using data from field surveys;
- The bus lane introduction is being studied, calculating T_{nb} with some assumptions made for the T_b case (e.g.: estimating the "maximum" T_b, knowing the bus lane setback and the average queue).

Another method for predicting the operational impacts derived from a bus lane schemes might be applying some of the information contained by manuals and other specialized traffic references. Some examples might be found in the Highway *Capacity Manual* (TRB, 2000) and *Transit Capacity and Quality of Service Manual* (TRB, 2003). The manuals provide straightforward guidance on capacities and speeds for both with bus lane and mixed traffic conditions. These are tested for range of factors such as: dwell time, dwell times variability, bus stop locations, traffic lights, right turning volumes, pedestrian crossings volumes and other operational conditions.

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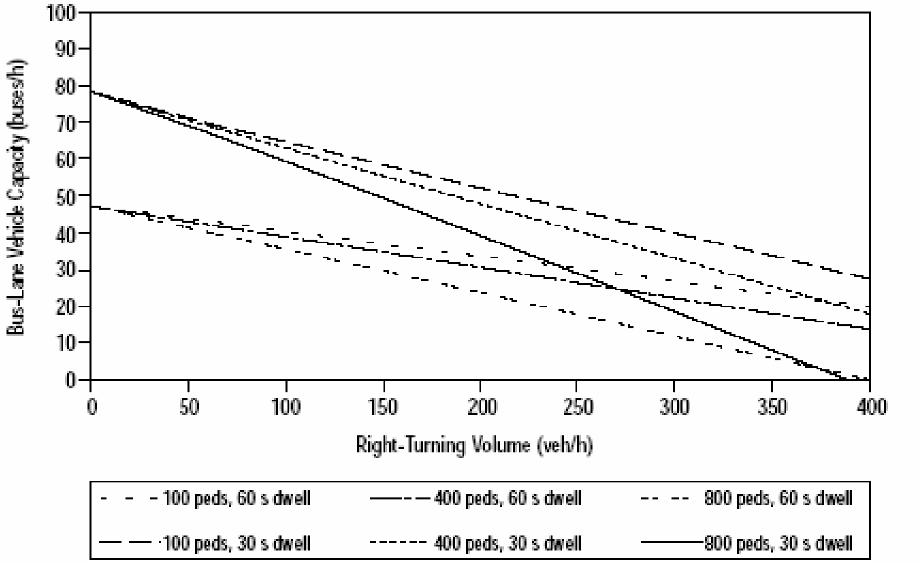
[1] A current procedure in this type of studies is the uniformization of traffic flows into passenger car unit (pcu). This can be accomplished by applying equivalence coefficients for each vehicle considered to account the differences between physical (vehicle length) and operational skills.

Figure 3.2 presents an example of this type of information and shows how the bus lane capacity drops when the right turning of general traffic increases at the end of the lane. Other aspects such as the dwell times increase and pedestrian crossing on the adjacent streets are shown to be prejudicial to the bus lane capacity.



Note:
Assumes 15-s clearance time, 25 percent queue probability, 60 percent coefficient of variation of dwell times, permitted right-turn signal phasing, shared right-turn lane, g/C = 0.5, nearside stops, 2 linear berths, and bus volumes minimal in relation to right-turn volumes ($P_{RT} = 1.0$).

Figure 3.2: Exclusive Bus-Lane Vehicle Capacity: Non-Skip Stop operation (TRB, 2000)

Again, the use of this data is very site concentrated on the bus lane corridor and ignores potential complex effects propagated within a wider area. It also should be regarded that this information was built for scenarios with characteristics that may not fit the profile of the studied bus lane. An example of this incompatibility is fact that the presented relationships were built up for American design and operational standards and by that the validity of results for Europe is not an indubitable question.

3.3.2. PASSENGER BASED APPROACH

Although having important aspects, the solely application of traffic analysis considerations does not consider a key issue of the problem: the rationality of public transport when compared with the private one. In fact, buses can carry more people than cars and that characteristic should be also accounted in the evaluation process.

One of the most referenced approaches on the evaluation of bus lane introduction schemes is the one suggested by Vuhic (1981). The work states that the conversion of a general traffic lane into a bus lane is justifiable whenever the passengers carried be buses exceed, or at least equal, the average number of passengers carried by cars per lane, as the following formula shows:

$$Q_b O_b \geq \frac{Q_a O_a}{N-1} \tag{3.2}$$

where:

- Q_b [veh/h]: Bus flow;
- Q_a [veh/h]: Car flow;
- O_a [passenger/veh]: Average bus occupancy;
- O_b [passenger/veh]: Average car occupancy;
- N: Number of lanes.

By accounting the vehicle's occupancies, this approach embraces the concept of "passenger flow" instead of the "vehicle time" previously presented for the traffic analysis studies.

Using very simple collected data, like average occupancy and traffic flows, this formula allows calculations of warrants for minimum bus frequency to justify the bus preferential treatment, and was recently used in some evaluation works (Lopes, 2003; Currie *et al.*, 2004).

Although it is claimed (Vuhic, 1981) that the resultant warrants are conservative because they do not account possible modal shift favourable to the bus, the fact is that the results disregard important operational issues like the level of congestion or possible traffic re-assignment effects caused by the introduction of the new bus lane.

Based on the passenger flow concept several local authorities and organizations calculated minimum bus frequencies to justify a bus lane treatment based on the local traffic conditions and occupancies (Table 3.1).

In fact, the range of methodologies to assess this warrants may vary from the empirical knowledge of the network based on field measurements, to the application of traffic engineering theory, to even modelling based approaches, although the latest are not yet so common (Currie, 2003). This way, the decision making based on this warrants must be fully aware of the simplifications made with especial regard for the liability in the methods used for the quantification of the time variables used.

Table 3.1: Minimum bus frequencies to justify a bus lane (Lopes, 2003)

Organization	Minimum Frequency (bus/hr)
PIARC – World Road Association	15-20
RATP - Régie Autonome de Transports Parisiens	15
ITEP - *Institut des Transports et de Planification*	20
US-DOT - Department of Transport	20-90
CML - Câmara Municipal de Lisboa	20
Carris - *Companhia Carris de Ferro de Lisboa*	15-20
OECD – Organization for Economic Co-operation and Development	20

Nevertheless, their consideration might be useful as a first approach, regarding that if the bus frequencies are satisfactory further operational analysis should be done based on the site specifications.

The main limitations of the approach are again related to the fact that they tend to rely on analysis made on a single corridor. This fundamental limitation neglects the impacts on surrounding traffic in the quantification of impacts process.

3.3.3. MIXED TECHNIQUES

To deal with the limitations of the presented approaches, some methodologies made an effort to incorporate both passenger demand and some basic operational issues in the evaluation process.

Jepson and Ferreira (2000) propose a more integrated approach, where minimum bus patronage to justify the bus lame introduction is calculated based on person delays in the segment of road where the bus lane is being introduced. This is formulated as:

$$\text{Min.(bus)} = \frac{d_{car1}.V_{car}.OCC_{car} - d_{car2}.V_{car}.OCC_{car}}{V_{bus}(d_{bus2} - d_{bus1})} \qquad (3.3)$$

where:

Min._{bus}[passengers/bus]: Minimum number of bus passengers to justify bus lane;
d_{car1}[seconds]: Average delay without bus lane;
d_{bus1}[seconds/vehicle]: Average delay without bus lane;
d_{car2}[seconds/vehicle]: Average delay with bus lane;
d_{bus2}[seconds/vehicle]: Average delay with bus lane;
V_{car}[vehicle/h]: Car volume;
V_{bus}[vehicle/h]: Bus volume.

The formula indicates that the time savings for bus passengers after the bus lane introduction should at least compensate the time losses for car passengers in order to justify the implementation of the bus preferential treatment.

The authors used the traffic engineering formula proposed by Austroads (Austroads 1991) to estimate the delays necessary for the calculation of the number of bus passengers that warranted the bus lane introduction for the various tested demand scenarios.

The approach compared the benefits resulting from the introduction of an extra lane as a general traffic or as a bus lane extended through the intersection. The study case was an intersection with random arrivals with a cycle time of 80 seconds and a green time on the main approach of 40 seconds as the base case. The results presented in Table 3.2 were calculated regarding the presented formulation and refer to the minimum number of bus passengers necessary to justify the introduction of a bus lane with no setback.

Table 3.2: Minimum bus/person volumes to justify bus lane introduction

Traffic Conditions: Cycle Time: 80s; Green Time: 40s; Approach Saturation Flow: 4000 vehicles/hour						
Number of Cars (vehicles/hour)	Approx. Degree of Saturation	Number of Buses to Justify a Bus Lane with bus lanes extended through traffic signals				Minimum hourly person throughput (bus passengers/hour)
		Bus Occ. 50	Bus Occ. 40	Bus Occ. 30	Bus Occ. 20	
500	0.25	##	##	##	##	##
750	0.375	##	##	##	##	##
1000	0.5	17	22	29	43	850
1500	0.75	31	39	52	78	1550
1650	0.825	50	62	82	122	2500
1700	0.85	59	74	98	147	2950
1750	0.875	71	89	119	182	3550
1800	0.9	88	111	149	245	4400
1850	0.925	115	146	203	306	5750
1900	0.95	165	219	*	*	8250
1950	0.975	260	307	*	*	13000
2000	1	*	*	*	*	*

* - Conditions with high degree of saturation where it is not practical to adopt bus lanes;

- Conditions where extra lane dedicated as general purpose lane does not improve the operations for general purpose traffic and a bus lane may be designated with no adverse impact to other vehicles.

Note that as the degree of saturation rises, the more difficult is to justify, even based on total person delay, the introduction of the bus lane instead of the general traffic lane. This result suggests that under over saturated conditions the introduction of a general traffic lane or the consideration of a bus lane setback (to abbreviate the lost of capacity) should be considered instead of the bus lane extended trough signals.

The simplicity and versatility of the method allows that different intersection schemes (number of lanes, green ratio, different occupancies, etc) can be analyzed in order to quantify the operational changes for buses and general traffic in the evaluation process of a bus lane scheme.

The main disadvantage is the fact that the method neglects key issues like the operational differences between vehicles, bus stop effects, bus lane capacity, queue propagation or traffic reassignment. Most of all, by being a methodology purely based on time changes near the intersections of tested bus lanes scheme, it overlooks the overall operational changes that may occur in a wider area.

3.4. MODELLING STUDIES

Traffic flow models currently represent an accepted tool for traffic studies. The capability to test different road use scenarios and quickly process the information needed for comparison is their main advantage when faced with the non-modelling approaches.

The application of traffic models to the bus lane evaluation problem was found required for circumstances where the complexities of the problem are expected (Lunes and Willumsen, 1988). Examples of those circumstances might be:

- Queues blocking back the upstream junction;
- Traffic reassignment with contra-flow or width flow bus lanes;
- Large system, complex and/or congested.

There are a few models especially dedicated to this problem like BLISS - Bus Lane Interactive Simulation System (Lunes and Willumsen, 1988) and BLAMP - Bus Lane Algorithmic Modelling Program (Robertson, 1985), but the tendency is for more flexible models due to their larger spectrum of testing possibilities.

The use of more classical assignment packages (e.g.: SATURN, CONTRAM) can be extremely useful for assessing a study area where the impacts are most felt. This fact represents a major differentiating factor from the non-modelling approaches, once it allows traffic diversion to be accounted regarding the “before” and “after” scenarios as it also enables the consideration of a study area wider than the previous bus lane corridor.

On the other hand, models based on micro simulation of vehicles (e.g. DRACULA, AIMSUM, PARAMICS, etc.) are able to replicate operational conditions to an accuracy level that makes them suitable tool for the assessment of time impacts over the analysed area.

The next section reviews some work made with traffic models in assessing the time impacts due to bus lane introduction, whether aiming the generalization of cause-effect relationships or the study of a specific site case.

3.4.1. THEORETICAL MODELS

Theoretical models are a generic approach to the problem of balanced road space allocation through the use of traffic flow models. They consist in the application of a model, specifically developed or a commercial one, to a generic road configuration and travel demand pattern. The main goal is to isolate the most influential elements to operational performance of the tested solution, i.e., the bus lane introduction.

Therefore, the applicability of this approach is suited for the development of basic relationships (e.g.: formulas for the calculation of average speeds) for further quantification of the time impacts resulting form the introduction of the bus lane.

By late 1970's, the *Transport and Road Research Laboratory* developed a framework to assess the economic justification of a with-flow bus lane where the time impacts were quantified by using theoretical traffic model especially developed for the purpose (Oldfield *et al.*, 1977).

The model represented a section of the road with two or three lane in each side and enabled the user to simulate the introduction of a bus lane. Setback length issues were also quantifiable along with diversion possibilities to minor roads, like Figure 3.3 shows.

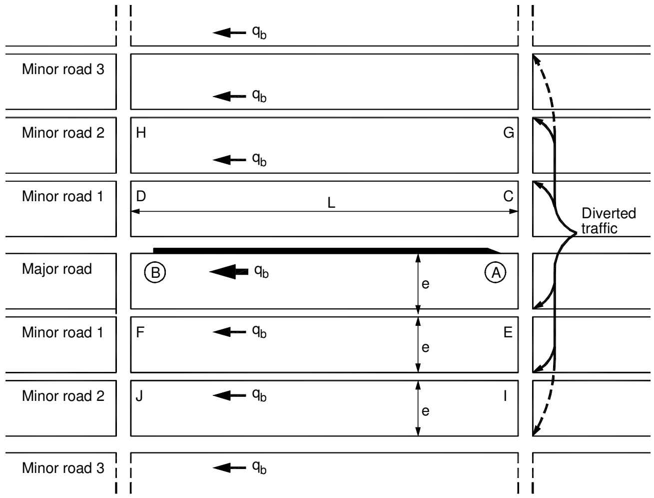


Figure 3.3: Theoretical model used in the bus lane study (Oldfield *et al.*, 1977)

The changes in travel time were simulated through means of speed-flow relationships, and were calculated for all vehicles operating in the modelled network. Travel distance information was also assessed, once the traffic reassignment possibility was contemplated.

Based on the information provided by the theoretical model, warrants on minimum bus frequencies for different levels of patronage were calculated for the scenarios considered.

In a different study, a decision model was developed to compare the person travel time (sec/mile) for the "before" and "after" bus lane introduction situation (Gan *et al.*, 2003). According to the authors, a bus lane is found suitable for implementation whenever:

$$PTT_{SEPARATED} \leq PTT_{MIXED} \tag{3.5}$$

Where:

$PTT_{SEPARATED}$ [sec/mile]: Person travel time with bus lane;
PTT_{MIXED} [sec/mile]: Person travel time without bus lane.

The necessary calculations are based on general bus and non-bus speed formulas that were developed using the simulation model CORSIM. To pursue with the task, a generic arterial street road profile was coded and tested for a large number of scenarios. The varying elements were:

- Traffic volumes: bus and non-bus volumes, percentage of right turners;
- Bus operation conditions: bus stop locations and configuration, mean dwell times;
- Traffic lights control: green ratio, cycle length, signal offset[2];
- Road space characteristics: number of lanes and free flow speed.

Statistical analyses was then proceed to evaluate the correlation between the above variables and the final following speed formulas were obtained for both scenarios (with and without bus lane) and regarding the type of vehicle (bus (BS) and non-bus (NBS)):

With bus lane:

$$BS = \beta_0 + \beta_4 e^{-\left(\frac{\beta_5 RV}{10000} + \frac{\beta_6 BusXDwell^{\beta_7}}{10000 XBB}\right)^{\beta_8}} + \beta_9 Dwell + \beta_{10} GC + \beta_{11} Cycle + \beta_{12} BB + \beta_{13} Lanes \tag{3.6}$$

$$NBS = \beta_0 + \beta_1 e^{-\left(\frac{\beta_2 TV}{10000}\right)^{\beta_2}} + \beta_4 e^{-\left(\frac{\beta_5 RV}{10000} + \frac{\beta_6 BusxDwell^{\beta_7}}{10000 xBB}\right)^{\beta_8}} + \beta_{10} GC + \beta_{11} Cycle + \beta_{12} BB + \beta_{13} Lanes \tag{3.7}$$

Without bus lane:

$$BS = \beta_0 + \beta_1 e^{-\left(\frac{\beta_2 TV}{10000} + \frac{\beta_5 RV}{10000} + \frac{\beta_4 BusXDwell^{\beta_5}}{10000 XBB}\right)^{\beta_6}} + \beta_7 Dwell + \beta_8 GC + \beta_9 Cycle + \beta_{10} BB + \beta_{11} Lanes \tag{3.8}$$

$$NBS = \beta_0 + \beta_1 e^{-\left(\frac{\beta_2 TV}{10000} + \frac{\beta_2 RV}{10000} \frac{\beta_4 BusxDwell^{\beta_5}}{10000 xBB}\right)^{\beta_6}} + \beta_8 GC + \beta_9 Cycle + \beta_{10} BB + \beta_{11} Lanes \tag{3.9}$$

Where:

RV [non-bus vehicle/h]: Number of right-turns;
TV [non-bus vehicle/h]: Number of through;
Bus [bus/h]: Number of buses;
Dwell [seconds]: Mean dwell time;
BB: Number of bus berths;
GC: Green ratio;
Cycle [sec]: Cycle length;
Lanes: Number of lanes;
β_i : Model coefficients for the characteristics of the considered scenario.

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[2] This variable was a qualitative ones, i.e., the possibilities were: “with” or “without signal coordination.

The results obtained were found to be “comparable” with those indicated by the *Operational Analysis of Bus Lanes on Arterials* (St. Jacques and Levinson, 1997) that suited as the base for the values presented by the *Highway Capacity Manual* (TRB, 2000).

The latest were also obtained through the use a traffic simulation model, TRAF-NETSIM, and allowed the construction of relationships in terms of bus lanes capacities and bus speeds for both with bus lane and mixed traffic conditions. For the three different types of bus lanes considered in the study it was found that the main elements influencing their performance were:

- Design aspects: location and frequency of bus stops, bus stop configuration (e.g.: presence or not of bus laybay);
- Bus Operations: dwell times and their variability, possible skip-stop operations, overtaking permission;
- Traffic conditions: bus volumes and general traffic, right turning permissions and volumes;
- Traffic light: times and presence or not of coordination.

Other studies, (Currie *et al,* 2003*)* and (Jepson *et al.*, 1999), used modelling software PARAMICS and SIDRA, respectively, were applied to study design influence, namely on the setback existence and length on the bus and car travel times.

The prior study compared a base scenario (2x2 arterial street with no bus lane) with a scenario that included the transformation of the kerbside lane into a bus lane for various setbacks hypothesis. The main conclusions presented in Figure 3.4 suggest that beneath values of 1000 veh/h the impacts on general traffic are low when compared with bus benefits on travel time. Although, when flows raise the benefits for buses decrease as bigger are the considered setbacks.

Another interesting result shows that under high traffic demand, the “no bus lane” solution might be preferable once even in the case were no setback is provided, bus travel times are affected by congestion in the downstream links.

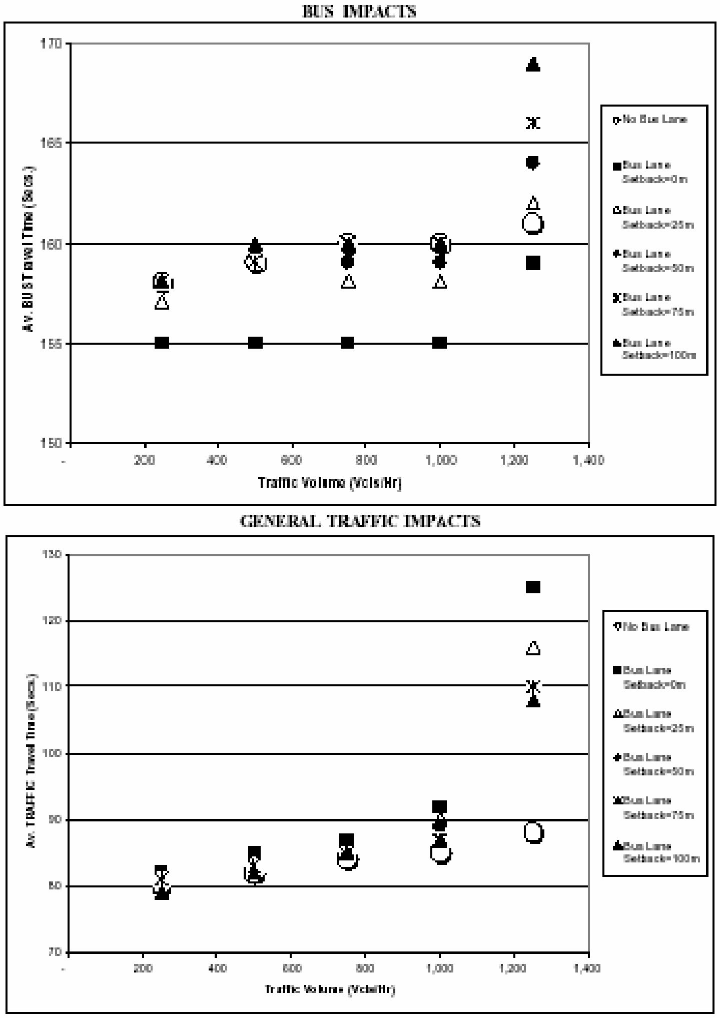

Figure 3.4: Bus and general traffic travel time impacts due bus lane introduction.

The other work (Jepson and Ferreira., 1999) considered a road section representing an arterial street and compared the scenarios where a general traffic lane or a bus lane with a setback is introduced.

Results in Table 3.3 show that as congestion rises the more difficult is to justify the introduction of a bus lane with setback instead of a general traffic. Calculations were made using the average delays per vehicle provided by SIDRA that were then computed into person delays, following the already presented methodology.

Table 3.3: Minimum bus volumes to justify bus lane with setback (Jepson and Ferreira, 1999)

Traffic Volume (vehicles/hour)	Degree of Saturation (Base Case)	Number of Passengers to Justify Bus Lane Set-back (passengers/hour)
500	0.25	##
1000	0.5	##
1500	0.75	##
2000	1.00	##
2100	1.05	910
2200	1.10	1430
2300	1.15	1795

- Conditions where extra lane dedicated as general purpose lane does not significantly improve the operations for general purpose traffic and a bus lane set-back may be designated with no adverse impact to other vehicles.

Note that the range of applicability of this relationship seems very dependable on the conditions for witch they were built for (e.g.: setback length, green times, number of lanes, etc) witch again reveals the limitations of these types of methods.

On the other hand, and once the analyst is fully aware of the range of application and simplifications made to achieve the generic relationships, they might represent a straightforward method for the quantification of operational Figures at an early stage of the evaluation.

3.4.2. “REAL-LIFE SCHEMES”

The use of traffic modelling applied to real-life situations can be an effective way for quantifying the operational impacts of a bus lane. The versatility of the approach makes it suitable for bus lane introduction studies as also for evaluation the already implemented solutions.

For the latest, if the study points out an unsatisfactory solution, bus lanes should be rethought and even removed as it occurred in some locations in the U.S.A. (Batz, 1986). Still, it must be emphasized that modelling studies should be more focused on the project phase rather than on the operational one, being this task more suitable for direct data collection and monitoring studies.

The biggest advantage of using this type of approach is the fact that each case can be considered with its own local specificities. This way, there is no need for considering generic road sections to provide operational Figures, once it is the model, based on the coded network that provides them.

A bibliographic review on this subject reveals a study covering 25 bus lane schemes across the United Kingdom (Hounsell and McDonald, 1988). Data was collected for the characterization of the peak-hour period, including the built up and decline conditions, through means of traffic surveys that involved traffic counting and license plate registration.

The study involved the use of three different modelling suites:

- TrafficQ: a traffic simulation model, with no assignment capacities (the routes must by defined by the user). This software was found to be suitable for modelling small (by the time: maximum 60 links) and complex urban sub-networks;
- CONTRAM: typical traffic assignment model where vehicles (or group of them) are distributed through the network allowing prediction of traffic conditions and re-assignment for the tested scenarios;
- BLAMP: a very simple interactive bus lane model that was found to have the disadvantage of not simulating blocking-back effect.

Scenarios representing the existing schemes were modelled and compared with a “no bus lane” situation. A full operational report was established for each scheme, along with its economical evaluation. Conclusions pointed the level of occupancy of buses, traffic intensity (volume/capacity), setback distance and traffic signal programming as the main features regarding bus lanes performance and economic viability.

In a post-implementation operational study developed in Toronto (Shalaby, 1999), “before” and “after” bus lane data was collected and used to calibrate a model using the simulation software TRANSYT-7F. The model was developed to replicate operational conditions of a 3 Km two-way arterial street with 16 signalized intersections, located in the city’s central area. The arterial was recently submitted to the introduction of two bus lanes (one in each way) and the main objective of the study was to compare the overall operational indicators for buses and general traffic for the “with” and “without” bus lanes scenarios.

Tests considered both morning and afternoon peak hour conditions and additional operational changes like taxi permission to ride in bus lanes and left turnings were also considered.

The significant benefits of using a traffic model were related with the simplicity to process a large amount of traffic data, namely in terms of vehicles speeds, travel times and calculations of overall measures of performance.

The following major results were obtained comparing the Figures for buses and general traffic between the “with” and “without” bus lanes scenarios:

- Performance for buses improved while deteriorated for the remaining traffic. Even so, buses still had greater travel times than cars due to operational specificities (e.g.: average speed, lower acceleration rates, dwell times, etc.);

- Overall operational performance (considering bus and autos together), the system speed maintained almost the same but fuel consumption decreased.
- The restriction of left turns had residual influence over performance while the taxi permission to ride in bus lanes was found to have benefits for the general traffic superior to the disbenefits imposed to buses.

Another research work studied the possibility of appliance of strong priority measures[3] in Southampton city centre (Waterson *et al*, 2003). With the objective of getting favourable impacts on modal shift in favour of the Public Transport, the authors used the traffic software CONTRAM and TRIPS to test the impacts of increasable “stronger” measures witch included the introduction of bus lanes schemes on the analysed area. The first program was used in assessing operational road impacts such as delays to vehicles and the latter as the public transport model (assessing time, distance, fares, etc).

The conclusions pointed that the results depend largely on local traveller’s characteristics and on the scheme itself. It was also concluded that too “strong” public transport priority measures may not always be beneficial for the overall network performance, and that buses times could inclusively raise near the boundaries of the tested area.

A final reference to the modelling study was developed for the Thessalonica central area (Basbas, 2004), and although the main objective was to evaluate the environmental changes related with a bus lane scheme, some operational were also assessed

The software used, witch later was found suitable for the work, was the traffic assignment model SATURN, being the demand O-D matrix estimated from traffic counts. Data related with buses for the “before” and “after” period was obtained from a previous work (Nakopoulos, 2003) and used to calibrate the model.

The model was used for the calculation of the operational changes on traffic and environmental indicators, resulting from the introduction of a 1750m 2-way bus lane on a city’s arterial street.

Results for the studied area suggested benefits on bus total travel times (-26%), significant fuel consumption reductions (-28%) and considerable pollutants emission reduction in the area close to the bus lane. The negative impacts were considered to be reduced to “small disbenefits” for other types of vehicles.

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[3] The author refers as “strong priority measures” to those measures that aim the creation of the maximum benefit for buses regardless of the disbenefits predicted for the general traffic. An example might be the creation of a bus lane with no provision of setback to abbreviate the probable capacity lost.

The presented studies confirmed the versatility of using traffic modelling as the biggest advantage to this approach. In fact, the capacity to model real-life schemes increases the confidence on the previewed results, once the site specificities can be accounted. Additionally, the possibility of processing large amounts of information, allows that that these methods can be applied to the operational evaluation on a whole impact area, instead of the typical corridor approach.

On the other hand, the suitability of this type of approach to the evaluation of a bus lane scheme is extremely dependable on the software's features. Also, the calibration and validation tasks might demand a relevant and time effort that must be accounted whenever the decision for this type of approach is made.

3.5. ECONOMICAL APPROACH

The impacts caused by the implementation of the bus lane scheme are beyond the previewed operational changes. Although benefits associated with journey times represent around 80% of the total economic benefits (Hounsell and McDonald, 1988), there are other aspects that can be accounted for the decision making regarding the implementation of the bus lane scheme.

The most typical approach is to pursue with an economic evaluation of scheme for the project time horizon. The study consists in a cost-benefit analysis where all the selected quantifiable parameters are assessed and converted into monetary values for the "before" and "after" bus lane scenarios. The main factors affecting the quality of an economic evaluation are:

- Full identification and selection of factors;
- Good estimate of costs and values to calculate them;
- Possible introduction of weighting factors.

The list of factors to consider in the economic evaluation of the bus lane scheme must account their relative importance in the overall evaluation as also the reliability of the methods to assess them. Nevertheless, the main factors for the economical evaluation of any bus lane scheme should at least consider the following items:

- Implementation costs: the assessment of the implementation costs should consider the financial effort involved in the conception (planning, design definition, data collection, etc), construction (physical implementation costs, capital costs, etc) and the maintenance (physical maintenance, traffic reinforcement, monitoring, information campaigns, etc) of the infrastructure. Most of these features have a commercial value or can be easily converted into monetary Figures.

- Passenger time impacts: time changes are usually the most influent factor in the economical evaluation process. Besides changes in travel times for each type of vehicle, it should be also accounted factors like: bus reliability gains, changes in walking times, etc. The methodology used for the quantification can vary from modelling approaches to the utilization of more direct traffic engineering formulations, as shown along the present chapter. The total travel times should be then converted into "passenger time" Figures for further transformation into monetary values. This conversion process should be established according to local economic characteristics in order to get a reliable hourly time value. Reported works on the subject (Bly and Webster, 1979 and Currie, 2004) relied on values provided from National Agencies. Additionally, and depending on the level of desegregation of the time results, different values of time can be assign for each component of the considered travel time (ex: time waiting, in-vehicle time, etc).

- Vehicle operational cost impacts: the variation of operational conditions imposed by the bus lane introduction has implications on the associated costs for each vehicle. The quantification of these costs is usually done by the application of cost formulas calibrated for each type of vehicle (e.g.: average fuel consumptions per vehicle), that are proportional to the vehicle's total travel distance and time. If a modelling suite is being used, more disaggregated information regarding the specific operational conditions (e.g.: delays, cruise times) can be provided to be used in more detailed cost assessment (Hounsell and McDonald, 1988), In the case of buses, if the time savings are significant they may allow the reduction of fleet and crew resources for the provision of the same service.

- Reassignment effects: this is caused by the new circulating conditions imposed by the bus lane introduction that may lead to the new route choice made by the non-bus vehicles. This effect may be relevant if congestion is high and there are alternative routes to the use of the street where the bus lane is being tested. The assessment of this factor is not a straightforward task and problems may arise due to the level of complexity of urban road environment. Traffic models are the best way to deal with the problem, regarding that the modelled area is wide enough to consider the bus lane as also the alternative routes. This way, the operational changes provided by the model will already consider the traffic reassignment effect and no extra calculations will be needed.

- Modal shift effects: improvements of operational conditions for buses and the (potential) disbenefits for general traffic may enhance favourable conditions for a modal shift in favour of the public transport. This change has multiple advantages in terms of economical viability of the tested scheme, like (Currie, 2004): travel time reduction for car and buses (decongestion effect), reduction vehicle operational costs, farebox revenue increase (extra bus passengers), external benefits (reduction in accident costs, environmental costs). The assessment of this type of effects can be made considering a validated transport model that for a given demand elasticity can preview, based generalized costs per vehicle, the level of modal shift that is likely to occur.

3.6. ADDITIONAL STUDIES

There are other important aspects that, depending on the scheme, may be contemplated in a wider evaluation analysis regarding a bus lane scheme. Example of those might be:

- Traffic safety studies;
- Logistic (loading and unloading);
- Parking provision and activity studies;
- Pedestrian accessibility;
- Environmental studies.

Among these approaches, the environmental one is probably the most mentioned (OTAN, 1976; Bly and Webster, 1979; Hounsell and McDonald, 1988 and Currie, 2004), being the changes in atmospheric pollution, noise level and visual impacts the main aspects to be accessed within the scope of the bus lane schemes.

These types of studies assume certain specificities that in most cases do not allow the transposition of results into monetary values. Nevertheless, their assessment might be important in the final decision regarding the evaluation of the bus lane. The decision to pursue with them is dependable of the time and money availability as also with the local operational characteristics.

3.7. CONCLUSIONS

The bibliographic review regarding the different approaches used to assess the operational impacts related with the bus lane schemes allowed some general conclusions such as:

- The implications of a bus lane introduction are vast and the varieties of existing approaches require a good selection according to level of detail wanted. In this context, the use of non-modelling approach can represent a good pre-evaluation approach for the bus lane, once they provide straightforward information relying only on basic inputs;

- For more complex traffic environments (e.g.: urban areas) the use of a modelling approach seems to be the more adequate analysis once it is able to consider the effects in the surrounding traffic effects environment. This fact contrasts with the typical corridor approach adopted by the other presented methodologies. The main disadvantage is the resource required to perform this type of analysis. On the other hand, the generalization of commercial software available advices the construction of a model built for each case instead of using theoretical relationships built for general road profiles;

- Field studies are needed, but the costs and implementing difficulties advice their use for monitoring matters instead of purely planning approach. They also can be important to evaluate the quality of the used methods in the evaluation procedure once the scheme is implemented;

- The quantification of the operational changes for the “with” and “without” scenarios is very important to any bus lane evaluation. Nevertheless, even if the operational results suggest major benefits, an economic evaluation should be performed in order to account other important aspects in the final decision making.

CHAPTER 4 - METHODOLOGY

4.1. INTRODUCTION

The previous chapter presented a number of different approaches to deal with the impacts associated with bus lanes schemes, with special focusing on the operational aspects of the problem. The analysis contributed for the definition of two main difficulties:

- Most of the studies are reduced to the evaluation of operational changes in the street where the bus lane introduction is being tested, neglecting potentially important impacts on the surrounding traffic environment;
- Analyses on a wider area are only feasible within the scope of traffic modelling.

This chapter presents a general methodology based on traffic modelling to evaluate the resulting operational impacts of bus lane schemes. The main aim of the proposed framework is to allow the quantification of the changes on operational indicators for the whole area where the impacts are expected, hopefully contributing for a more supported decision making regarding the evaluation of bus lanes.

4.2. OBJECTIVES

The proposed methodology is a general modelling framework to assess the time impacts caused by the bus lane introduction on the surrounding traffic environment. The methodology is based on two basic principals:

- The size of the study area must allow the quantification of the performance impacts for all the traffic significantly affected by the bus lane scheme instead of only considering the area near the tested corridor.
- The evaluation is based on the comparison of results between the performance indicators provided by the model for the “before” and “after” bus lane introduction scenarios;

Being a general framework the range of applicability can be extended to a diversity of real-life schemes. Although subject to the software limitations, the versatility of traffic modelling also allows for various types of bus lanes schemes to be evaluated, such as:

- Conversion of a general traffic lane;

- Removal of a parking lane;
- Creation of an extra lane.

Additionally, the framework can be applied to schemes such as contra-flow bus lanes or even for the evaluation/optimization of already implemented ones.

The limitations of the methodology are mainly related with the level of accuracy with witch the employed traffic model can calculate the selected performance indicators. This is highly related with certain model limitations in dealing with bus lanes and with the quality and quantity of available information for the coding and calibration/validation process.

Being a purely operational approach, it must be mentioned that the presented framework will not be sufficient to conclude on the economic feasibility of the proposed bus lane scheme. Nevertheless, the quantification of the operational changes will be an important contribution to this goal.

4.3. OVERVIEW OF THE PROPOSED METHODOLOGY

The proposed methodology lies on the comparison between the performance indicators regarding the “before” and “after” scenarios for a bus lane scheme.

Although it is argued that the range of application of the proposed framework is vast, the further explanation will assume a situation where a bus lane is being studied to replace an existing general traffic lane. Hence, the “before” and “after” scenarios refer to “without” and “with” bus lane, respectively.

As Figure 4.1 shows, the definition of the scheme to be tested is the preliminary requirement for the proposed evaluation methodology. At this stage, it is assumed that a basic evaluation has been made and there are indicators that the solution is physically feasible for implementation and it is likely to produce overall benefits.

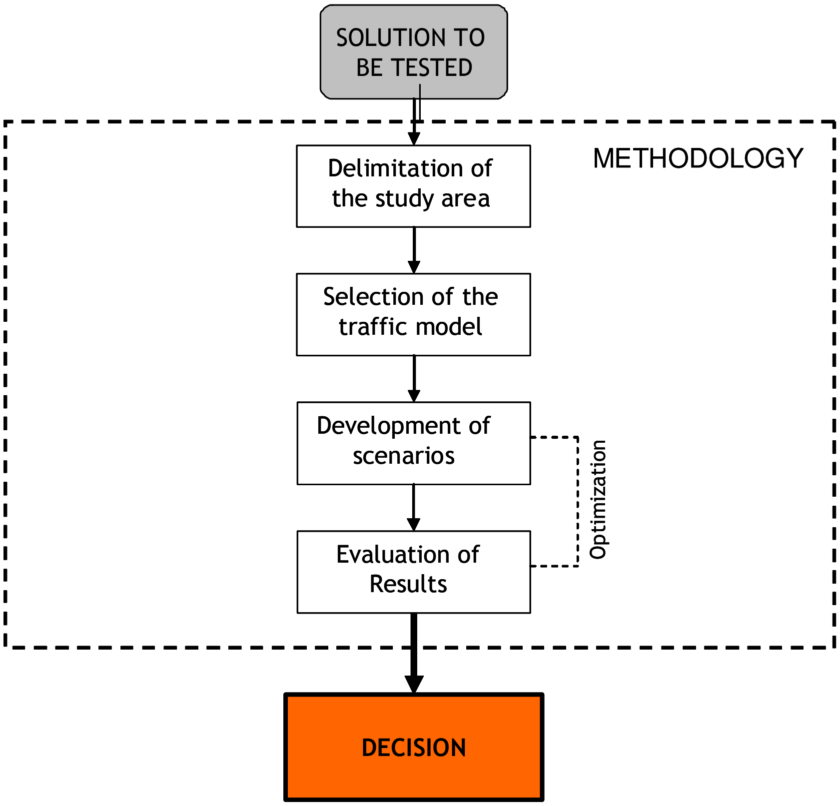

Figure 4.1: Proposed methodology

In order to quantify the changes in the operational conditions for the "before" and "after" scenarios the proposed methodology is divided in the following four stages:

1. Delimitation of the study area: the delimitation of the study area is a key element in the presented methodology. The main objective of this stage is to define a region that is wide enough to consider the locations where the major operational changes will occur. The calculation of the performance indicators will account the operational changes for the vehicles operating within this study area, therefore all the inside road network must be evaluated. This represents a rupture with the simple corridor analysis, once it valorises the importance of surrounding traffic in the evaluation process.

2. Selection of traffic model: by embracing an area wide analysis, the use of modelling becomes almost inevitable by the advantages that it brings regarding the testing of several design solutions and the automatic treatment of information. The model will provide the operational results used in the calculation of the performance indicators for the evaluation.

3. Development of scenarios: once the main objective of the evaluation is to compare the performance indicators between the "before" and "after" scenarios, it is necessary to code

them under the chosen traffic modelling environment. This process requires a number of tasks that go from the data collection to the final validation.

4. Evaluation of results: this is the stage where the operational outputs provided by the traffic model are treated and analysed in order to quantify the performance indicators for the two scenarios. The process should embrace all vehicles travelling within the study area during the period of analysis. Besides providing these aggregate results, traffic models can assist in the location of the more problematic areas for further optimization. If that is the case, the scenario development stage must be revisited to insure that the new changes will be contemplated in the "after" scenario.

4.4. DELIMITATION OF THE STUDY AREA

The study area is the region within the road network where are more likely to occur significant operational changes as a result of the bus lane introduction. This will be the area analyzed in the evaluation stage and therefore its correct definition is an important step for guaranteeing quality results.

The *Traffic Appraisal in Urban Areas* (HMSO, 1999) points some issues that should be considered for the definition of study areas for the generality of modelling studies, emphasizing that it should be wide enough to contain:

- The routes currently used or likely to be used in the future by traffic affected by the scheme;
- The areas where significant traffic congestion relief would be provided by the scheme;
- The areas susceptible to significant disbenefits produced by any extra traffic induced by the scheme;
- The impact of changes in traffic levels on both existing and new/improved roads in the areas affected;
- The areas over witch economic benefits are to be assessed.

The pointed issues reveal the concern to include the regions where the changes are being tested as also the ones where the secondary effects will be more significantly felt, witch means that traffic reassignment plays a key role. This fact will be accounted in the proposed evaluation system as it will be demonstrated along the current chapter.

The variables used to assess the study area are traffic flows and time related measurements (e.g.: average travel times, speeds and delays), although it is the modeller's decision to establish the level of changes to be consider. In this matter, a compromise between the wanted level of accuracy and the size of the study area has to be established in order to guarantee the best relation between the quality of the evaluation and the associated resources (e.g.: time, costs of data collection, etc).

The assessment of the operational changes can be done manually but this is only recommended for simple road schemes networks. Problems arise when evaluating serious changes within complex and congested urban networks. In these cases the local knowledge of the network, although very important, is usually insufficient once the amount of information to process is too big, therefore justifying the use of traffic models to ensure the quality of the analysis.

The use of an existent validated city model can help to overcome the problem by providing a good estimate of the influence area of the tested scheme. The process is done by comparing the predicted differences in the chosen operational indicators for both “before” and “after” (Figure 5.2) and the select the area will include the links where those changes are considered to be significant. Furthermore, the selected area in the model can be used as the base for the future modelling in terms of network coding as also for characterization of demand.

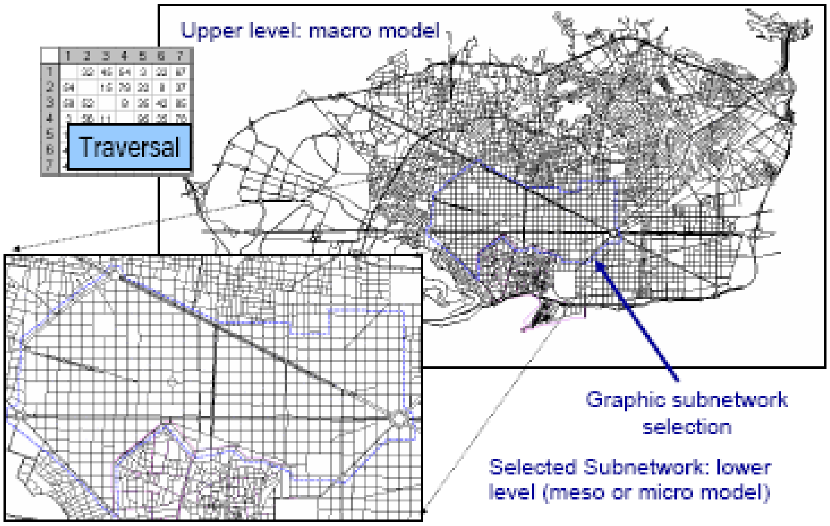

Figure 4.2: Delimitation of the study area from a macroscopic model (Barceló *et al.*, 2005)

4.5. TRAFFIC MODELING

4.5.1. TYPES OF MODELS

The proposed methodology for the evaluation of the bus lane introduction scheme relies on the use of a traffic modelling software for the comparison between operational indicators for the “before” and “after “scenarios”. Besides the possibility of evaluating scenarios before their physical implementation, the main advantages of using traffic modelling for the bus lane introduction studies are:

- Capacity for testing different operational scenarios;
- Capability for automatic processing of large amounts of information;
- Capacity for outputting important operational results that would be almost impossible to measure (e.g.: tracking all vehicles for the calculation of total travel times);
- Consideration of more complex traffic phenomena that might be decisive to the evaluation (e.g.: traffic reassignment, queue spreading, etc.).

If the advantages of their use are evident, the decision of witch type of traffic models to use is dependent on the level of accuracy wanted as also on the complexity of the scheme in evaluation.

Within the scope of available traffic models types, two families of model can be suitable for the analysis of bus lane impacts within the scope of this methodology: traffic assignment models and simulation (micro or macro) models.

The traffic assignment models can be seen as the last step of the classic 4 step transport models. They “assign” trips from an estimated O/D matrix through the available routes within a defined network. This path choice is made by minimizing the travel “costs” to the road users that mainly depends on the time and distance to pursue the trip between an O/D pair. Independently of the assignment methodology used, there is no doubt that these models are important to assess the reassignment effects and can be useful to assess operational impacts caused a network alteration such as a bus lane introduction.

Traffic simulation models belong to a different type of traffic models and aim to represent roadway networks and traffic conditions for a specific time period. There are various types of traffic simulation models ranging from macroscopic to microscopic models.

The macroscopic models depict traffic flow in a generalized form, such as platoon of vehicles on a less detailed network. The main advantage of these models is their less data requirements, although this fact has obvious impacts on the resulting outputs. These are often too aggregated to the level of accuracy needed for the bus lane operational results.

The microsimulation traffic models are a modelling tool of individual vehicle movements within a coded network. Each vehicle is moved through the network on a split second by split second basis according to its physical characteristics (length, maximum acceleration rate, etc.), the fundamental rules of motion and rules of driver behaviour (car following rules, lane changing rules, gap acceptance, etc.).

This leads to a more realistic representation of how vehicles actually move on the network, but requires significantly extra data and computing time (Diekmann, 2000). The level of detail might play an important role in the comparison between operational changes for the "before" and "after" tested scenarios, especially for closer scope on the main problems that will need further optimization.

Currently, the use o microsimulation traffic models appears to be the best solution for the type of problem such as a bus lane introduction but it should be reminded traffic assignment models are also need for the route definition in the "before" and "after" scheme. Luckily, the interaction between these two types of models is being developed in the way that the microsimulators are beginning to include their own assignment algorithms or can automatically process the routes defined by the assignment models.

4.5.2. CHOOSING THE MODEL

The choice of the traffic model to be used is an important task within the proposed evaluation framework because it is directly related with the quality of results. As previously mentioned, the use of a microsimulation model is more indicated for the proposed methodology once it can provide the operational results needed for the further calculation of the performance indicators.

The quality of these results is related with the specificities of each modelling suite and the planner should be fully informed on the advantages and limitations of the chosen model. The SMARTEST project (Bernauer, *et al.*, 1997) tested several commercial microsimulation packages on various items and presents excellent overview data to the model selection process.

In the specific case of the bus lane introduction study, some standard requirements to assist the selection of the traffic model are presented as follow:

- Existence of an assignment package: the present methodology is based on the assumption that traffic reassignment is a key aspect for this type of study, thus the microsmulation model should incorporate this feature at an internal or external (using a compatible assignment model) level;
- Disaggregated results: it is important that the operational indicators are presented by vehicle type (car, buses, etc) for their further computation into "passenger" indicators. Also route and link results might be important to better focus the analysis of certain corridors;
- Bus lane coding facility: the possibility to code bus lanes without any consideration of intermediate solutions (e.g.: code bus lane as a separate link, not considering setback

coding, etc) represents a good indicative on the suitability of the model. It can also facilitate the comparison of outputs, because this way the node-link structure will be the same for both scenarios;

- Bus operational features: the possibility of coding bus features such as bus stop, dwell times, frequencies and routes is also a determinant aspect, because they will guarantee a more realistic modelling of the bus operational characteristics that are indispensable for the evaluation;
- Characteristics per vehicle type: the definition of different operational parameters for vehicle type (e.g. length, acceleration, reaction time, etc.) can be significant for the results once it enhances more realistic results;
- Data transferability: if a high tier model is to be used as an initial approach (e.g. selecting the study area), an excellent characteristic of the microsimulation model would be the easy transferability of data between two models;
- Other aspects: the quality and availability of data, previously knowledge of the software by the analyst, time and budget restraints might also influence decision.

4.6. DEVELOPMENT OF SCENARIOS

Once the microsimulation model is chosen, it is time to pursue with the construction of the "before" and "after" scenarios. As already mentioned, and for simplicity reasons, it will be assumed that the "before" and the "after" scenario refer to the "without" and "with" bus lane, respectively.

The development of the two scenarios within a microsimulation model environment is not very different from the common procedure of the generality of the modelling approaches. The process begins with the data collection that is essential for the definition of the two essential pieces of any modelling suite: supply and demand characterization. The further tasks, calibration and validation, will be already based on the model outputs.

This section will approach these construction stages, emphasizing the differences between them in the construction of the "with" and "without bus lane scenarios, as also the simplifications that the use of an existent high tier model contemplating the study can provide.

4.6.1. “WITHOUT” BUS LANE SCENARIO

4.6.1.1. Data collection

The use of modelling is a time consuming task and the level of accuracy of the results relies on quantity and quality of the information gathered for the construction process. The type of data to collect is subject to the requirements of the selected software although a generic presentation can be made:

- Geometric data: this type of data encloses information on the physical characteristics of the network. Link lengths, number of lanes, lane widths, and junction dimensions are examples of this type of data. The most reliable source of information comes from direct field inspections, although the collaboration with the traffic responsible local authorities can provide helpful advances;

- Control data: it relates to the information on the traffic management system (number, phases, cycles, schedules, detection system, coordination, priority signing, roundabouts, etc.). Again, the authority responsible for the maintenance of the traffic lights and signs should be contacted for the provision of information, although a field inspection is always useful;

- Traffic data: this type of information is essential for the demand characterization of the model, namely for the construction of the O/D matrix (Dowling *et al.*, 2002). The most usual way to do it is by performing traffic counts associated with roadside interviews. The counts are performed manually or trough automatic count stations located in strategic points of the network to be modelled. The period of collection should be larger than the modelled one and the counts should be done simultaneously are preferably aggregated by vehicle type during 15 minutes periods. Additional information such as licence plate surveys (Hounsell and McDonald, 1988) or initial matrix derived from a higher level model (Barceló *et al.*, 2005) can also be accounted within the characterization of demand;

- Bus data: the bus data is essential for the bus lane evaluation process. The level of bus data required by the model normally embraces items like: bus demand (or headway) for every bus route, bus average travel times, number and location of bus stops, type of bus stops (with or without bus bay), average dwell times, average occupancy per section, existing bus lanes, etc. Most of the bus related information can be obtained near the local bus operator(s). In fact, this approach is highly recommended because the operator’s local know-how can assist in the identification of the most problematic areas and design of the best bus lane solution;

- Calibration data: it refers to data collected for adjusting the network performance closer to the real-life conditions. Calibration data is collected at the same time as traffic data, and some examples might be: traffic counts, travel times, delays or queue lengths.

- Validation data: it is similar to the calibration data, but the collection is done at different sites from those used for the calibration. This information will be tested against the predictions of the already calibrated model and the error between the modelled and collected data will be assessed. If difference is inside the acceptable range of error, then the model is considered validated and can be used.

It should be remarked that, although being the best source of information, a full scheme of field measurements tends to demand great financial effort. Therefore, a rigorous assessment of the priorities for data collection should be made, considering every source of information that might be available. Some examples of this situation are: an existing macroscopic model, prior studies information, specialized bibliography and operators and local's authority information.

4.6.1.2. Supply characterization

The supply characterization is the process where the information gathered in the data collection process is prepared and then coded as an input of the microsimulation model. The type of information relates to the physical (e.g.: lengths, number of lanes, etc) and operational (free flow speed, signal timings) data that will allow the full characterization of the nodes and links of the network to be modelled.

Figure 4.3 exemplifies how the use of a higher tier model containing the study area might represent a useful shortcut to the data collection and coding processes. The information contained in the macroscopic model can be converted to the microsimulation input format, providing an initial solution of the supply side of the "without" bus lane scenario

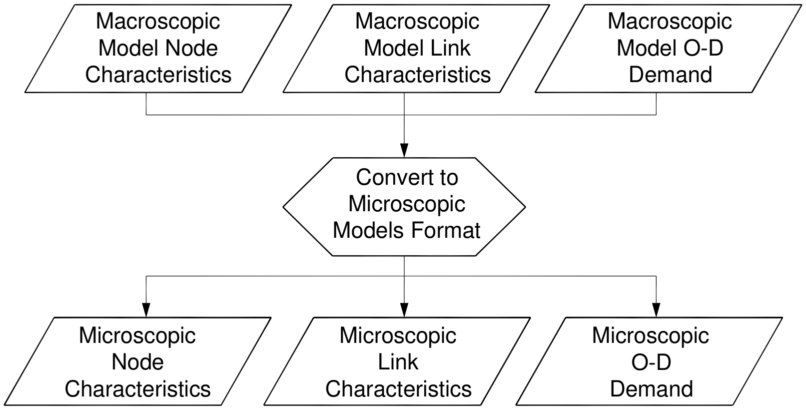

Figure 4.3: Data conversion process

Nevertheless, the transferability of the information between programs is not always a clear cut question because data from the macro model may not be directly processed by the microsimulation software. In this case, some extra programming might be worthwhile, even if the common information is not much.

Additionally, it should not be expected for the transferred information to be sufficient even for running the microsimulation. This type of information is usually reduced to lengths, free flow speeds or node coordinates. So, extra inputs requirements should be fulfilled with the data obtained in field.

4.6.1.3. Demand Characterization

The demand characterization is the process that leads to the construction of the O/D matrix for the analyzed network regarding the study time period. The analyzed network is the representative road network located within the study area and the time period chosen for a bus lane impact study should be representative of the period of highest demand, i.e., peak hour.

The estimation of the O/D matrix is commonly based on one of the following two approaches:

- Data collected from direct observation (e.g.: counts, license plate surveys or road side interviews);
- Derived from some sort of trip distribution model (e.g. trip generation model).

The first approach is evidently preferable, although the costs involved may require some mixed techniques. The *Guidelines for Applying Traffic Microsimulation Software* (Dowling *et al.*, 2002) provides excellent guidance on the latest.

The existence of a validated macroscopic model can also be helpful to the demand characterization as already shown in Figure 4.4, although the condition that the study time periods has to be the same for the macro and micro models must be guaranteed. Additionally, the density of links and zoning system within the study area in the macroscopic model cannot highly differ from the ones to be coded in the microsimulation. If this happens the information will be too aggregated and possibly not worthwhile to convert.

Figure 4.5 shows the trip arrangement when transferred from the original macroscopic to the microscopic traffic simulation environment. The resulting zones for the “cropped” matrix are the same as the macro for the interior trips (yellow). Additionally, new zones will be created by the consideration of the trips that have their origin and/or destination outside the study area (blue, green and red).

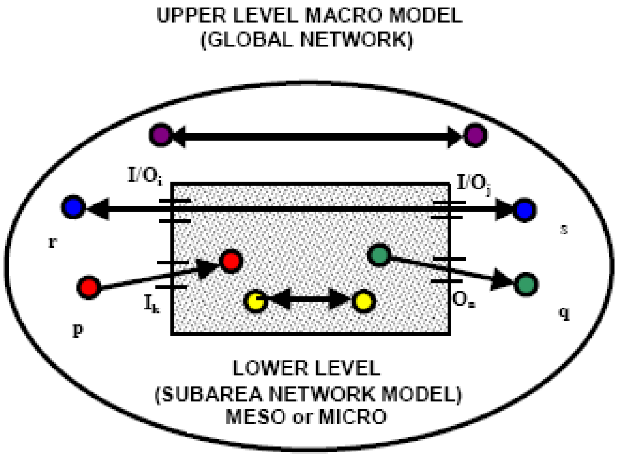

Figure 4.4: O/D matrix estimation from a macroscopic model (Barceló *et al*., 2005)

The complexity of the conversion process is mostly associated with the level of compatibility between the two softwares. Even if made through automatic procedures, the analyst should be aware that further verifications and arrangements in the microsimulation will most probably be needed.

4.6.1.4. Calibration

The calibration stage uses the collected traffic data to allow parameter adjustments to the model. The main objective is to approximate the model outputs to the field measurements.

The methodology used to pursue with the calibration stage depends on the model parameters and also on its outputs capabilities, but a general approach should embrace the following tasks (Dowling *et al*., 2002):

- Error checking: this task aims the identification and correction of coding errors related with the supply and demand characterization;
- Capacity calibration: this stage seeks to calibration the model regarding capacity field measurements. The parameters changed are the ones affecting directly the vehicle behaviour like the ones related with the car following, lane changing or gap acceptance;
- Demand calibration: the calibration for demand aims to approximate the modelled flows and route choices (if the assignment model exists) to the field measurements. The parameters used, once the network capacity is already validated, are those that might influence the traffic flows like: free flow speed, link costs function, vehicle generation, etc.

- Statistical treatment: Figures between the modelled and measured Figures are needed to assess if the overall calibration as reached the acceptable standards goals. The variables mostly used for this assessment are the traffic flow and travel times because they are the easiest measurable ones. Examples of the most used calibration measurements and their targets are presented in Appendix A.

The complexity of the calibration process added to the stochastic nature of the microsimulation results are currently leading to the development of automatic procedures to ease up the necessary work. The goal is to automatically find the most adequate parameter combination for reaching the best calibration targets (Hourdakis *et al.*, 2003 and Park and Qi, 2004).

4.6.1.5. Validation

The validation step is the last of the construction of the model and the objective is to assess at what level the modelled "before" scenario is "correctly" representing real life conditions. This will be made by comparing data that so far was not used in the previous stages against the modelled data. The process is similar to the calibration and again uses the same targets although with different tolerances

4.6.2. "WITH" BUS LANE SCENARIO

The development of the "with" bus lane scenario in the microsimulation traffic model environment follows the same methodology used for the development of the "without" bus lane scenario, although the last 2 stages, calibration and validation, are not needed. In fact, most of the work done can be rearranged to fit the new modelling necessities.

Regarding the previously presented construction stages, the differences in the supply characterization between the two scenarios are usually small and involve only the recoding of the "without" scenario in order to consider the "with" bus lane scenario design, as the example of Figure 4.6 shows.

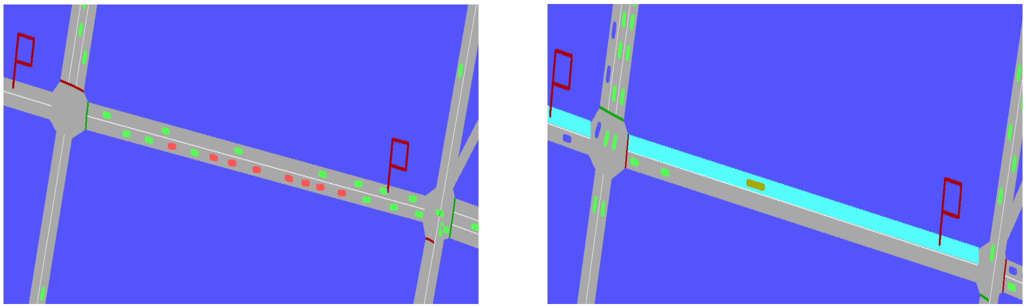

Figure 4.5: Coding for "without" and "with" bus lane scenarios

There are also conceptual differences to account when coding the “without” bus lane scenario. Examples of this situation are the calibration (except the error checking) and validation stages that do not have to be considered in this case once no extra field data for a “with” bus lane scenario can be collected.

Yet, some relevant differences may occur within the demand definition process especially of a macroscopic model is being used. These aspects will be discussed in the following section.

4.6.2.1. Demand characterization

In the case of the demand characterization for the “with” bus lane scenario, the procedure can differ whether or not the macroscopic model was used in the estimation of the O/D matrix.

In the first case, the “cropping data” procedure will also be applied to the “with” bus lane scenario, following the scheme:

- Recode the macroscopic model considering the new bus lane;
- Run the macroscopic model;
- “Crop” the O/D matrix representative of the inside the study area.

The procedure is similar to the one used in the “without” bus lane but now the “cropping” process considers the predicted reassignment effect due to the bus lane introduction for the whole area modelled by the macroscopic model. The practical implication of this procedure is that the O/D matrix estimated for the “without” and the “with” bus lane scenarios will be most probably different. The difference level will increase if the previously defined study area is too small to account this reassignment factor.

Figure 4.7 aims to illustrate this difference by showing the example of trips that in the “without” bus lane “cropping” process are accounted (blue), but will not be for the “with” bus lane scenario if this methodology is proceeded (dotted line).

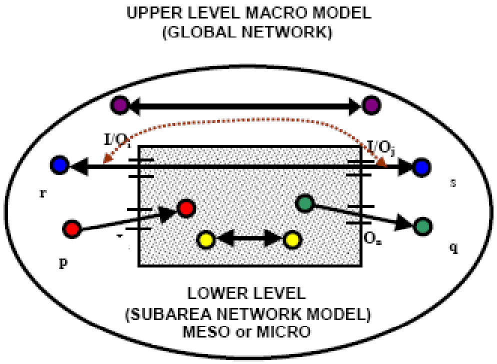

Figure 4.6: O/D matrix estimation from a macro model (Barceló et al., 2005)

Note that this procedure is highly dependable on the capabilities of the macroscopic model for the assignment proposes and for having a level of coding that allows, at least in a approximated way, the consideration of bus lane coding.

In the case where the O/D matrix is estimated from the data collected, i.e., there is no macroscopic model to consider, the demand will be the same for both scenarios. Note that although the O/D matrix will be the same, that does not stand for used routes. In fact, the probability for not happening is high, once the reassignment effect that will be considered, internally or externally (using a compatible assignment model) by the microsimulation model.

4.7. EVALUATION PROCESS

As Figure 4.7 presents, the evaluation process is based on the comparison between the operational changes between the "with" and "without" scenarios. In order to proceed with the evaluation some stages need to be accounted, namely:

- Definition of the scope of analysis;
- Choice the operational indicators;
- Evaluation and decision making.

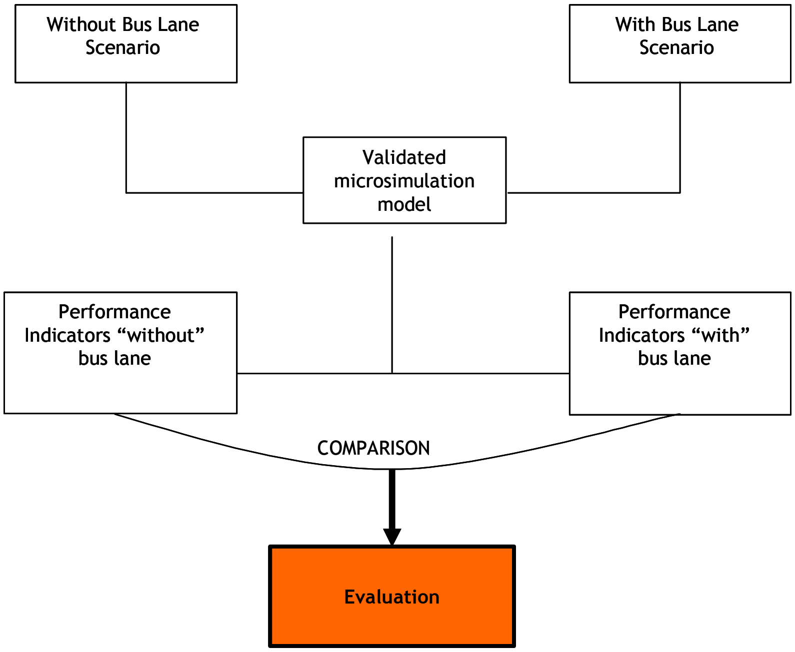

Figure 4.7: Evaluation process

4.7.1. SCOPE OF ANALYSIS

The scope of analysis proposed in this methodology is extensive to the all the study area. Thus, all the operational Figures selected for comparison should be presented aggregated for the “with” and “without” scenario. It is based on these Figures that decisions on the feasibility of tested bus lane scheme should be made.

The procedure aims to embrace one of the main objectives of the proposed methodology, i.e., the quantification of time impacts for all traffic significantly affected by the bus lane introduction.

The approach comes clearly in opposition with the common “corridor” evaluation one, once the latest only studies the operational conditions along the street where the bus lane is being tested. The sole adoption of the latest as the evaluation approach would deny the possibility of traffic also extremely affected (surrounding traffic) by the bus lane introduction to be considered within the evaluation process.

On the other hand, and especially when small operational differences are quantified, the “corridor” analysis can be very helpful for the identification of the most problematic areas for a further optimization on the bus lane design.

4.7.2. PERFORMANCE INDICATORS

The performance indicators play a key role in the evaluation process, because it is based on their quantification that the evaluation is preceded. This judgement is crucial for the final evaluation, i.e., to decide whether or not the tested scenario is likely to be beneficial if implemented.

The proposed methodology does not fixate a specific traffic model, and since the outputs definitions tend to vary from software to software, the choice of the performance indicators might be tricky.

To deal with this specificity, it is recommended that the analyst must be fully aware of the definition of each operational output as also have a clear idea of the methodology used for its quantification.

Nevertheless, there some examples of basic outputs that most of the microsimulation traffic models should be able to directly or indirectly (processing the outputs) produce and that can be used. Their use is indicated for the evaluation for the whole study area, as also, if calculated in a corridor/link basis, for the identification of the most congested points in the network. Thus, the current methodology proposes the following performance indicators:

- Total Travel Time: it is the product of the link volume and the link travel time, summed all over the links. It is an indicator of the overall time spent by vehicles in the system during the period of analysis. A decrease in the total travel time would usual reflect an improvement in operational performance of the system, although this does not always stands, per example, when comparing networks with different demand patterns. Some models have the ability to desegregate the total travel time in their two main components: total delay and total cruise time;

- Total Delay: as the name indicates, it is the product of link volume and the "delay" time in that link, summed all over the links. The definition of delays may vary from model to model, per example, some models consider it to be the difference between free flow time and effective travel time while others consider the stopped time along the link, etc. To avoid misleads it is essential that the analyst consults the software documentation for clarification on the subject;

- Total cruise time: it is the product of link volume and the link "cruise" time, summed all over the links. Again, and as a result of being the complement of the total delay in the total travel time calculations, the definition of cruise time may not always be constant between models. This desegregation of the travel time might be useful in the comparison between alternatives, especially for a deeper understanding for the nature of the changes;

- Total travel distance: it is the product of the link volume and the link length, summed all over the links. It is an indicator of the travelled distance inside the network for the studied time period;

- Overall average speed: it is the ratio between the total travel distance and the total travel time. This measure is an overall indicator on the system operational conditions, and has the advantage of abbreviating the effects of the dependency of traffic demand expressed by the others indicators. Thus, a decrease in the overall average speed between similar networks, even with different demand patterns, will normally mean deterioration in the operational conditions.

Additionally, the passenger indicators of performance are important for the evaluation of public transport strategies (Shalaby, 1999). These indicators differ from the previously presented by the adding the average occupancy per vehicle to the number of parcels in the product, coming as:

- Total passenger time: it is the product of the total travel time and the average vehicle occupancy;

- Total passenger distance: it is the product of the total travel distance and the average vehicle occupancy;
- Passenger speed: it is the product of the total passenger distance and the total passenger time.

An obvious requirement for the calculation of these indicators is the availability of desegregated data by vehicle type (provided by the model) as also reliable estimates of the average occupancy of each considered vehicle type.

Note that the consideration of the average occupancy works as a "weighting" factor for the calculation of the indicators. In practise, a greater "weight" will be given to the vehicles that averagely carry more people (e.g.: buses), and so the changes in their operational conditions will have stronger influence in, per example, the calculation of the passenger speed.

In the estimation of the performance indicators it must be acknowledge the stochastic nature of the microsimulation models that will provide different results for each input seed. Thus, it is necessary to run the model several times, each of them with a different seed, in order to take the average for all selected indicators.

The statistical notion of confidence interval can be applied to this case in order to provide some orientation on the variation of results. In fact, it is known that the confidence interval for the mean regarding a small number of samples values can be estimated by using the t-Student distribution, as shown:

$$\overline{X}(N) \pm t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{N}} \qquad (4.1)$$

Where:

$\overline{X}(N)$: Estimate the mean from n simulation runs (samples)

$S^2(N)$: Estimate of σ from n simulation runs (samples)

N: Number of simulations

α: Level of significance

$t_{n-1,1-\alpha/2}$: Critical value of the t-test for n-1 degrees of freedom and significance α

The formula shows that interval will enlarge if the N decreases and/or if the wanted level of significance decreases. Note that this is only applicable if the distribution of the sampling average is normally distributed. This happens if one of the two conditions is verified:

- The distribution of the studied indicator is normally distributed.
- The number of replicas is sufficiently high (N>30) – Central Limit Theorem

Another approach to the problem might be to consider an incremental approach (Law, A.M. and Kelton, W.D., 2000), that calculates the number of replicas needed for a given allowable percentage of error, by (re)calculating the half length of the confidence interval (from initial estimations of the average and standard deviation) until the matching of both values.

After the estimation of confidence intervals for the various indicators, it will be necessary compare the Figures for the “with” and “without” scenarios. Problems may arise if the confidence intervals intercept. In this case, hypothesis tests using the common t-test should be considered to analyse the trueness of the null hypothesis for a given significance (Dowling *et al.*, 2002). In this case, the null hypothesis would correspond that the difference between the means of the tested indicator for the two scenarios is zero.

4.7.3. EVALUATION AND DECISION

Once the statistical treatment is completed the comparisons between indicators from the two scenarios can be made and the decision making is of course dependable of the results of the evaluation.

In the cases where the overall time benefits within the study area are expected from the bus lane introduction, then the Figures should consist as an element for a further evaluation. A final decision on the feasibility of the tested scheme is dependent on other factors than the purely operational ones and therefore it is desirable to proceed with the economic evaluation.

Even so, it must be mentioned that the operational aspects are indispensable to any economic evaluation and therefore the results for the “before” and “after” scenario that can be assessed using the presented methodology can play a very important role in the final decision making.

CHAPTER 5 - CASE STUDY

5.1. INTRODUCTION

The following chapter will be centred on a study to evaluate the operational impacts of the introduction of a with flow bus lane in an arterial street located in the city of Porto, Portugal.

The work will provide the opportunity to test the capabilities of the methodology described in chapter 4 for the evaluation of the operational impacts caused by the bus lane introduction. Hopefully, the application to a real-life scheme might allow drawing some conclusions on the quality of the approach as also highlight some important aspects to the study of this type of bus priority measure.

Additionally, and by considering three different demand test scenarios, the methodology was used to pursue some secondary objectives, namely:

- Confirm the importance of traffic reassignment in the evaluation process;
- Demonstrate the significance of considering the study of an impact area instead of pursuing with a simpler corridor analysis.

5.2. STUDY SITE AND DESIGN

The chosen location for the bus lane introduction testing was “Rua da Constituição”, one of the busiest one-way arterial streets in the city of Porto. The street starts after the junction with “Prof. Bento Jesus Caraça” and ends in “Rua Pedro Hispano”, providing a major interior East - West connection along the city and with a length of approximately 2,7 km (Figure 5.1).

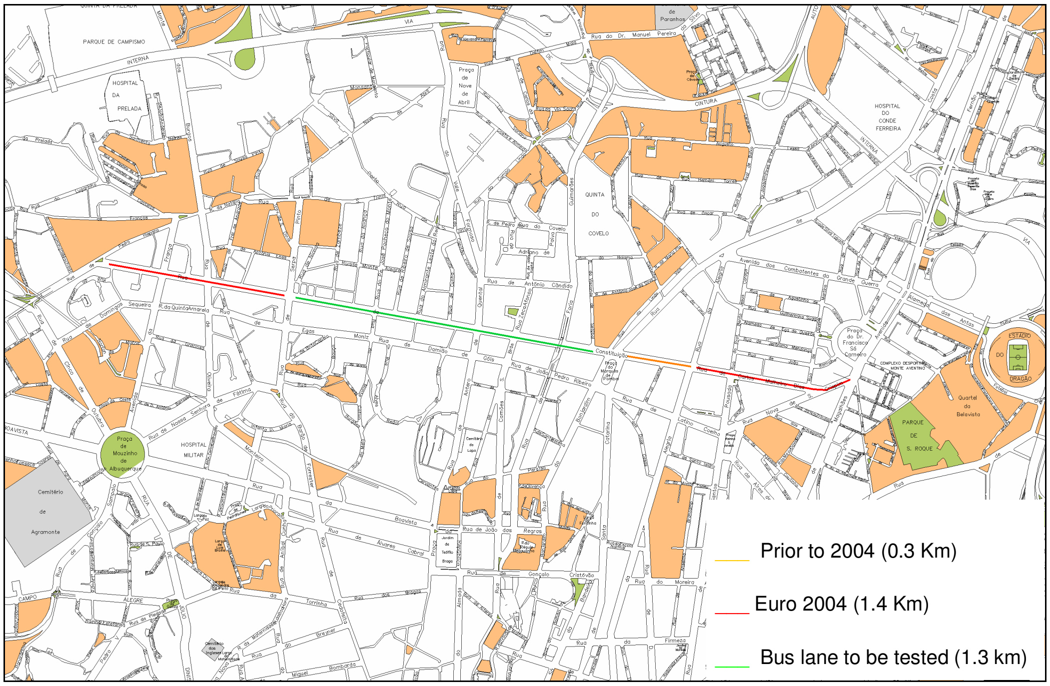

Figure 5.1: Study site and bus lane location

The street crosses highly traffic congested city locations like “Praça do Marquês” and provides access to (in “Faria Guimarães” intersection) and from (in “Rua de S.Brás/José Afonso”) the city’s main ring road (VCI – “Via de Cintura Interna”). Furthermore, there are road junctions with important (North-South) radial arterial streets such as “Rua Antero de Quental”, “Rua Serpa Pinto” or “Rua Oliveira Monteiro”.

As for the existing bus lanes, the earliest one to be introduced was between “Rua da Alegria” and “Praça do Marquês” with a total of 0,3 km long. By the year 2004, and for the occasion of Euro 2004, the Porto’s City Council (“Câmara Municipal do Porto”) decided to extend the bus lanes from “Praça Francisco Sá Carneiro” to “Rua da Alegria” (0,6 km) and from “Rua Serpa Pinto” to “Rua Oliveira Monteiro” (0,8 km).

The pointed reason for this decision was the expected decrease on bus travel times and increase in passenger capacity along the corridor, witch was hopped to strongly contribute for the quality of the bus service provided for the coming visitors. Note that the bus lanes where designed trough the conversion of available parking space in order to minimize the capacity lost for general traffic.

The sections that were left out of this bus lane scheme, i.e., sections between “Praça do Marquês” and “Rua de Serpa Pinto”, are precisely the ones that this study proposes to evaluate.

The methodology pursued to define the design intended to test the bus lane introduction, changing the least possible in the existing scheme in order to better isolate the consequences that were exclusively due to the tested alteration.

This way, it was decided to test a bus lane that would be the result of a conversion an existing general traffic lane, instead of, per example, convert the existent parking lane. The transformation obeyed to the following three main conditions:

- The existing circulating scheme would maintain: this implied that the possible turns at the junctions are the same for the “with” and “without” bus lane scheme. It also implies that, for the right turn case, setback would have to be provided;
- The tested bus lane would be a nearside width flow type: this condition was set for technical reasons, once all buses operating in the street have door opening devices located on their right side.
- No changes or attempts for optimizing the traffic signals would be made and only the necessary arrangements in the junctions would be accounted (e.g.: removal of right side lane in junction “Rua Faria Guimarães” for consistency with the new lane distribution).

5.3. DEFINITION OF THE STUDY AREA

As presented in the previous chapter the definition of the study area is one of the key steps in the proposed methodology. Besides the described aspects that have to be regarded in this case, the use of a validated macroscopic model that covers the all city can play an extremely important role in the study area definition.

For this case study, it was used the Porto’s Assignment Model (MATRA), property of the City Council, witch is an application of the commercial software SATURN - *Simulation and Assignment of Traffic to Urban Road Networks* (Van Vliet, 2005) to the city’s main road network. MATRA started being developed in November 2005 and is a currently used tool for the evaluation of traffic appraisal schemes within the city. Further information on the model’s construction can be found in Appendix B.

In order to be used in the definition of the study area, MATRA was re-coded to include the proposed bus lane in “Rua da Constituição” and tested against the base version for changes in demand flow and delays (Figure 5.2).

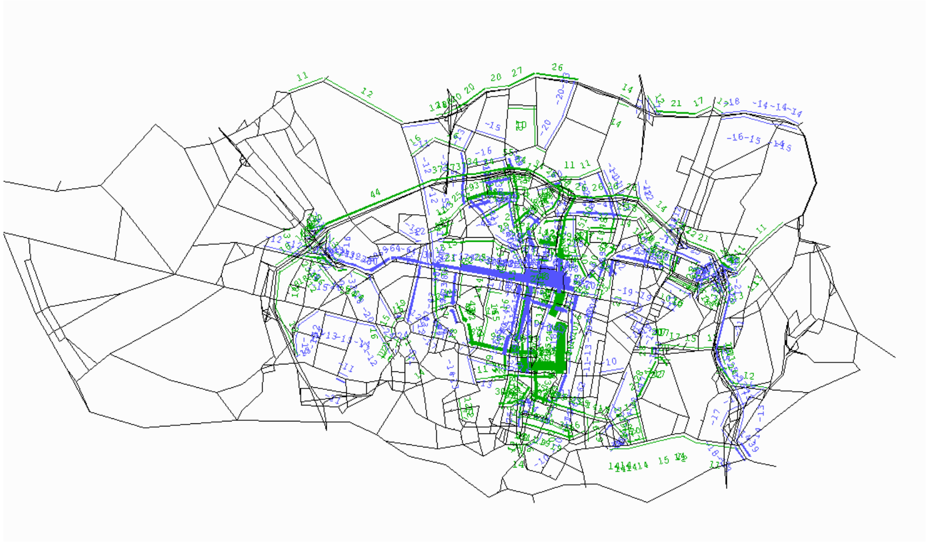

Figure 5.2: Definition of the study area: demand flow variations

The resulting impact area (Figure 5.3) was found to be much wider than the small region surrounding the sections where the bus lane introduction is being tested. In fact the new study area has about 4.5 Km^2 and it can be roughly defined by the following borderlines:

- South: “Rua Gonçalo Cristóvão”
- West:”Rua Oliveira Monteiro”
- North: “Rua do Covelo”
- East: “Rua de Santos Pousada”

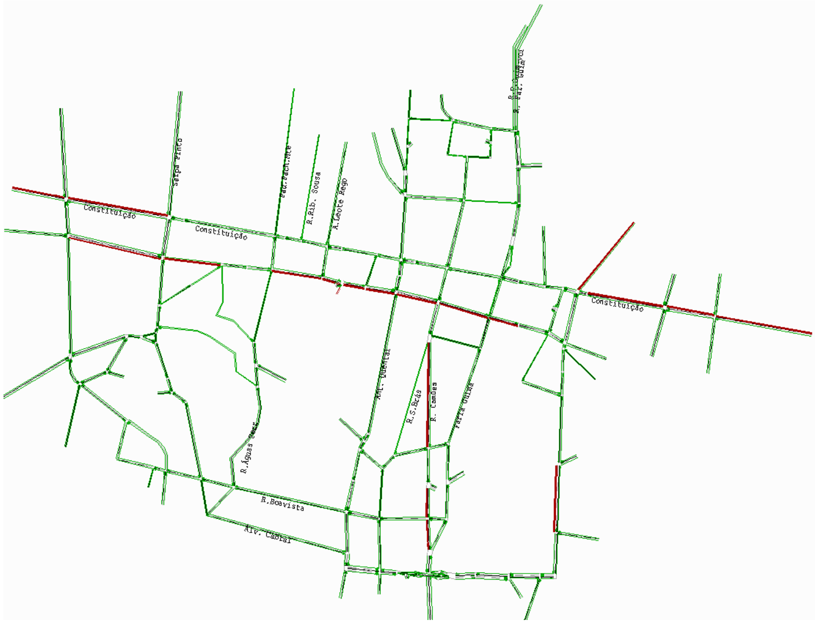

Figure 5.3: Selected study site

5.4. TRAFFIC MODELS

The selection of the traffic model to pursue with the construction and further evaluation of “with” and “without” bus lanes scenarios followed the described methodology of the previous chapter. Therefore, the decision lied on the consideration of two traffic models for the evaluation process: the SATURN - *Simulation and Assignment of Traffic to Urban Road Networks* (Van Vliet, 2005) and DRACULA - *Dynamic Route Assignment Combining User Learning and Microsimulation* (Liu, 2005).

The selection of SATURN was based on the fact that MATRA was developed using this model to the city’s network. This option allowed the construction of the model for the study area network with a decrease in the time and costs once the definition of the network’s supply and demand was obtained by “cropping” the original city network. Another direct advantage of using SATURN was the previous knowledge of the program main features by the analyst, witch also contributed for the less time needed for the modelling and evaluation of results.

As for the results provided the fact that, unlikely many traditional assignment models, SATURN operates with cyclic flow profiles (Van Vliet, 2005) to simulate the movement of vehicles on the network. This guaranteed an extra level of detail when dealing with some important aspects when working with bus lanes (e.g.: queue spreading, delays at junctions, stacking back effect, etc.). The possibility of obtaining disaggregated results for vehicle type and the straightforward codification of bus lanes were also main requirements that were fulfilled by SATURN.

In the Dracula’s case, the main reason for choosing the program lied on the fact it is a microsimulation model compatible with the SATURN coding. In fact, with only a few small arrangements, the software processes the Saturn’s supply and demand characterization files, lowing down the modelling needs. Additionally, the software is able to provide the required outputs for the evaluation of a bus lane introduction scheme.

During the modelling process, certain model limitations were found. The acknowledgment of those limitations was important once they influenced the final results. Table 5.5 relates to the limitations found when coding bus lanes and bus operations as equally to the methodologies used to overcome them.

The consideration of two different models to quantify the performance indicators does not alter the methodology to the analysed case once the analysis will be carried out separately. In fact, since the working philosophies for both models are different, the range for comparison between the results is limited to the major operational changes tendencies within the study area.

On the other hand, the use of two different software's will hopefully emphasize the importance of certain modelling possibilities and limitations that are important to consider whenever dealing with the quantification of the operational changes associated with a bus lane scheme.

Table 5.1: Limitations of the chosen models

Limitation	SATURN	DRACULA
Bus speeds	The buses operate at same speed as cars whenever using a general traffic lane or a bus lanes. This limitation does not allow the consideration the different operational conditions (acceleration, deceleration, etc) that the two modes have.	Vehicles operational and physical characteristics can be modelled using DRACULA.
Bus stops	No bus stop related information (e.g.: location, average dwell times, etc) is considered in the data processing. This fact unables the consideration of the effect that bus stopping has on buses and car travel times	Bus stops can be coded in DRACULA. Using the information provided by the local bus operator, 51 bus stops were coded. The program was converted to allow buses to stop at every bus stop for 15 sec.
Bus lane operation	The bus lane operate as having unlimited capacity, so no delays are associated to buses whenever they travel in the bus lanes.	DRACULA is able to simulate the bus-bus interference as also other important aspects of the bus lane operation.
Bus lane setbacks	The setback codification is problematic once it is impossible to associate bus-only movements at a lane level. Sensitivity tests suggested that in order to avoid unrealistic delays the setbacks should not be considered in the SATURN codification	The problem of bus-only turn assignment detected in SATURN was also found when coding the bus lane setback in DRACULA. This time the sensitivity tests pointed to a solution where a setback was considered but the bus had to merge back into the general traffic lane in order to pursue with their in-front movement
Bus operational outputs	The bus operational outputs were presented disaggregated by route and link and the average figures were presented assuming that all the vehicles finished their journey in the studied time period.	An effort was made for reformulating the program to so that the aggregate results by vehicle type could be presented.

5.5. DEVELOPMENT OF SCENARIOS

The scenario development followed the requirements exposed in the previous chapter. A base scenario representing the actual circulating conditions in the study area was developed along with three other “demand” scenarios for the “with” bus lane scenario. This option was taken to evaluate the effect that the consideration of traffic reassignment effects can have in this type of studies.

5.5.1. “WITHOUT” BUS LANE SCENARIO

The “without” base lane scenario represents the base case for the analysed case study. The use of MATRA for the selection of the study area allowed a quicker characterization process of the supply and demand in the scenario construction using both SATURN and DRACULA.

In the first case, and since MATRA is an application of SATURN to the whole city area, the construction of the base case (supply and demand) scenario was based on the “cropped” network and matrix resulting from the selection of the study area.

The codification using DRACULA benefited from the compatibility between the two softwares. In fact, with only a few alterations in the SATURN’s files, DRACULA was able to interpret the relevant information and process it in a microsimulation environment.

The application of the “cropping” process also allowed that the two networks could be “structurally” equal, i.e., have the same node, link and zones distribution (Table 5.2 and Figure 5.4). This aspect was found to be very useful for an easier interpretation of results and for the comparison of outputs between the two considered softwares.

Table 5.2: Supply characterization

NETWORK	MATRA	“Cropped” Network (SATURN and DRACULA)
Nodes	1321	160
Links	2324	266
Zones	108	48

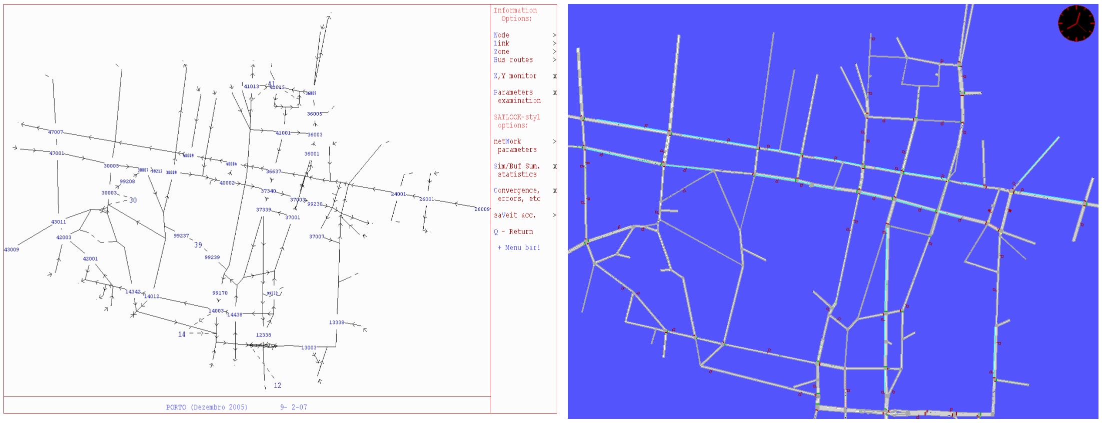

Figure 5.4: SATURN and DRACULA models of the study area

The calibration and validation of the base scenario was performed the same way for SATURN and DRACULA. As explained in the previous chapter, the calculation of the relevant statistical parameters based on the comparison between the modelled and measured values was performed and the results are summarized in Table 5.3. The detailed information regarding this subject can be found in Appendix C.

Table 5.3: Calibration and Validation results

Parameters	Calibration (16 Counts)	Validation (15 Counts)
SATURN		
GEHM	2,92	5,14
GEHM*	1,34	3,87
GEH5	0,75	0,60
P85	0,81	0,74
DRACULA		
GEHM	2,37	5,61
GEHM*	1,52	4,43
GEH5	0,81	0,40
P85	0,88	0,47

The results pointed values close to the recommend ones in the case of calibration for both SATURN and DRACULA, while in validation the tendency was for a bigger difference. Once time and resources limitations existed, an extra piece of information was used for validation based on a work made on “Rua da Constituição” (CMP, 2003). Table 5.4 shows the comparison between modelled and measured travel times precisely in the area of the tested bus lane scheme. The surveyed routes are shown in Figure 5.5.

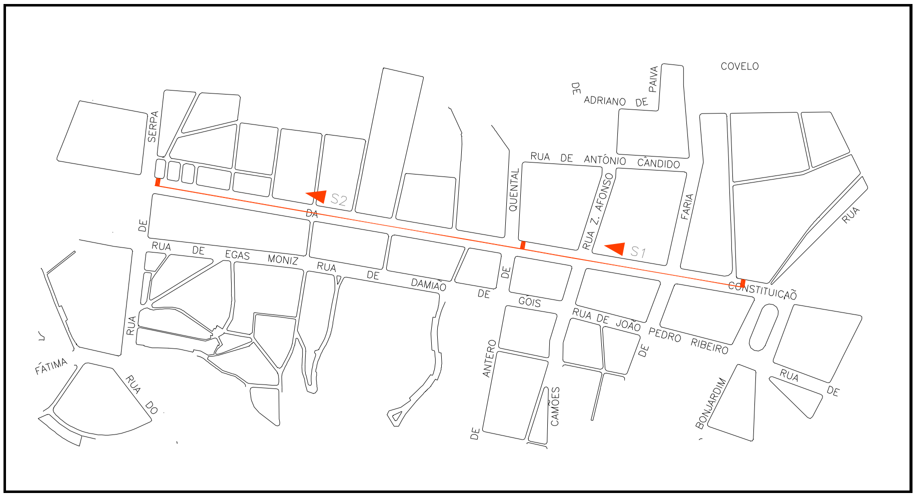

Figure 5.5: Measured routes (CMP, 2003)

Table 5.4: Validation trough measured journey times

	Modelled	Measured	Absolute Difference	Difference (%)
SATURN				
S1 (sec)	158	175	-17	-11%
S2 (sec)	124	146	-22	-18%
DRACULA				
S1 (sec)	152	175	-23	-15%
S2 (sec)	148	146	2	1%

The values are close to the recommended ones for the validation purposes (<15%) and attending to the relevance of the measurements location to the following work, it was decided to considered the base case scenario for both SATURN and DRACULA as valid for the study purposes.

5.5.2. “WITH” BUS LANE SCENARIO

Once the base case was considered valid for the study purposes the development of the “with” bus lane scenario was the following task. The supply characterization required the codification of the bus lane under evaluation while the demand characterization was assessed using three different methods.

As mentioned in the study objectives, one of the purposes of this study case was to evaluate the impact that the consideration of traffic reassignment effects might have on the overall operational results. Therefore, it was necessary to consider different demand scenarios representative of several levels of traffic reassignment. These were:

- BL0 scenario: it represents the “no reassignment scenario”, therefore the traffic demand would be the equal (same O/D matrix and same travel routes) for the “with” and “without” bus lane scenario. It can be seen as a conservative or short term scenario once it is clear that the bus lane will cause (at least at some level) lost in capacity to the non-bus traffic. So, if there is no contemplation for reassignment in the analysis, than it almost certain that the congestion will rise near the new bus lane scheme and the bus lane introduction will be harder to justify based on the operational changes.

- BL1 scenario: This scenario represents the case described in 4.6.2.1, where the traffic demand is the same for the “with” and “without” bus lane scenario (same O/D matrix) but the routes may not be because there is the possibility of traffic reassignment within the study area. This can be interpreted as an example of when the demand characterization is made and a higher tier model is not considered for O/D matrix estimation, i.e., the traffic reassignment effect is restricted to the selected study area.

- BL2 scenario: it represents the case where a higher tier model, in this case MATRA, was used to the demand characterization of both "with" and "without" bus lane scenarios. The practical effect of this procedure is the fact that O/D matrix will be different for the "with" and "without" bus lane scenarios. It probably represents the best approximation of the demand, once traffic reassignment as a result of the supply change (introduction of the bus lane) is not restraint to the study area.

5.6. EVALUATION PROCESS

Once the scenarios were defined, the following task was to pursue with the evaluation process. As mentioned in Chapter 4, the conclusions should be drawn after the confrontation between the chosen performance indicators the "before" and "after" bus lane scenario.

The analysis will include the calculation of the overall operational indicators for each scenario, using SATURN and DRACULA, for the following areas:

- The study area: once the methodology used assumes that the operational impacts should be assessed considering all the vehicles operating in the selected impact area of the tested bus lane scheme;

- Selected corridor: a corridor analysis is introduced as a complement in order to help detecting the main operational differences between the tested scenarios. The option of analyzing more than just the sections where the new bus lane is being tested was taken to allow some level of queue spreading. Thus, the figures presented regarding the corridor analysis were calculated based on the time components and performed flow for a corridor along "Rua da Constituição" starting in section " C. M. Dias - B. J. Caraça" and ending in section "Constituição -Av.França".

The two approaches were applied to the scenarios considered to allow conclusions to be drawn on the feasibility of the tested bus lane scheme and quality of the proposed methodology.

5.7. PRESENTATION AND DISCUSSION OF RESULTS

5.7.1. SATURN – STUDY AREA RESULTS

The performance changes between the tested scenarios and the base case within the impact area are presented in Table 5.5, witch contains the aggregate the results for the two modes of transport considered: buses (Table 5.6) and cars (Table 5.7). All of these tables refer to the performed flows (actual flows) for the considered morning peak period (60 minutes). The "passenger" results were calculated considering an average bus occupation of 50 passenger per bus and 1.3 for the cars (CMP, 2005).

Considering the software limitations, one exception occurs for the bus information aggregated by route in Table 5.8, where figures assume that all buses have finished their journeys within the tested time period.

Table 5.5: SATURN: Total changes in performance within the study area

Absolute totals		Without BL	With BL			Relative Difference		
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Total Delay	veh.h	798,4	1566,1	1019,7	880,7	96%	28%	10%
Link cruise time	veh.h	722,5	684,5	720,7	712,4	-5%	0%	-1%
Total Travel Time	veh.h	1520,7	2250,6	1740,3	1592,9	48%	14%	5%
Total Passenger Time	pass.km	2824,3	3960,6	3178,0	2981,5	40%	13%	6%
Total Travel Distance	veh.km	22475,0	21360,6	22516,3	22276,3	-5%	0%	-1%
Total Passenger Distance	pass.km	42636,7	40647,4	42527,3	42278,6	-5%	0%	-1%
Passenger Speed	km/h	15,1	10,3	13,4	14,2	-32%	-11%	-6%
Overall Average Speed	km/h	14,8	9,5	12,9	14,0	-36%	-12%	-5%
Total Trips Loaded	veh/h	16120	16120	16120	16079	0%	0%	-0,3%

Table 5.6: SATURN: Changes in bus performance within the study area

Bus totals		Without BL	With BL			Relative Difference		
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Total Delay	veh.h	8,5	12,7	10,0	9,9	50%	18%	17%
Link cruise time	veh.h	9,0	8,6	8,9	8,9	-4%	-1%	-1%
Total Travel Time	veh.h	17,4	21,3	18,8	18,7	22%	8%	7%
Total Passenger Time	pass.km	870,0	1062,5	940,0	935,0	22%	8%	7%
Total Travel Distance	veh.km	275,6	264,5	272,2	273,5	-4%	-1%	-1%
Total Passenger Distance	pass.km	13777,5	13222,5	13610,0	13675,0	-4%	-1%	-1%
Overall Average Speed	km/hr	15,8	12,4	14,5	14,6	-21%	-9%	-8%

Table 5.7: SATURN: Changes in car performance within the study area

Car totals		Without BL	With BL			Relative Difference		
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Total Delay	veh.h	789,9	1553,4	1009,7	870,8	97%	28%	10%
Link cruise time	veh.h	713,5	675,9	711,8	703,5	-5%	0%	-1%
Total Travel Time	veh.h	1503,3	2229,3	1721,5	1574,2	48%	15%	5%
Total Passenger Time	pass.km	1954,3	2898,1	2238,0	2046,5	48%	15%	5%
Total Travel Distance	veh.km	22199,4	21096,1	22244,1	22002,8	-5%	0%	-1%
Total Passenger Distance	pass.km	28859,2	27424,9	28917,3	28603,6	-5%	0%	-1%
Overall Average Speed	km/h	14,8	9,5	12,9	14	-36%	-13%	-5%

Table 5.8: SATURN: Changes in bus routes performance within the study area

			Without BL	With BL					
Route	Buses/h	Distance (m)	Speed (Km/h)				Relative Difference		
			Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
4	2	809	11,3	7,7	11,3	11,3	-32%	0%	0%
5	2	1445	14,1	7,9	13,4	14,9	-44%	-5%	6%
16	2	809	11,3	7,7	11,3	11,3	-32%	0%	0%
38	2	515	27,8	27,4	27,8	27,8	-1%	0%	0%
47	2	4180	19,1	15,2	13,8	17,7	-20%	-28%	-7%
51	2	1223	9,9	6,5	8,6	5,9	-34%	-13%	-40%
53	3	2158	18,5	13,4	11,9	17,5	-28%	-36%	-5%
71	4	3059	17,4	16,7	17,7	17,7	-4%	2%	2%
72	2	3059	17,4	16,7	17,7	17,7	-4%	2%	2%
90	2	515	27,8	27,4	27,8	27,8	-1%	0%	0%
302	4	2387	19,2	19	19,1	19	-1%	-1%	-1%
303	6	2895	14,3	7	15,3	15,2	-51%	7%	6%
701	4	1392	15,9	14,1	9,2	14,7	-11%	-42%	-8%
702	4	1392	15,9	14,1	9,2	14,7	-11%	-42%	-8%
703	4	1392	15,9	14,1	9,2	14,7	-11%	-42%	-8%
21a	6	2779	17,2	7,3	18,2	18,6	-58%	6%	8%
21b	6	2153	11,2	10,9	11	11,1	-3%	-2%	-1%
300a	4	1445	14,1	7,9	13,4	14,9	-44%	-5%	6%
300b	4	1223	9,9	6,5	8,6	5,9	-34%	-13%	-40%
301a	6	1445	14,1	7,9	13,4	14,9	-44%	-5%	6%
301b	6	1223	9,9	6,5	8,6	5,9	-34%	-13%	-40%
46a	4	1445	14,1	7,9	13,4	14,9	-44%	-5%	6%
46b	4	1223	9,9	6,5	8,6	5,9	-34%	-13%	-40%
502a	4	1831	18,7	18,2	14,7	17	-3%	-21%	-9%
502b	4	1201	21,4	21,3	21,4	21,3	0%	0%	0%
50a	6	1445	14,1	7,9	13,4	14,9	-44%	-5%	6%
50b	6	1223	9,9	6,5	8,6	5,9	-34%	-13%	-40%
54a	4	1634	16,2	15,9	17,4	16,6	-2%	7%	2%
54b	4	2038	19	18,1	18,5	19,1	-5%	-3%	1%
600a	6	1634	16,2	15,9	17,4	16,6	-2%	7%	2%
600b	6	1931	19	18,1	18,5	19,1	-5%	-3%	1%
77a	6	1967	23,8	23,9	23,2	22,9	0%	-3%	-4%
77b	6	1833	16,2	16,6	16,8	16,8	2%	4%	4%
82a	4	1831	18,7	18,2	14,7	17	-3%	-21%	-9%
82b	4	1201	21,4	21,3	21,4	21,3	0%	0%	0%
84a	4	1831	18,7	18,2	14,7	17	-3%	-21%	-9%
84b	4	1201	21,4	21,3	21,4	21,3	0%	0%	0%
92a	2	1634	16,2	15,9	17,4	16,6	-2%	7%	2%
92b	2	1931	19	18,1	18,5	19,1	-5%	-3%	1%
95a	2	1634	16,2	15,9	17,4	16,6	-2%	7%	2%
95b	2	1931	19	18,1	18,5	19,1	-5%	-3%	1%

Note: For practical reasons and since the impact area did not include totality of most of the routes, the “a” and “b” in the route name was used to indicate the direction of the route. Thus, per example, 21a should be interpreted as the direction “São Roque - Boavista” and 21b the opposite.

The results obtained for the tested scenarios (BL0, BL1 and BL2) are unanimous in suggesting a general deterioration of the operational conditions within the selected impact area (Table 5.5) if the bus lane introduction was to be implemented. There were although some differences between the scenarios witch will be closely analyzed as follow.

5.7.1.1. Scenario BL0

Comparison between operational indicators between scenario BL0 and the base case presented in Table 5.5 show a relevant increase in the time dependent indicators. Thus, there is an increase in the total travel time (+48%) witch is strongly influenced by changes in the total delays (+96%). Once these scenarios have the same travel pattern, the decrease in total travel distance (-5%) represents another evidence of strong congestion in the study area after the bus lane introduction. A direct consequence of the previous results is the decrease in the aggregated overall average speed (-36%), fact that should be enhanced as a very representative sign of the deterioration of the operational conditions.

Analyzing separately the results for the buses presented in Table 5.6, it can be concluded that they follow the same tendency as the aggregated. In fact, the level of congestion raises to a level, that even buses, the main potential gainers from the introduction of the new bus lane scheme, are not benefited in terms of overall average speed (-21%). The bus results are presented disaggregated by route in Table 5.8, witch evidences a decrease in bus circulating speeds for the generality of the routes operating inside the tested area, including those (route 21a and 303) using the new bus lane scheme.

The decrease in car speed (-36%) presented in Table 5.7 was more expected due to the lost of road capacity resulting from the introduction of the bus lane in “Rua da Constituição”. An important conclusion is the preponderance of the car mode in the aggregate performance measures (Table 5.5). This trend is only slightly abbreviated in the “passenger” weighted measures although the results are still unfavourable to the bus lane introduction. Thereby, the aggregate total passenger time (+40%) increased slightly less than the occurred for cars (+48%) and more than for buses (+22%).

These results strengthen the idea that when unrealistically the traffic reassignment effect is not accounted, like in the case of the BL0 scenario, the operational disbenefits will tend to overcome the expected benefits.

5.7.1.2. Scenario BL1

An analysis to the performance results for the tested scenario BL1 still show evidence of deterioration when faced against the base case, as shown in Table 5.5 Note that this effect is not as accentuated as it is for BL0, what was already predictable once in the scenario BL1 some level of traffic reassignment was allowed.

The aggregated travel time increased (+14%) while the total travel distance stabilized (Table 5.5. These results are again strongly influenced by the increment in total delay (+28%), suggesting that the existing alternative routes within the impact area will not be able to effectively abbreviate the negative impacts of the bus lane introduction.

Buses still reveal a drop in their operational conditions (Table 5.6), as the global decrease in average speed (-9%) and the increase in total travel time (+8%) prove. Despite this overall deterioration, bus routes 21a and 303 get now their speeds increased by around 1 km/h (Table 5.8), fact that evidences some benefits resulting from the bus lane introduction.

Results presented in Table 5.7 predict negative impacts in car total travel time and speed (+15% and -13%) and show that the lost of capacity in one important arterial street like “Rua da Constituição”, will have a major negative influence, even when traffic reassignment is contemplated in the construction of the tested scheme.

Since the car mode strongly influences the aggregate results, the overall average speed (-12%) and the passenger speed (-11%) decreased, confirming the described overall negative impacts.

5.7.1.3. Scenario BL2

The results for the BL2 scenario are also unfavourable to the bus lane introduction, although the negative impacts are smoother then in the tested scenarios BL1 and BL0. Therefore, the total travel times are expected to increase by 5% and the tendency for small differences in total travel distances when compared to the base case (-1%) is maintained. The delay component increases (+10%) although in a much smoother way than for the other scenarios. In terms of speeds, the absolute difference is less than 1km/h (-5%) for the aggregated overall average speed and -6% for the passenger speed

The bus results are very similar to the ones on BL1, i.e., they show unfavourable situation for buses when compared with the base scenario, like the increase in overall average speed (+8%). Analysing the route results presented in Table 5.8, it is shown again that for routes 21a and 303 the average speed improves with the introduction of the bus lane, although the increase in the first is now more evident (+1,4 km/h).

As for the changes in car performances, they show a small increase in total travel times (+5%) that is reflected in the decrease in the overall average speed (-5%). These results can be related to the fact that for BL2 the universe for car traffic reassignment was not delimited by the boundaries of the study area, and so the possibility of diversion was greater. This led to a higher avoidance of congested routes and consequently less car total travel times and higher average speeds (Table 5.7) than the ones in BL0 and BL1. This effect comes only as a secondary consequence to buses because they were coded as fixed demand for any of the three studied scenarios, witch can explain the closeness of bus results between BL1 and BL2.

5.7.2. SATURN – CORRIDOR ANALYSIS RESULTS

The results regarding the corridor analysis are presented in tables 5.9 (all vehicles), 5.10 (bus) and 5.11 (car). The tables contain the summary of results for the chosen corridor while extra information regarding each section may be consulted in Appendix D.

Table 5.9: SATURN: Total changes in performance along the corridor

Absolute totals - Corridor		Without BL	With BL			Relative Difference		
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Total Delays	veh.h	141,4	732,7	269,3	161,2	418%	90%	14%
Link Cruise Time	veh.h	112,1	83,8	90,7	90,2	-25%	-19%	-19%
Total Travel Time	veh.h	253,4	816,5	360,0	251,4	222%	42%	-1%
Total Passenger Time	pass.h	424,0	1215,1	551,4	408,5	187%	30%	-4%
Total Travel Distance	veh.km	3478,7	2682,0	2898,5	2875,5	-23%	-17%	-17%
Total Passenger Distance	pass.km	6059,5	4672,5	5249,0	5219,2	-23%	-13%	-14%
Passenger Speed	km/h	14,3	3,8	9,5	12,8	-73%	-33%	-11%
Overall Average Speed	Km/h	13,7	3,3	8,1	11,4	-76%	-41%	-17%

Table 5.10: SATURN: Changes in bus performance along the corridor

Bus totals - Corridor		Without BL	With BL			Relative Difference		
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Total Delays	veh.h	0,9	2,4	0,7	0,7	161%	-21%	-24%
Link Cruise Time	veh.h	1,0	0,8	1,0	1,0	-25%	-4%	-4%
Total Travel Time	veh.h	1,9	3,2	1,7	1,7	63%	-12%	-14%
Total Passenger Time	pass.h	97,1	157,8	85,6	83,9	63%	-12%	-14%
Total Travel Distance	veh.km	31,6	24,4	30,4	30,4	-23%	-4%	-4%
Total Passenger Distance	pass.km	1578,2	1217,5	1520,5	1520,5	-23%	-4%	-4%
Overall Average Speed	Km/h	16,3	7,7	17,8	18,1	-53%	9%	11%

Table 5.11: SATURN: Changes in car performance along the corridor

Car totals - Corridor		Without BL	With BL			Relative Difference		
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Total Delays	veh.h	140,5	730,3	268,6	160,5	420%	91%	14%
Link Cruise Time	veh.h	111,0	83,1	89,7	89,2	-25%	-19%	-20%
Total Travel Time	veh.h	251,5	813,3	358,3	249,7	223%	42%	-1%
Total Passenger Time	pass.h	327,0	1057,3	465,8	324,6	223%	42%	-1%
Total Travel Distance	veh.km	3447,1	2657,7	2868,1	2845,1	-23%	-17%	-17%
Total Passenger Distance	pass.km	4481,2	3455,0	3728,5	3698,7	-23%	-17%	-17%
Overall Average Speed	Km/h	13,7	3,3	8,0	11,4	-76%	-42%	-17%

Additionally, and for the purpose of better identifying the operational changes in each section of the corridor, charts containing data from all scenarios were constructed for the following indicators:

- Performed flow along the corridor (Figure 5.6)
- Queued flow (Figure 5.7)
- Total travel time for buses (Figure 5.8)
- Average travel time for buses (Figure 5.9)
- Total travel time for cars (Figure 5.10)
- Average travel time for cars (Figure 5.11)

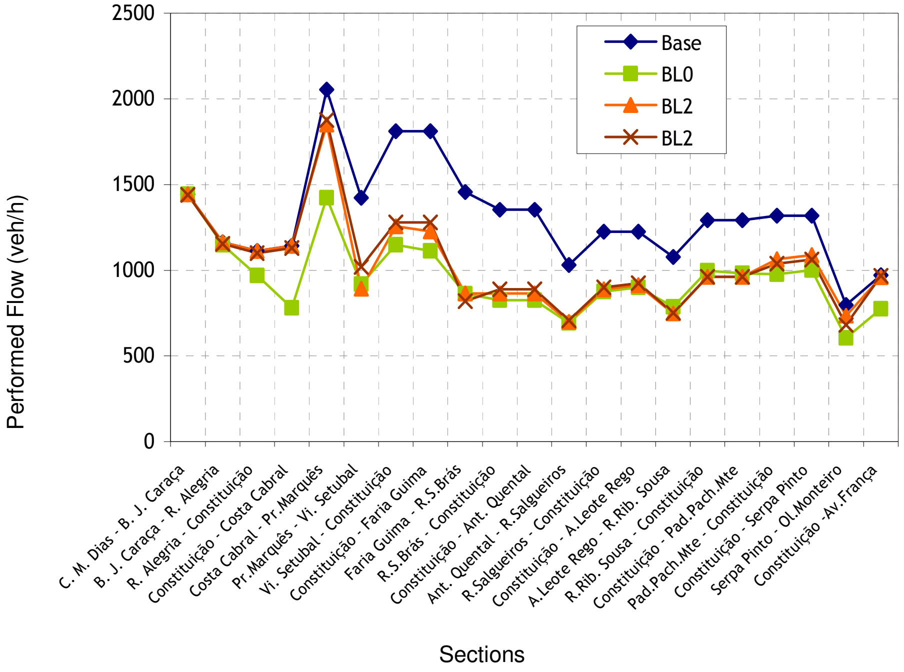

Figure 5.6: SATURN: Performed flow along the corridor

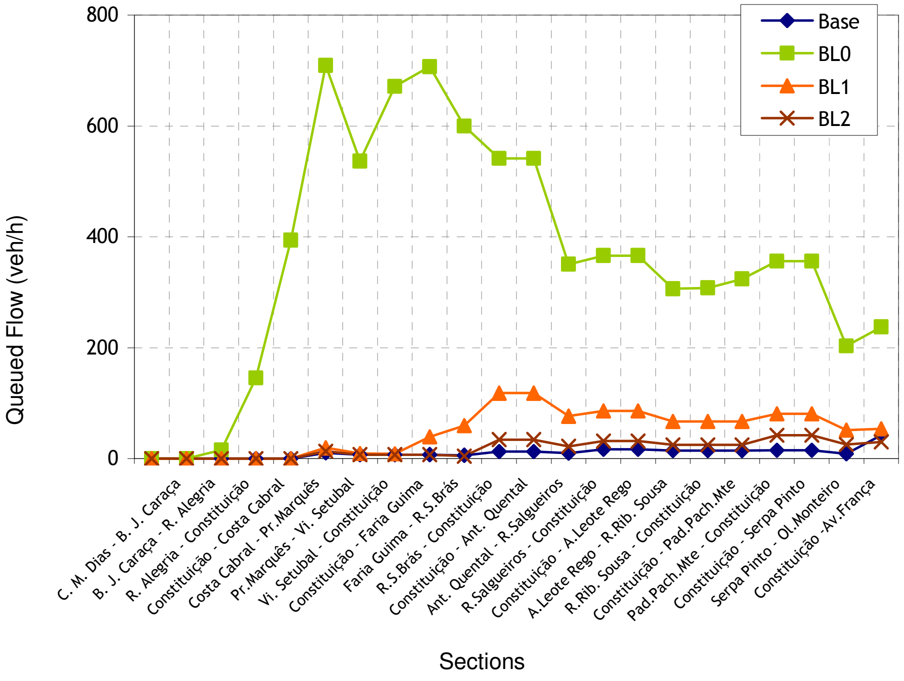

Figure 5.7: SATURN: Queued flow along the corridor

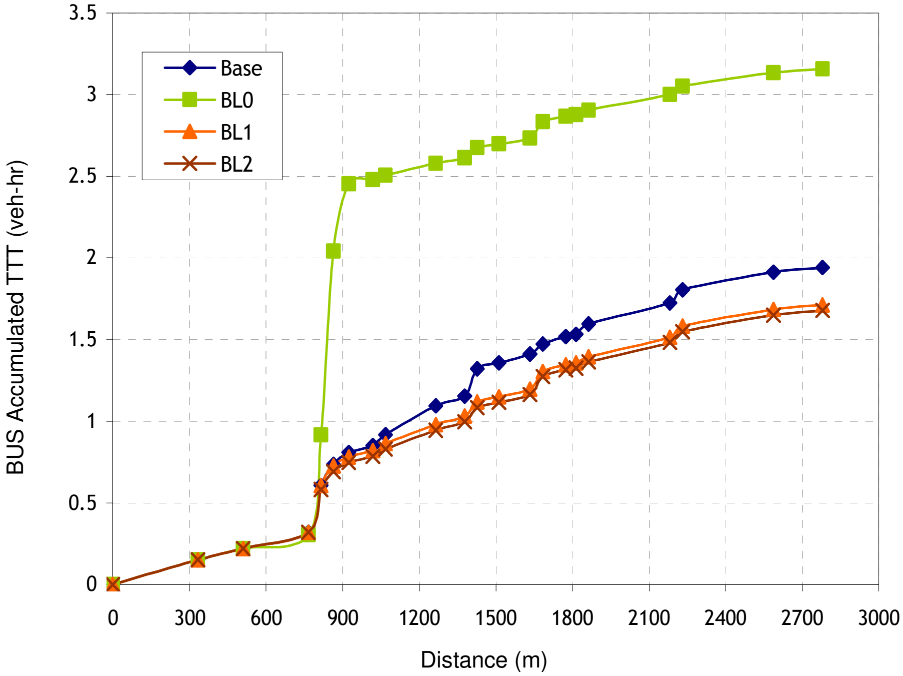

Figure 5.8: SATURN: Bus total travel time along the corridor

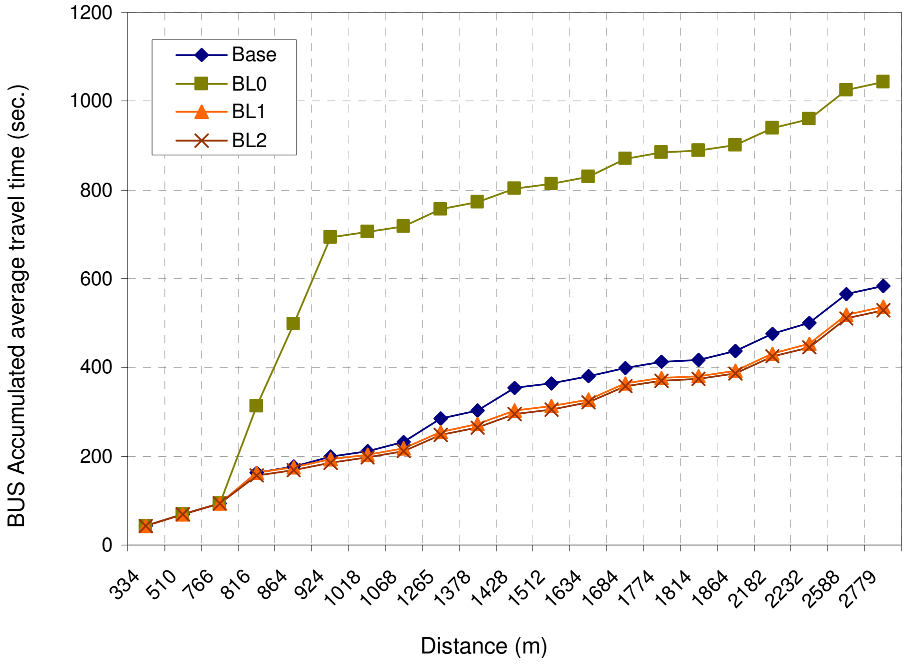

Figure 5.9: SATURN: Bus average travel time along the corridor

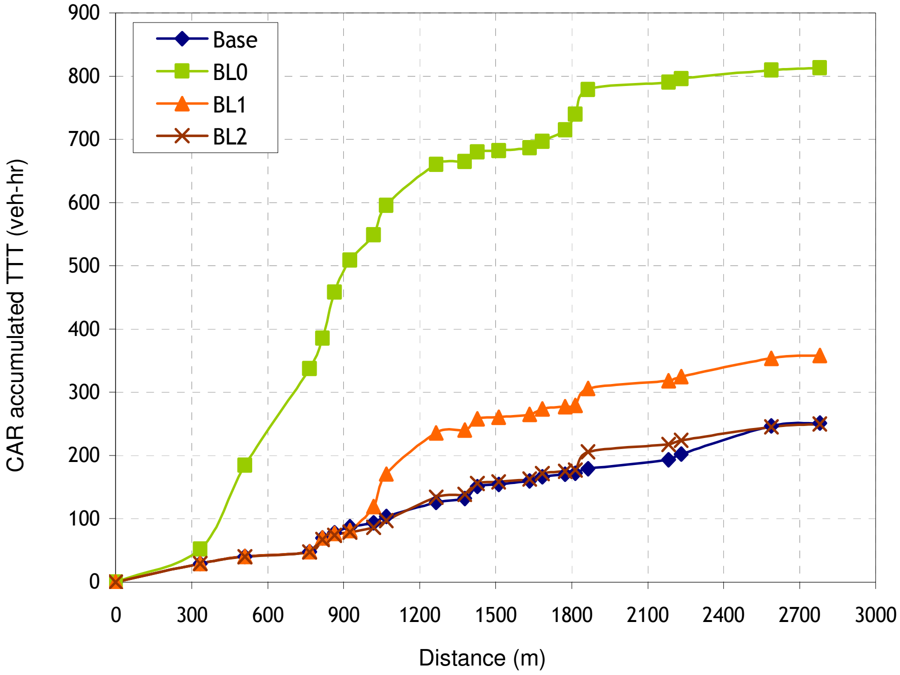

Figure 5.10: SATURN: Car total travel time along the corridor

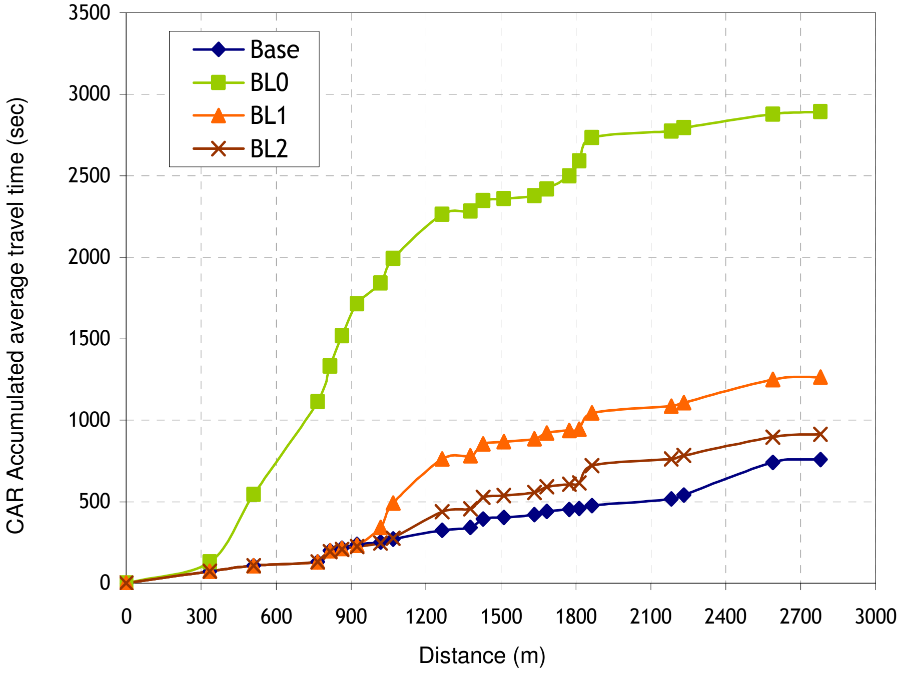

Figure 5.11: SATURN: Car average travel time along the corridor

5.7.2.1. Scenario BL0

The figures presented in Table 5.9 show strong negative results in operational conditions when comparing BL0 to the base scenario. The increase in total travel time (+223%) and decrease overall travel speed (-76%) evidence the existence of extreme congestion after the bus lane introduction. In fact, and as expected, congestion level is so high along the corridor that the increase in total travel times is accentually high either for cars (+223%) as for buses (+63%), as in tables 5.10 and 5.11 show.

Furthermore, the changes in total travel distance (-17%), and once the travel demand pattern is the same for both scenarios, also reveal the deterioration in operational conditions along the corridor. This is a key factor for the abrupt decrease of the overall travel speed (-76%).

Figure 5.6 shows the variation of performed flow, helping the identification of the critical sections. The BL0 scenario and the base case have the same demand flow along the corridor, so the differences for performed flows reveal whether or not the section is congested. This difference starts growing before the first section (“Visconde Setúbal – Constituição”) of the tested bus lane and stagnates from then on, witch evidences the bottleneck effect caused by the new bus lane and its major impacts on the queue propagation upstream.

Figures 5.8 and 5.9 helps evaluate the impacts from this bottleneck effect for the bus mode. It shows a rapid increase of the bus total and average travel times for BL0 within the sections where the bus lane is interrupted (“Constituição - Costa Cabral” to “Pr. Marquês – Visconde Setúbal). This effect stops in the sections where the bus lane is introduced (“Visconde Setúbal – Constituição”), highlighting the predicted beneficial effect in bus travel times induced by the bus lanes. Thus, it may be concluded that the congestion caused by the introduction of the new bus lane is prejudicial to buses in BL0, mainly because buses themselves get exposed to general traffic congestion in the sections where they share the road with cars.

On the car side, figures 5.10 and 5.11 reveal that the difference in total travel time increases right from the beginning of the analyzed corridor confirming the effects of car queuing propagation already exposed in Figure 5.7. In the this case the bottleneck effect appears to be also located in section “Faria Guimarães - R. S. Brás”, and from then on the growing rate of the total travel time becomes the same as the base case. This effect is the main responsible for the very low operational performance of cars in BL0, as the decrease in overall average speed of 3,3Km/h (-76%) confirms.

5.7.2.2. Scenario BL1

The results for the BL1 scenario still show a deterioration of the operational conditions as presented in the Table 5.9. There is a global increase in total travel time (+42%) and a decrease in total travel distance (-17%), leading to a negative impact on the overall travel speeds (-41%).

These aggregate results are especially influenced by the negative car impacts, like the total increase in total travel time (+42%) and the decrease in total travel distance (-17%) proves. In relation to the latest, and contrary to BL0 scenario, the total travel distance differences might not be solely due to increase of queuing delay, since the demand pattern for these two scenarios is different.

In order to analyze this situation, the comparison between Figures 5.6 and 5.7 is indicative on the level of reassignment along the corridor. Thus, in spite of the performed flow is less that in the base case for all the sections, the queued flow, i.e., difference between demand and performed flow, only increases between section “Visconde Setúbal – Constituição” and “R. S. Brás – Constituição”. This evidences that, due to reassignment effects, the demand drops along “Rua da Constituição” contributing to the better operational results than the obtained for BL0.

A direct consequence of the demand changes is the fact that the bottleneck effect in (“Constituição - Costa Cabral” to “Pr.Marquês – Visconde Setúbal”) affecting bus and cars in BL0, is no longer significant in BL1. Nevertheless, the saturation in “Faria Guimarães - R.S.Brás” still contributes negatively for the performance results (figures 5.8 and 5.10).

The bus results for BL1 suggest a positive impact on bus operational conditions along the studied corridor. Table 5.10 shows a decrease in total travel time (-12%) and a consequent increase in overall travel speed (+9%), witch is due to the positive effect of the new bus lane scheme especially until section “Antero de Quental” (figures 5.8 and 5.9). These results show that the consideration of the reassignment effect enhanced the conditions for buses operating in the studied corridor by eliminating the bottleneck previewed for BL0 the scenario

Nevertheless, these bus operational improvements are still small to prevent the aggregated results from being unfavourable to the bus lane introduction (Table 5.9). In fact, even just considering the “passenger” measures, the negative car results still have the greatest influence due to the large difference in demand between the two considered modes.

5.7.2.3. Scenario BL2

The aggregate operational results for the BL2 scenario show aggregated results contrary to the bus lane introduction, although considerably better than the previous analyzed scenarios. Table 5.9 reveals a decrease in total travel time (-1%) but the overall average speed is increased (+17%). This is related with the changes in total travel distance (-17%) that is mainly related traffic demand drop on the studied corridor (figures 5.6 and 5.7) due greater possibilities for traffic reassignment.

A direct consequence of this fact is felt on the relative importance of some operational changes along the corridor, as a closer analysis on the car results reveals (Figures 5.10 and 5.11).~They show that car average travel time for the whole corridor is less in the base case (758 sec) than it is in BL2 (913 sec), but since actual flows are different, the car total travel time is less for BL2 (250 veh.hr) than it is for the base case (252 veh.hr).

An interesting result presented in Figure 5.10 is the difference between total travel times for BL2 and BL1 (between "Constituição - Faria Guimarães" and "R.S.Brás – Constituição"), which reinforces the importance of the traffic reassignment in the evaluation process. Although both scenarios have similar "absolute" demand along the corridor, for BL2 there is a higher number of car right-turners, making their way to VCI (Porto's main ring road), and this way diverging from the highly congested corridor. Meanwhile, and since for BL1 this possibility did not exist, cars had no option than to use the congested "Rua da Constituição", witch leads to a greater increase in the total travel times than the predicted for BL2.

Changes in the bus operational conditions along the corridor are very similar to those obtained for BL1, i.e., there is a global improvement especially due to the decrease in total travel time (–14%). Again, the main benefits will occur along the new bus lane, especially between sections "Visconde Setúbal" and "Antero Quental" (figures 5.8 and 5.9), precisely where the speeds for the base case are slower. This fact enhances the theory that the operational advantages for buses provided by bus lanes tend to be more significant in places where high congestion existed.

As for the "passenger" performance indicators, there is a decrease in total passenger time (–4%), although the passenger speed dropped (-14%) because of the changes in total passenger distance (-14%). Again, results suggest that the large difference between car and bus flows in the corridor unables the improvements in the bus operation to be significant in terms of aggregated figures even when weighting the modes of transport by their average occupancy (Table 5.9).

5.7.2.4. Synthesis of results

The results provided by SATURN for the tested scenarios (BL0, BL1 and BL2) were unanimous in consider that the introduction of the proposed bus lane scheme would not be beneficial to the improvement of the aggregate operational conditions within the study area as well as in the analyzed corridor.

A closer analysis of the results provided by the software for each scenario allowed the identification of the following general features:

- The results obtained for the car mode showed always deterioration of their operational conditions as a result of the bus lane introduction. More, they were dominant in the calculation of aggregated results, not allowing bus operational improvements (e.g.:

corridor analysis for BL1 and BL2) to have a significant impact. This situation stands true even when calculated the passenger performance indicators, witch highlights the importance of high bus demand to justify the introduction of a priority measure such as a bus lane;

- The most favourable results to the introduction of the bus lane were obtained for scenarios where the traffic reassignment was considered in the demand characterization process, i.e., BL1 and BL2. In fact, the discrepancy of results obtained particularly between BL0 and the other scenarios, reveals the decisive importance of the demand characterization in the evaluation process. This is equally valid for the area and corridor analysis;
- Results demonstrated that the level of congestion as consequence of the bus lane introduction can worse the operational conditions to a level that even buses do not get benefit from the scheme implementation. This stands true for both area wide analyses as for corridor if the demand is very high (BL0). In fact, the corridor analysis results revelled that the bus lane introduction along the corridor might create bottlenecks responsible for the deterioration of operational conditions for both car and buses (where the bus lane is not considered) on the upstream sections.
- The importance of performing an area wide analysis was reinforced with the comparison of bus results from the corridor analysis. This way, the bus results for the studied area showed a deterioration of the operational conditions in spite of the fact that these conditions were improved along the corridor in the case of BL1 and BL2. This demonstrates that local (corridor) improvements and global (impact area) operational deterioration might coexist. This fact emphasizes the dangers of treating bus priority measures as a local problem instead of taking a more area wide approach as defended in the proposed methodology.

5.7.3. DRACULA – STUDY AREA RESULTS

The DRACULA operational outputs used to evaluate the impacts caused by the bus lane introduction within the study area are summarized in tables 5.12 (all vehicles), 5.13 (bus) and 5.14 (car). For simplicity, the figures are the averaged values of each indicator for 30 different seed model runs. Full information, including standard deviations and estimation of confidence intervals for the mean figures are presented in Appendix E.

Table 5.12: DRACULA: Total changes in performance within the study area

Absolute totals		Without BL	With BL			Difference		
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Queuing Delay	veh.h	852	1310	1021	956	54%	20%	12%
Link cruise time	veh.h	552	490	515	529	-11%	-7%	-4%
Total Travel Time	veh.h	1403	1801	1535	1486	28%	9%	6%
Total Passenger Time	pass.km	2766	3344	2993	2941	21%	8%	6%
Total Travel Distance	veh.km	20411	18778	20194	20202	-8%	-1%	-1%
Total Passenger Distance	pass.km	38035	35805	37621	37679	-6%	-1%	-1%
Passenger Speed	km/h	13,8	10,7	12,6	12,8	-22%	-9%	-7%
Overall Average Speed	km/h	14,5	10,4	13,2	13,6	-28%	-10%	-7%
Total Trips Loaded	veh/h	15962	15962	15927	15899	0%	0%	-0,4%

Table 5.13: DRACULA: Changes in bus performance within the study area

Bus totals		Without BL	With BL				Difference	
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Queuing Delay	veh.h	13,2	14,7	14,7	14,9	11%	11%	12%
Link cruise time	veh.h	6,1	5,9	5,8	5,9	-3%	-5%	-4%
Total Travel Time	veh.h	19,3	20,6	20,5	20,7	7%	6%	7%
Total Passenger Time	pass.km	967	1030	1024	1037	7%	6%	7%
Total Travel Distance	veh.km	236	234	233	234	-1%	-1%	-1%
Total Passenger Distance	pass.km	11807	11697	11672	11721	-1%	-1%	-1%
Overall Average Speed	km/h	12,3	11,4	11,5	11,3	-7%	-7%	-8%

Table 5.14: DRACULA: Changes in car performance within the study area

Car totals		Without BL	With BL			Difference		
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Queuing Delay	veh.h	839	1296	1006	941	55%	20%	12%
Link cruise time	veh.h	545	484	509	523	-11%	-7%	-4%
Total Travel Time	veh.h	1384	1780	1515	1465	29%	9%	6%
Total Passenger Time	pass.km	1799	2314	1969	1904	29%	9%	6%
Total Travel Distance	veh.km	20175	18544	19961	19968	-8%	-1%	-1%
Total Passenger Distance	pass.km	26228	24108	25949	25958	-8%	-1%	-1%
Overall Average Speed	km/h	14,6	10,4	13,2	13,7	-28%	-10%	-6%

A general analysis to the results point to a degradation of the operational conditions for the all the three tested scenarios. The main highlights regarding each scenario will be presented as follow.

5.7.3.1. Scenario BL0

Table 5.12 shows the time impacts resulting from the bus lane introduction for the selected study area revealing an increase in total travel time (+28%), witch reflects the changes in its components: delays (+54%) and cruising time (-11%). These, conjugated with the decrease in total travel distance (-8%), contribute to the overall average speed drop (-28%), confirming the tendency for deterioration of the operational conditions.

As for the buses, the results in Table 5.13 point equally to losses in operational performance, although less than for cars. Examples of this fact are the increase in total travel times (+7%) and decrease in total travel distance (-1%), leading to a drop in the bus overall average speed (-7%). These differences are lower than the SATURN ones presented in Table 5.6.

A relevant aspect presented in Table 5.13 is the different bus overall average speed previewed by DRACULA and SATURN for the base case. Thus, the DRACULA speed is lower, fact that is consistent with the consideration of bus dwell times and differentiated operational conditions between cars and buses that microsimulation allowed to consider.

The “car” results are again the main responsible for the negative aggregate figures. In fact, they represent more than 98% of the total travel times and total travel distance, witch explains the closeness in results between tables 5.12 and 5.14.

5.7.3.2. Scenario BL1

The results in Table 5.12 confirm the deterioration of the aggregate operational conditions for BL1, quantifiable in the increase in total travel times (+9%) and decrease in the overall average speed (-10%). These changes are smaller than the ones predicted by DRACULA for BL0, demonstrating once again the importance of the consideration of traffic reassignment in the evaluation process.

The operational changes for buses are relatively small but with a tendency for the deterioration of the operational conditions as the total travel times (+6%) and total travel distance (-1%) testify (Table 5.13).

Table 5.14 shows that once again, the car mode is the responsible for the major aggregate changes in the operational conditions. Thus, relative aggregate changes and relative car changes are the same, i.e., increase in total travel times (+9%) and decrease in total travel distance (-1%) leading to changes in overall average speed (-10%).

5.7.3.3. Scenario BL2

The results for BL2 still show an increase in total travel times (+6%) and a negative impact in the overall average speed (-7%) (Table 5.12). Therefore, the worsening of the operational conditions due to the introduction of the tested bus lane is once again confirmed even for the scenario where traffic reassignment is incorporated. More, the deterioration of operational conditions within the study area affects again negatively both buses and cars, so the analysis of “passenger” indicators will obviously be also unfavourable to the bus lane introduction.

Table 5.13 shows the changes in total travel time (+7%) and total travel distance (-1%), confirming that the Dracula bus results for the study area do not change significantly for the three considered scenarios. Nevertheless the tendency is always for a slight worsening of their overall average speed in relation to the base case, witch demonstrates that the main objectives of the new bus lane scheme will not likely be achieved.

The car mode results in Table 5.14 help understand why the deterioration of the aggregated operational results is less accentuated for BL2 with relation to the other tested scenarios. This is essentially due to the fact that car results are better for BL2, as the change in overall speed (–6%) testifies.

5.7.4. DRACULA – CORRIDOR ANALYSIS RESULTS

The DRACULA mode aggregated results for the corridor analysis are shown in Table 5.15, while Tables 5.16 and 5.17 present the results for buses and cars respectively. The results show again the averaged figures obtained after 30 model runs and more information on the variation of these operational indicators along the corridor is presented in Appendix F.

Table 5.15: DRACULA: Total changes in performance along the corridor

Absolute totals - Corridor		Without BL	With BL			Difference		
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Total Delays	veh.h	75	151	90	82	101%	19%	8%
Link Cruise Time	veh.h	77	56	63	63	-27%	-18%	-18%
Total Travel Time	veh.h	152	208	153	145	36%	0%	-5%
Total Passenger Time	pass.h	291	392	297	290	35%	2%	0%
Total Travel Distance	veh.km	2406	1794	2030	2021	-25%	-16%	-16%
Total Passenger Distance	pass.km	4216	3380	3692	3701	-20%	-12%	-12%
Passenger Speed	km/h	14,5	8,6	12,4	12,8	-40%	-14%	-12%
Overall Average Speed	Km/h	15,8	8,6	13,3	14,0	-45%	-16%	-11%

Table 5.16: DRACULA: Changes in bus performance along the corridor

Bus totals - Corridor		Without BL	With BL			Difference		
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Total Delays	veh.h	1,2	1,8	1,3	1,4	54%	12%	17%
Link Cruise Time	veh.h	0,7	0,7	0,7	0,7	-4%	-4%	-1%
Total Travel Time	veh.h	1,9	2,5	2,0	2,1	32%	6%	10%
Total Passenger Time	pass.h	95	125	101	105	32%	6%	10%
Total Travel Distance	veh.km	22,4	21,5	21,6	22,1	-4%	-3%	-1%
Total Passenger Distance	pass.km	1118	1076	1081	1103	-4%	-3%	-1%
Overall Average Speed	Km/h	11,8	8,6	10,7	11,1	-27%	-9%	-6%

Table 5.17: DRACULA: Changes in car performance along the corridor

Car totals - Corridor		Without BL	With BL			Difference		
		Base	BL0	BL1	BL2	BL0-Base	BL1-Base	BL2-Base
Total Delays	veh.h	74	150	88	80	102%	19%	8%
Link Cruise Time	veh.h	76	55	62	62	-27%	-18%	-19%
Total Travel Time	veh.h	151	205	151	142	36%	0%	-5%
Total Passenger Time	pass.h	196	267	196	187	36%	0%	-5%
Total Travel Distance	veh.km	2383	1773	2009	1999	-26%	-16%	-16%
Total Passenger Distance	pass.km	3098	2304	2611	2598	-26%	-16%	-16%
Overall Average Speed	Km/h	15,8	8,6	13,3	11,1	-45%	-16%	-30%

For better guiding of the further scenario analysis, the information on some performance indicators was also illustrated in the following charts:

- Total travel time for buses (Figure 5.12);
- Average travel time for buses (Figure 5.13).
- Total travel time for cars (Figure 5.14);
- Average travel time for cars (Figure 5.15).

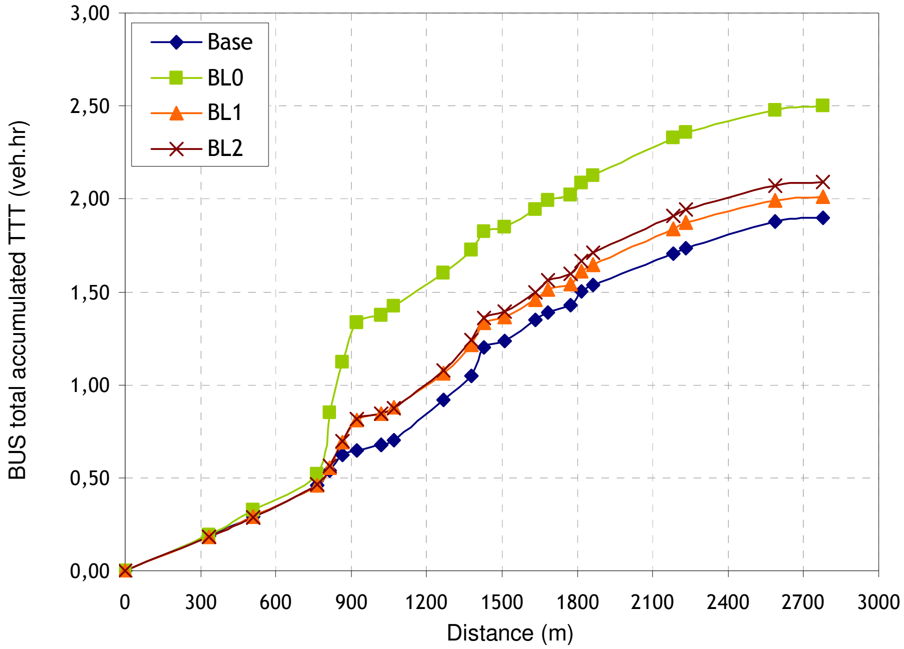

Figure 5.12: DRACULA: Bus total travel time along the corridor

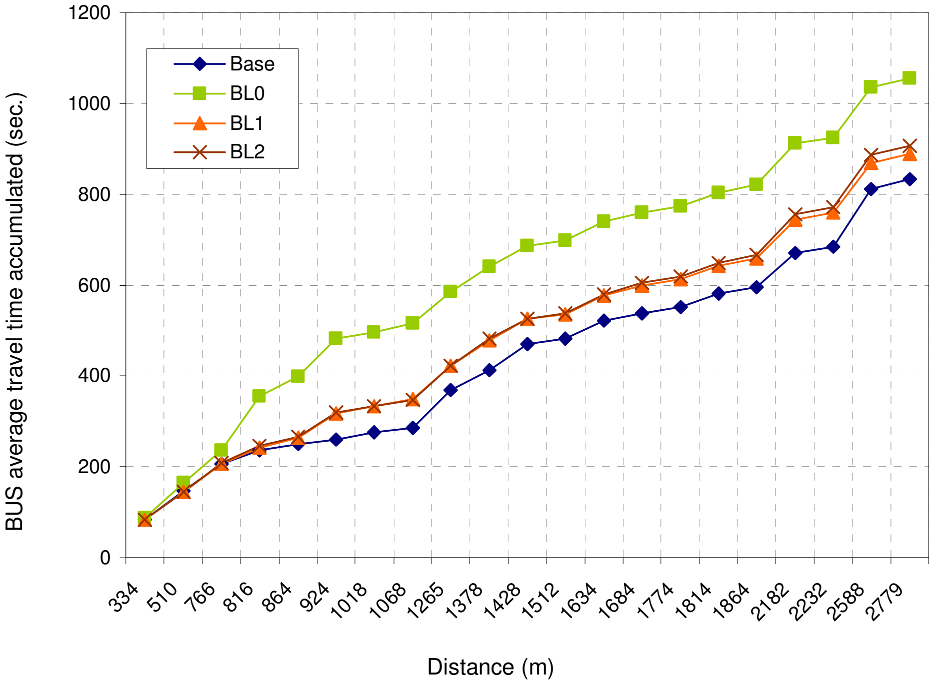

Figure 5.13: DRACULA: Bus average travel time along the corridor

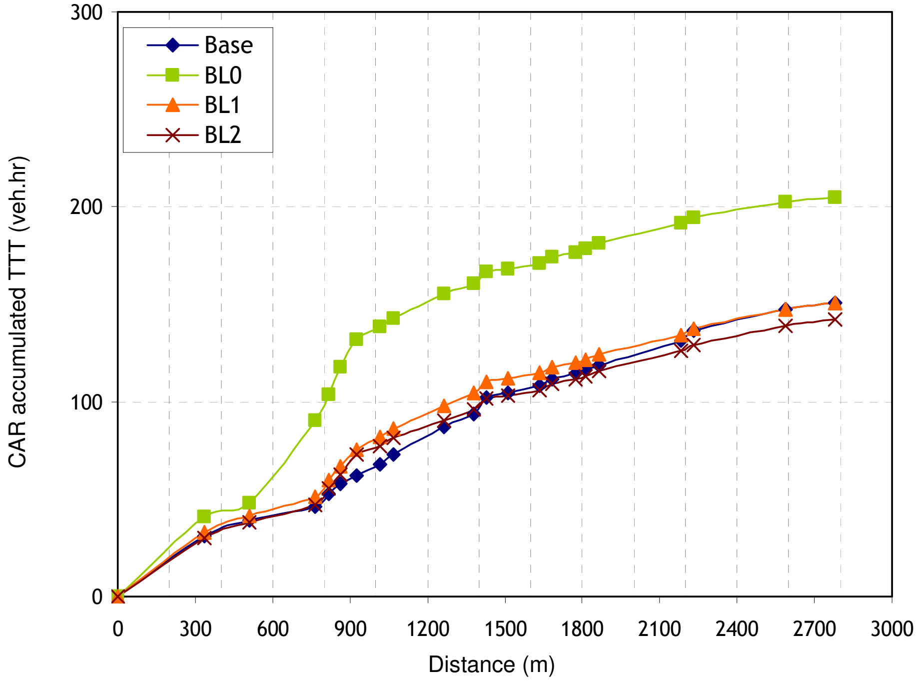

Figure 5.14: DRACULA: Car total travel time along the corridor

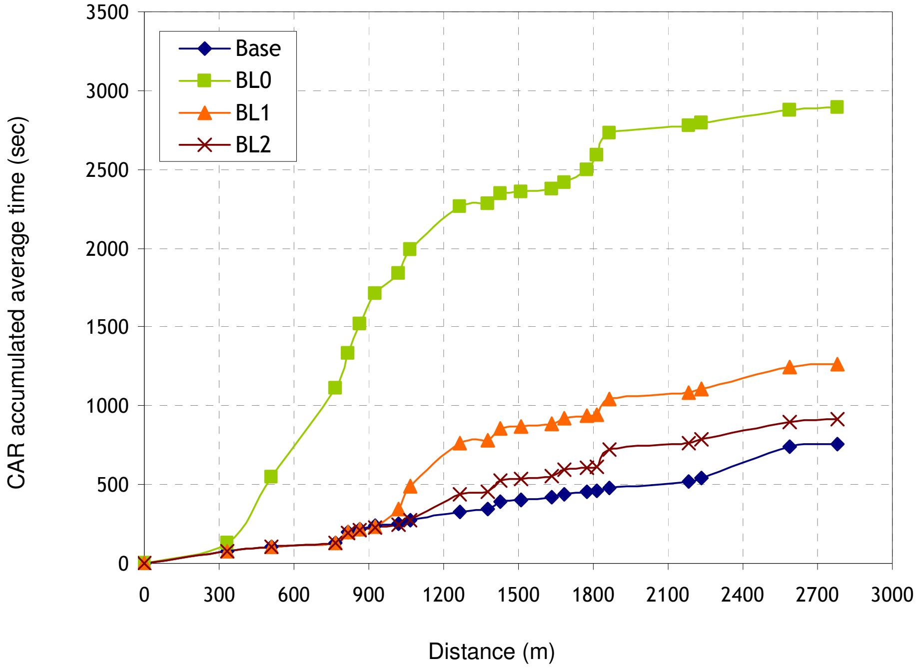

Figure 5.15: DRACULA: Car average travel time along the corridor

5.7.4.1. Scenario BL0

The analysis of the results presented in Table 5.15 show a clear increase in congestion along the corridor when comparing BL0 to the base scenario. The total travel time (-36%) and total travel distance (-25%) changes originate a relevant decrease in the overall average speed (-45%). The car influence in the aggregate results is equally evident as it was for the study area analysis. This is confirmed by the closeness between the operational measures tables 5.15 and 5.17.

Buses experiment a decrease in their overall average speed (-27%) along the corridor as stated in Table 5.16. These results are strongly influenced by the increase in congestion in the upstream sections of the new bus lane, i.e., from section "Constituição - Costa Cabral" to "Pr.Marquês – Visconde Setúbal" (figures 5.12 and 5.13). These sections are precisely the ones where the continuity of the bus lane corridor is interrupted, buses get exposed to the existing congestion and their operational conditions deteriorate.

Figure 5.14 shows the maintenance of the bottleneck effect caused by section "Pr.Marquês – Visconde Setúbal", that is responsible for higher rate of increase in the car total travel times since the beginning of the considered corridor. On the other hand, the section "Faria Guimarães - R.S.Brás" where Saturn's results indicated a tendency for congestion has clearly less importance for the deterioration of the operational conditions within Dracula's analysis. The latest might have an important role in the difference between figures for car performance in both used programs.

5.7.4.2. Scenario BL1

The aggregated operational conditions for the BL1 scenario denote smaller negative impacts than the previewed for BL0 scenario. Still, the performance indicators present a decrease in the overall average speed (-16%), although that aspect is solely due to the decrease in total travel distance (-16%) once the total travel time maintains unaltered (Table 5.15).

Figure 5.12 represents the evolution of the bus total travel time along the corridor and allows the detection the bottleneck effect in sections “Constituição - Costa Cabral” to “Pr.Marquês – Visconde Setúbal”. This is the main cause for the increase in total travel time (+6%) along the corridor. As for the travel time gains in the new bus lane, they were found to be almost null as shown in Figure 5.13, mainly because of the bottleneck effect rise. The small length of the sections, the fact that all of them are controlled by traffic lights, the high number of right turning and the presence of four bus stops along the new bus are all factors that might have influenced this result. In fact, they manage to restrain the bus speed in the way they force buses to stop very frequently. This does not allow high bus speeds to be accomplished and by this the free-flow conditions offered by the new bus lane are not fully utilized.

The car results follow the tendency of the aggregate results. Table 5.17 and Figure 5.14 show small changes in the total travel times along the corridor, although the overall average speeds (-16%). This effect is a due to the changes in total travel distance that are a consequence of the decrease in car demand caused by traffic reassignment along the corridor. In fact, and comparing Figures 5.7 and 5.8 it is clear that the total travel times remain unaltered much due the car demand difference rather then for the changes in average travel time.

5.7.4.3. Scenario BL2

The performance indicators for the BL2 scenario demonstrate a small deterioration when compared with the base scenario. The decrease of the total travel time (-5%) can be explained by the drop in car demand along the corridor as the comparison between Figure 5.13 and 5.14 shows. This fact reflects on the decrease in total travel distance (-16%), leading to the global decrease in the overall travel speed (-11%).

The bus results presented in Table 5.16 are very close to the BL1’s ones, i.e., there is a tendency for the increase in total travel times within the sections where bus lane is interrupted. This is reflected in the increase in total travel times (+6%) and total travel distance (-1%), confirming the deterioration in operational conditions for buses along the corridor if the tested bus lane was to be introduced. This way, the operational advantages for buses due to the free-running conditions provided by the bus lane were shown to be insignificant. This fact enhances the influence that other aspects (traffic lights, bus stop operations, etc.) have on the bus operational conditions on an urban traffic environment.

The changes in the car mode are again the most influential on the aggregate results and that fact explains the closeness between tables 5.15 and 5.17 results. On a closer perspective, Figure 5.13 shows that the new bus lane is responsible for the increase in the car's total time near the sections "Constituição - Costa Cabral" to "Pr.Marquês – Visconde Setúbal" and From then on the total travel time tends to approximate to the base case results.

5.7.4.4. Synthesis of results

The conjunction between the study area and corridor analysis based on the DRACULA results for the tested scenarios allowed some general features to prevail. Additionally, and as at this stage the SATURN main results were already isolated, extra considerations were introduced on the results provided by the two softwares:

- Results for both corridor and study area showed the deterioration of the operational conditions for buses and cars for all the considered scenarios witch confirm that the tested bus lane introduction in "Rua da Constituição" cannot be justified based on the operational improvements;

- The consideration of reassignment effects in the demand characterization of the tested scenarios was, like for the SATURN results, very significant in overall results for both type of analysis. Furthermore, the BL0 (no assignment) scenario was again the one with the worse operational performance and BL2 (larger reassignment possibilities) the one with better results;

- The corridor analysis results suggested a small deterioration of the operational conditions for buses even after the bus lane introduction. This means that bus free-flow conditions offered by the tested bus lane are unable to compensate the raising of congestion on the upstream sections that all vehicles (including buses) will face. These results differ from the ones obtained by SATURN, evidencing the importance of the way bus lane operation is simulated, and how that can affect the evaluation in the analyzed corridor. This way, microsimulation tools (DRACULA) proved to be more a appropriate for the evaluation of the operational aspects regarding the bus lanes ;

- When comparing the SATURN and DRACULA, the figures were always bigger in the first case, although the difference between relative changes was not very significant. Different results were expected since they both have distinct operating philosophies, but the relative closeness for the previewed changes when comparing scenarios might be good indicator for testing the robustness of the proposed methodology.

CHAPTER 6 – CONCLUSIONS

The developed research was focused on the evaluation of bus lane schemes with an especial emphasis on the predicted operational changes for the “with” and “without” bus lanes scenarios. The work reviewed the methodologies used to evaluate the bus lanes and classified them regarding the different techniques used for the quantification of operational changes. The main conclusions of this review indicated that:

- Most of the studies are reduced to the evaluation of operational changes in the street where the bus lane introduction is being tested, neglecting the potentially important impacts on the surrounding traffic environment;
- Analysis on a wider area is essential, although only feasible within the scope of traffic modelling.

Based on these conclusions a new methodology was proposed to quantify the operational changes due to bus lane schemes within the area where the impacts were expected to be significant. The methodology relies mostly on traffic modeling capacities and its versatility allows the testing of a range of situations associated with the implementation of bus lanes, namely:

- Conversion of a general traffic lane;
- Removal of a parking lane;
- Creation of an extra lane.

A case study was held to evaluate the operational feasibility of a bus lane introduction scheme in a one-way arterial street in Porto (“Rua da Constituição”) using the commercial traffic models SATURN and DRACULA. This application to a real-life scheme allowed conclusions to be drawn regarding quality of the proposed methodology to the operational evaluation of bus lanes schemes and highlight some aspects that should be regarded in this type of study. The most significant were:

- Traffic modeling was confirmed as an excellent evaluation tool for the study of bus lane schemes once it demonstrated capabilities for dealing with the complexity of congested urban traffic networks. Nevertheless, extra attention regarding the modelling simplifications has to be accounted in order to correctly interpret the results. In this matter, it was shown that the differences between the two used models originated contradictory bus operational results in the studied corridor. The capacity for modelling highly detailed bus operational features (bus stops operations, differentiate vehicle’s characteristic, etc.) was found to be important to this fact, witch suggests traffic microsimulation as a more suitable modelling tool for the evaluation of bus lanes. This way, the developments enhanced by this dissertation in the DRACULA software should be seen as a relevant result;

- Results confirmed that the area of analysis is crucial in the evaluation of operational impacts. In the case of buses this fact was particularly exposed once within the area wide approach the operational changes pointed to a deterioration of conditions, whilst analysing the corridor where the bus lane was being tested some level of improvement was detected (SATURN). This result emphasized the importance of calculating the performance indicators for a study area instead a corridor based perspective. Regarding these results, the proposed methodology might be seen as positive contribution;

- The corridor analysis was found to be useful to better understand some important impacts that are inaccessible in an area wide analysis (e.g. stacking back due to non-bus lane continuity). This analysis assisted the location of bottlenecks that could be further analyzed if an optimization process was pursued;

- Traffic reassignment was found to be a key element in the evaluation of a bus lane scheme once results tend to be very sensitive to variations on this matter. This again confirms the importance of considering a study area (wider than just the corridor) for the demand characterization in the development of tested scenarios whether this is made with a high tier model or not. Results showed that the consideration of traffic reassignment effects provided more favorable results for the bus lane introduction scheme than the no-reassignment scenario. The differences between the results for the scenarios that considered reassignment effects was relatively small witch indicates the study area can be only big enough to consider the major reassignment possibilities. On the other hand, it was shown the no-reassignment scenario revealed much higher negative impacts on the operational indicators for the study area, witch again emphasized the need for the traffic reassignment questions to be carefully accounted in the evaluation process.

- The general ideia defending high bus demands to justify the bus lane introduction was confirmed, especially in cases where the mode demand is so unbalanced. In fact, the case study results showed that difference between mode demand (car and bus) was so big that even when buses travel times decreased due to the new bus lane, these results were insignificant in terms of overall operational indicators.

- The generalized idea that bus lanes are always favorable to bus was contradicted, not only by the study area results (both models) that showed the deterioration for the overall operational conditions to buses but also by the corridor analysis (Dracula), alerting for the negative effects of queuing in the upstream links might have on the deterioration of operational conditions for buses. On the other hand, cars experienced a severe deterioration of their operational conditions in all tested scenarios. These results alert for the fact that the sole introduction of local bus lanes might not always be an effective bus priority strategy, especially on the typical urban traffic environment where the sections tend to be small and operational performance is much related with the efficiency of the traffic signals. The consideration of a group of bus lanes within a wider area or the use of mixed approaches embracing other bus priority strategies (e.g. signal priority, bus stop re-location) is therefore essential to guarantee significant advantages to buses within the area in analysis.

In spite of the results obtained by the application of the proposed methodology it must be regarded that there is still a large range for development that should be achieved in future research.

First of all, the validation of the model predictions against the real-life results if the bus lane was to be introduced was not performed. This had to do with the limitation of time and resources and also because the previewed operational benefits were faraway from justifying such change. Nevertheless, further testing is needed, especially on different study cases and bus lanes schemes, in order to correctly evaluate the suitability of the methodology for the bus lane evaluation.

Additionally, the recognized importance of the operational features in the bus lane performance should lead to a deeper study on the aspects regarding the optimization of the original bus lane configuration (e.g.: changes in traffic lights timings, increase in bus demand, permitted movements, removal of parking space, bus stop relocation, bus lane resign, afternoon peak-hour study, etc) in order to guarantee that the solution is to be implemented with maximum overall benefits.

Future developments of the framework should also include the assessment of other questions such as bus travel time reliability or taxi/emergency vehicles permissions that would reinforce its operational nature. On the other hand, the rapid development of the traffic modeling capabilities suggests that the range of applicability of the proposed methodology could be perhaps extended to the assessment of other important elements (e.g.: pollutant emissions) that can be accounted in the bus lane evaluation process.

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APPENDIX A: CALIBRATION AND VALIDATION

Table A.1: Calibration and Validation Parameters

Criteria & Measures	Acceptability Targets
Hourly Flows, Model vs. Observed	
Individual Link Flows	
Within 15%, for 700vph<Flow<2700 vph	>85% of cases
Within 15%, for 100vph<Flow<700 vph	>85% of cases
Within 15%, for 400vph<Flow<2700 vph	>85% of cases
Total Link Flows	
Within 5%	All Accepting Links
GEH Statistic.Individual Link Flows	
GEH<5	>85% of cases
GEH Statistic.Total Link Flows	
GEH<4	All Accepting Links
Travel Times, Model vs. Observed	
Journey Times Network	
Within 15% (or one minute, if higher)	>85% of cases
Visual Audits	
Individual Link Speeds	
Visually acceptable Speed.Flow relationship	To analyst’s satisfaction
Bottlenecks	
Visually acceptable Queuing	To analyst’s satisfaction

(Source: FREEWAY SYSTEM OPERATIONAL ASSESMENT, Technical Report I.33, Paramics Calibration & Validation Guidelines, DRAFT, Wisconsin Department of Transportation, District 2, June 2002)

The GEH is statistic is computed as follows:

$$GEH = \sqrt{\frac{(V-C)^2}{(V+C).0{,}5}}$$, Where

GEH: The statistic;

V: Model estimate directional hourly volume at a location;

C: Directional hourly count at a location.

Table A.2: Parameters and criteria for calibration and validation (Van Vuren, 1996; Tavares, 2003)

Parameters	Criteria
P85 = %Links with $\begin{cases} \lvert V_m - V_o \rvert \leq 100 & \text{if} \quad V_o \leq 700 \\ \dfrac{\lvert V_m - V_o \rvert}{V_o} \leq 15\% & \text{if} \quad 700 < V_o \leq 2\ 700 \\ \lvert V_m - V_o \rvert \leq 400 & \text{if} \quad V_o > 2\ 700 \end{cases}$	$\geq 85\%$
GEHM = $\overline{GEH}^{*}$	≤ 2
GEH5 = % Links with GEH ≤ 5	$\geq 85\%$
TP = %Jorneys $\dfrac{\lvert tp^o - tp^m \rvert}{tp^o} \times 100 < 15\%$ or 1 minute	$\geq 85\%$

* . Within 85% of the links

V_O: Directional hourly count at a location.

V_M: Model estimate directional hourly volume at a location;

APPENDIX B: DEVELOPMENT OF MATRA

B.1. INTRODUCTION

The assignment model used in this work was the commercial software SATURN - *Simulation and Assignment of Traffic to Urban Road Networks* developed by the Institute for Transport Studies of the University of Leeds and currently commercialized by WS Atkins of Epson.

The model application to the Porto's main road network was pursued by the author for the Porto's City Council "Câmara Municipal do Porto" and had the technical supervision of the Faculty of Engineering of Porto. The model was latter named MATRA ("Modelo de Afectação de Tráfego do Porto"). The work was a part of the European Commission program IDEA.STCC and was financially supported by INTERREG III. FEDER and by the Câmara Municipal do Porto, and was pursued from November 2004 to March 2006.

The development of this city model followed the general the methodology for the assignment models (Tavares, 2003) and the next sections aim to summarize the main aspects of the process.

B.2. AREA OF ANALYSIS

Being the "Câmara Municipal do Porto" the responsible for the planning and operation of the road network within the city limits, it was decided that the area for analysis would enclose the entire 41.5km2 of city's area. Thus, it is limited in the North/East by the "Estrada da Circunvalação" (Porto 2nd ring road), at the South by the Douro river and at the West by the Atlantic Ocean (Figure b.1).

The model covers the city's main road system (red) and especial emphasis was provided to the nodes within central area (inside VCI – 1st ring road) in terms of codification once they were coded as simulation ones (Van Vliet, 2004).

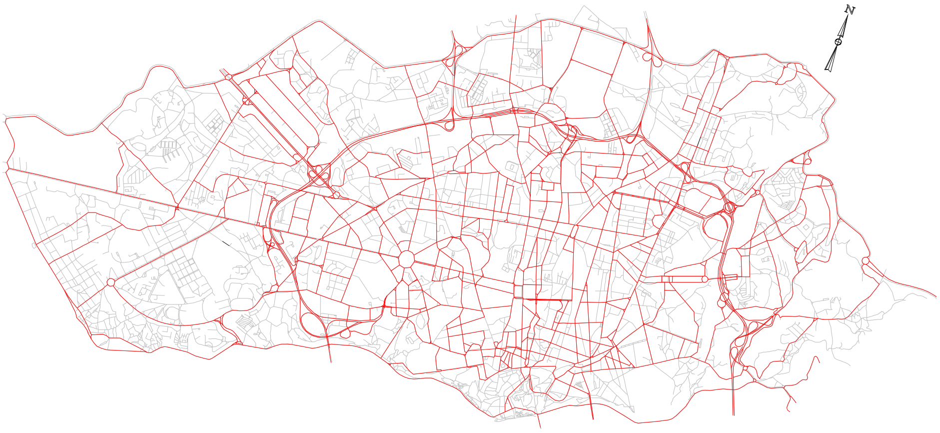

Figure B.1: Modeled road system.

B.3. ZONING

The adopted zoning was inspired by previous transport projects that were previously held in the city, namely the MUSIC (YNCG *et al.*, 1999) and the general Mobility Survey (INE, 2002). The final zoning has a total of 109 zones, being 87 of them internal and the remaining 22, exterior to the modeled area (Figure b.2 and Table b.1).

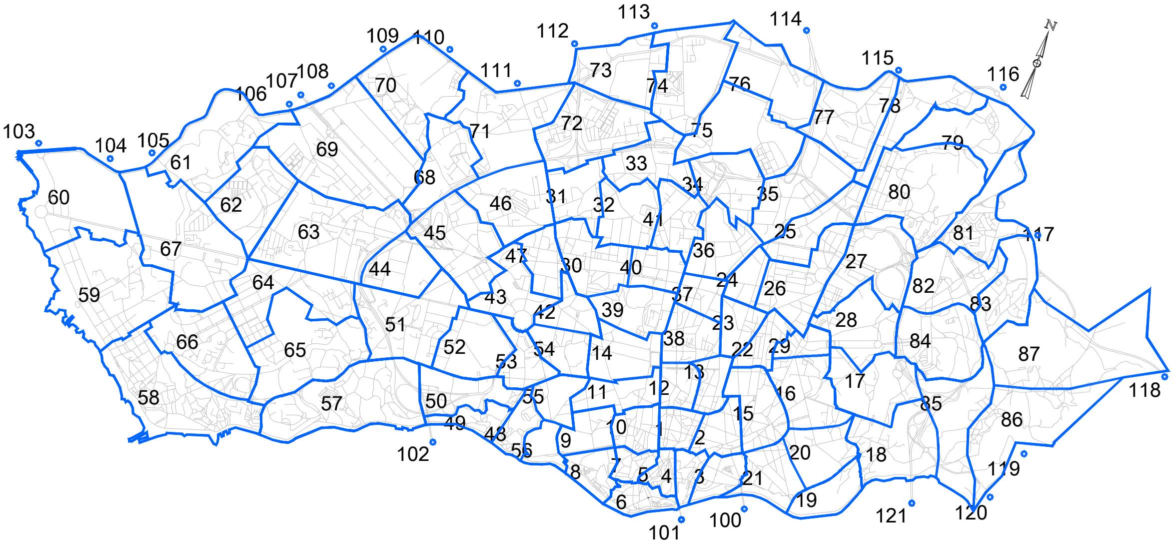

Figure B.2: MATRA: Zoning system

Table B.1: Zone Identification

Zonas			
Número	Nome	Número	Nome
1	Aliados	56	Restauração
2	Batalha	57	Fluvial
3	Guindais	58	Foz Velha
4	Sé	59	Foz Nova
5	Mouzinho Silveira	60	Parque Cidade
6	Ribeira	61	Vilarinha
7	Cordoaria	62	Antunes Guimarães
8	Alfândega	63	Foco
9	H.S. António	64	Gomes da Costa
10	Carlos Alberto	65	Pasteleira
11	Cedofeita	66	Império
12	Trindade	67	Boavista Oeste
13	Bolhão	68	Requesende
14	Alvares Cabral	69	Zona Industrial
15	Campo 24 Agosto	70	Viso
16	Bonfim	71	Santa Luzia
17	Bonjóia	72	Miosótis
18	Noeda	73	Ameal
19	Colégio Órfãos	74	Alameda 25 Abril
20	Soares Reis	75	Paranhos
21	Fontainhas	76	Pólo Universitário
22	Santos Pousada	77	Areosa
23	Doze Casas	78	Fernão Magalhães
24	Marquês	79	S. João Deus
25	Costa Cabral	80	Contumil
26	Velásquez	81	S. Roque
27	Antas	82	Maceda
28	Flores	83	Cerco do Porto
29	Joaquim Urbano	84	Corujeira
30	Ramada Alta	85	Freixo
31	Monte Burgos	86	Azevedo
32	Carvalhido	87	Lagarteiro
33	9 de Abril	100	Ponte do Infante
34	Campo Lindo	101	Ponte Luís I (INF.)
35	Salgueiros	102	Ponte Arrábida
36	Covelo	103	Matosinhos Marginal
37	João Pedro Ribeiro	104	Marginal
38	Bonjardim	105	Matosinhos II
39	Monte Cativo	106	Pedro Hispano
40	Constituição	107	Via Rápida
41	Vale Formoso	108	Sra Hora Oeste
42	Oliveira Monteiro	109	Sra Hora Este
43	MouzinhoAlbuquerque	110	Xanana Gusmão
44	Bessa	111	Padrão
45	Sidónio Pais	112	Via Norte
46	Prelada	113	S. Mamede
47	Av. França	114	A3/A4
48	D. Pedro V	115	EN105
49	Arrábida	116	Rebordões
50	CDUP	117	EN 15
51	Venezuela	118	IC 29
52	Agramonte	119	EN 209
53	Campo Alegre	120	EN108
54	Rodrigues Freitas	121	Ponte do Freixo
55	Júlio Dinis		

B.4. SUPPLY CHARACTERIZATION

Attending to the SATURN working philosophy (Van Vliet, 2005), the first necessary task for coding the network was the selection, inside of the area of analysis, of the "simulation" and "buffer" areas. It was decided that, at this stage, the division would be as followed:

Simulation area (zones 1 to 57): internal area to the city's major ring road ("VCI – Via de Cintura Interna");

Buffer area (zones 58 to 87): remaining city's area.

External area (zones 100 to 121): "fictitious" zones that are essential to represent the "in and outs" gates located at the system boundaries. They represent the main accesses to the city and were named after them.

The selection of roads to include in the model was mainly done by the registered demand level in absolute and relative values. This way, it is expected to contain the main roads as also the one's that have a higher level of congestion.

The necessary supply data was collected from November 2004 to March 2005. The ones related with the physical characterization (lengths, stacking capacity, number of lanes, etc) were site collected while the operational inputs (excluding the traffic signal timings) were generally established by reference traffic bibliography.

Table B.2 and Figure B.3 summarizes the resulting from supply characterization process

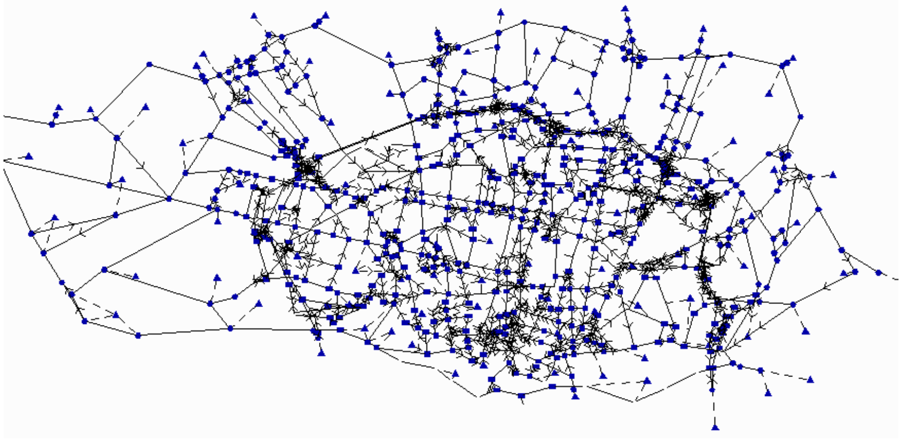

Figure B.3: MATRA'S modelled area

Table B.2: Model general characteristics

	Simulation Area	Buffer Area	Total
Nodes	1020	299	1321
Links	1866	458	2324

B.5. DEMAND CHARACTERIZATION

The characterization of demand is the process that led to the estimation of the basic Origin/Destination (O/D) matrix representative of the trips made by cars, between the defined zones.

The adopted methodology was based on roadside interviews and traffic counting. In order to rationalize the financial effort the zones were aggregated in sectors and the stations were located near signalized intersections (Figure b.4). The sample size for the interviews was 10% of the total counted traffic (Table b.3).

The data collection and estimation of the base year matrix was held down by the private consortium TIS.RDT and lasted from April 19th to June 16th 2005. The studied time period was from 7:30 a.m. to 9:30 p.m. on weekdays, a period that was found to be representative of the morning peak-hour conditions.

Figure B.4: Location of the counts/surveys stations

Table B.3: Data collection summary

Total number of stations	149
Number of counted movements	172
Number of inquired movements	117
Observational period (days)	29
Number of people involved	512
Number of counted vehicles (passenger cars/ heavy vehicles)	272.280 / 13.112
Total number of inquiries	18.741

The resulting O/D matrix had a total of 129.125 trips for the respective two hour period. The matrix in use represents one hour period and is half

The bus demand was considered as a “fixed demand” and codified by considering the existing routes and frequencies offered by the urban local bus operator (STCP). The PCU conversion factor for buses was fixed as 2.

B.7. CALIBRATION AND VALIDATION

The calibration and validation tasks were performed by comparing the modeled flows against the counted ones. The comparison was made by calculating sugngested parameters in the *British Guidelines – Department of Transport* (Van Vuren, 1996).

Table B.4: Calibration and Validation results

Parameters	Suggested Criteria	Calibration (141 counts)	Validation (53 counts)
P85 = %Links with $\begin{cases} \lvert V_m - V_o \rvert \leq 100 & \text{if} \quad V_o \leq 700 \\ \frac{\lvert V_m - V_o \rvert}{V_o} \leq 15\% & \text{if} \quad 700 < V_o \leq 2\ 700 \\ \lvert V_m - V_o \rvert \leq 400 & \text{if} \quad V_o > 2\ 700 \end{cases}$	≥ 85%	84,40%	50,94%
GEHM = $\overline{\text{GEH}}^{*}$	≤ 2	1,42	4,64
GEH5 = %Link counts with GEH ≤ 5	≥ 85%	83,69%	52,83%
TP = % time routes $\frac{\lvert tp^o - tp^m \rvert}{tp^o} \times 100 < 15\% \text{ ou } 1 \text{ minute}$	≥ 85%	Not used	

* - For 85% of the links.

The results obtained for the calibration were calculated from the traffic counts register during the demand characterization period and are mainly accomplished the suggested criteria.

As for the validation, the counts were obtained from automatic traffic counts from the city’s UTC system that are located predominately in the central area. Results presented an appreciable different between the suggested criteria and the calculated ones, witch might be related with the geographical concentration of the validation counts. Nevertheless, and attending to the size of the modeled network and the amount of work done in order to calibrate the model, MATRA was considered valid to be applied to the Porto’s traffic reality, regarding that for each future studied zone calibration/validation tasks would be performed.

APPENDIX C: CALIBRATION AND VALIDATION RESULTS

Table C.1: SATURN Calibration results

Node A	Node B	Street	Sections	Traffic Flow		Difference		GEH
				Counted (veic/hr)	Modelled (veic/hr)	Absolute	Relative (%)	
13009	13001	R.Sá Bandei	R.Sá Bandeir - G.Cristóvão	297	296	-1	-0,45	0,08
24001	24002	R. Alegria	Constituição - R.Aur.Sousa	476	478	2	0,35	0,08
47003	47001	R.Egas Moniz	R.Egas Moniz-Ol.Monteiro	958	955	-3	-0,31	0,1
14354	14454	R.Ani.Cunha	R.Sac.Cabral - R.Boavista	488	493	5	1,12	0,25
36005	36009	R. Far. Guim	Faria Guima - R. do Covelo	1754	1733	-21	-1,19	0,5
30011	99318	Constituição	Pad.Pach.Mte - Constituição	1269	1302	33	2,63	0,93
99230	37005	J.P.Ribeiro	J.P.Ribeiro - Pr.Marquês	913	942	29	3,2	0,96
23337	99288	Sta.Catarina	J.Oli.Ramos - Sta.Catarina	477	502	25	5,28	1,14
36010	36009	R. Far. Guim	R.F.Guim-vci - R. do Covelo	1406	1317	-89	-6,3	2,4
14538	38005	R. Paraíso	Largo Lapa - R. Camões	365	320	-45	-12,38	2,44
40006	40007	Ant. Quental	Ant.Quetal - Constituição	402	473	71	17,69	3,4
99170	14003	Ant. Quental	Ant. Quental - Pr.República	1156	1289	133	11,49	3,8
24001	99192	R. Alegria	Constituição - R. Alegria	268	365	97	36,01	5,43
43009	43011	NªSrªFátima	NªSrªFátima - R.Ol.Monteir	220	329	109	49,64	6,59
14342	14454	R.Boavista	B. Forrester - R.Ani.Cunha	885	1120	235	26,55	7,42
30347	47007	Ol. Monteiro	Ol. Monteiro - Constituição	343	587	244	71,09	11,31

Table C.2: SATURN: Validation results

Node A	Node B	Street	Sections	Traffic Flow		Difference		GEH
				Counted (veic/hr)	Modelled (veic/hr)	Absolute	Relative (%)	
13019	13338	Sta.Catarina	G.Cristóvão - Sta.Catarina	218	232	14	6,53	0,95
14013	14005	Mártires da Lib	Mártires da Lib - Pr.República	498	521	23	4,64	1,02
40005	40006	Ant. Quental	Ant.Cardoso - Constituição	439	473	34	7,77	1,6
36437	99314	R. Far. Guim	Faria Guima - Faria Guima	1877	1794	-82	-4,4	1,93
14003	14012	Ant. Quental	Cosntituição - D. de Góis	1436	1521	85	5,92	2,21
43011	43009	NªSªFátima	R.Ol.Monteir - NªSªFátima	396	326	-69	-17,79	3,71
40341	40007	Ant. Quental	Constituição - D.Góis	559	472	-86	-15,5	3,82
38003	12338	Ant. Quental	D. de Góis - Cosntituição	889	744	-144	-16,36	5,09
37001	36001	Ant. Quental	D. de Góis - Pr. Republica	803	962	159	19,8	5,35
39003	40005	T. Faria G.	Faria Guima - Faria Guima	370	497	127	34,32	6,1
36537	36002	Camões	R. Camões - G.Cristovão	592	429	-162	-27,53	7,21
40007	40006	R.Boavista	Ant. Quental - R. Figueiroa	635	837	202	31,74	7,43
12017	12002	Álv. Cabral	R. Figueiroa - Pr.República	510	344	-165	-32,55	8,03
14009	14007	G.Cristóvão	G.Cristóvão - Camões	362	184	-177	-49,25	10,79
40005	39003	Constituição	Vi. Setubal - Constituição	767	1131	364	47,5	11,83

Table C.3: DRACULA: Calibration results

Node A	Node B	Street	Sections	Traffic Flow		Difference		GEH
				Counted (veic/hr)	Modelled (veic/hr)	Absolute	Relative (%)	
13009	13001	R.Sá Bandei	R.Sá Bandeir - G.Cristóvão	297	260	-37	-12%	2,22
24001	24002	R. Alegria	Constituição - R.Aur.Sousa	476	502	26	5%	1,18
47003	47001	R.Egas Moniz	R.Egas Moniz-Ol.Monteiro	958	847	-111	-12%	3,69
14354	14454	R.Ani.Cunha	R.Sac.Cabral - R.Boavista	488	455	-33	-7%	1,52
36005	36009	R. Far. Guim	Faria Guima - R. do Covelo	1754	1707	-47	-3%	1,13
30011	99318	Constituição	Pad.Pach.Mte - Constituição	1269	1197	-72	-6%	2,05
99230	37005	J.P.Ribeiro	J.P.Ribeiro - Pr.Marquês	913	918	5	1%	0,17
23337	99288	Sta.Catarina	J.Oli.Ramos - Sta.Catarina	477	477	0	0%	0,00
36010	36009	R. Far. Guim	R.F.Guim-vci - R. do Covelo	1406	1429	23	2%	0,61
14538	38005	R. Paraíso	Largo Lapa - R. Camões	365	430	65	18%	3,26
40006	40007	Ant. Quental	Ant.Quetal - Constituição	402	430	28	7%	1,37
99170	14003	Ant. Quental	Ant. Quental - Pr.República	1156	1191	35	3%	1,02
24001	99192	R. Alegria	Constituição - R. Alegria	268	379	111	41%	6,17
43009	43011	NªSrªFátima	NªSrªFátima - R.Ol.Monteir	220	309	89	40%	5,47
14342	14454	R.Boavista	B. Forrester - R.Ani.Cunha	885	1084	199	22%	6,34
30347	47007	Ol. Monteiro	Ol. Monteiro - Constituição	343	313	-30	-9%	1,66

Table C.4: DRACULA: Validation results

Node A	Node B	Street	Sections	Traffic Flow		Difference		GEH
				Counted (veic/hr)	Modelled (veic/hr)	Absolute	Relative (%)	
13019	13338	Sta.Catarina	G.Cristóvão - Sta.Catarina	218	248	30	14%	1,97
14009	14007	Mártires da Lib	Mártires da Lib - Pr.República	362	163	-199	-55%	12,28
39003	40005	Ant. Quental	Cosntituição - D. de Góis	370	447	77	21%	3,81
43011	43009	NªSªFátima	R.Ol.Monteir - NªSªFátima	396	266	-130	-33%	7,15
40005	40006	Ant. Quental	D. de Góis - Cosntituição	439	428	-11	-3%	0,53
14013	14005	Álv. Cabral	R. Figueiroa - Pr.República	498	479	-19	-4%	0,86
12017	12002	G.Cristóvão	G.Cristóvão - Camões	510	336	-174	-34%	8,46
40341	40007	Ant. Quental	Ant.Cardoso - Constituição	559	427	-132	-24%	5,94
36537	36002	R. Far. Guim	Faria Guima - Faria Guima	592	379	-213	-36%	9,67
40007	40006	Ant. Quental	Constituição - D.Góis	635	825	190	30%	7,03
40005	39003	Ant. Quental	D. de Góis - Pr. Republica	767	1014	247	32%	8,28
37001	36001	T. Faria G.	Faria Guima - Faria Guima	803	982	179	22%	5,99
38003	12338	Camões	R. Camões - G.Cristovão	889	739	-150	-17%	5,26
14003	14012	R.Boavista	Ant. Quental - R. Figueiroa	1436	1512	76	5%	1,98
36437	99314	Constituição	Vi. Setubal - Constituição	1877	1668	-209	-11%	4,96

APPENDIX D: SATURN CORRIDOR RESULTS

Table D.1: SATURN: CAR corridor results for the Base Scenario

								Base scenario											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
26009	26001		C. M. Dias	C. M. Dias . B. J. Caraça	334	334	30	1444	1444	12			73	73	29,27	29,27	38,06	482,17	16,5
26009	26001	24001	C. M. Dias					961	961	0	43	17,24							
26001	24001		Constituição	B. J. Caraça . R. Alegria	176	510	16	1163	1163	5			34	107	10,99	40,26	14,28	204,73	18,6
26001	24001	99321	Constituição					855	855	0	18	5,82							
24001	99321		Constituição	R. Alegria . Constituição	256	766	23	1114	1114	7			24	131	7,42	47,68	9,65	285,10	38,4
24001	99321	24337	Constituição					1114	1114	0	1	0,31							
99321	24337		Constituição	Constituição . Costa Cabral	50	816	5	1144	1144	2			69	200	21,92	69,60	28,50	57,18	2,6
99321	24337	36337	Constituição					1144	1144	0	64	20,33							
24337	36337		Pr.Marquês	Costa Cabral . Pr.Marquês	48	864	12	2065	2054	7			15	215	8,56	78,16	11,13	98,61	11,5
24337	36337	36437	Pr.Marquês					1432	1424	0	3	1,71							
36337	36437		Constituição	Pr.Marquês . Vi. Setubal	60	924	9	1432	1424	4			23	238	9,10	87,26	11,83	85,46	9,4
36337	36437	99314	Constituição					1432	1424	0	14	5,54							
36437	99314		Constituição	Vi. Setubal . Constituição	94	1018	11	1819	1812	6			13	251	6,54	93,81	8,50	170,30	26,0
36437	99314	36537	Constituição					1819	1812	0	2	1,01							
99314	36537		Constituição	Constituição . Faria Guima	50	1068	7	1819	1812	4			20	271	10,06	103,87	13,08	90,58	9,0
99314	36537	36637	Constituição					1464	1458	0	13	6,54							
36537	36637		Constituição	Faria Guima . R.S.Brás	197	1265	29	1464	1458	12			54	325	21,87	125,74	28,43	287,20	13,1
36537	36637	99315	Constituição					1162	1157	0	25	10,12							
36637	99315		Constituição	R.S.Brás . Constituição	113	1378	16	1367	1354	6			17	342	6,39	132,13	8,31	152,97	23,9
36637	99315	40007	Constituição					1367	1354	0	1	0,38							
99315	40007		Constituição	Constituição . Ant. Quental	50	1428	7	1367	1354	3			51	393	19,18	151,31	24,93	67,69	3,5
99315	40007	40004	Constituição					867	859	0	44	16,55							

Table D.1: SATURN: CAR corridor results for the Base Scenario (cont.)

Cont.

Node A	Node B	Node C	Street	Section	Distance (m)	Distance accumul. (m)	Free flow time (sec)	Base scenario Demand Flows (veh/h)	Actual Flows (veh/h)	Link Cruise Time (veh.hr)	Delays (sec)	Total Delays (veh.hr)	Travel Time (sec)	Travel Time accumul. (sec)	Total Travel Time (veh.hr)	Total Travel Time accumul. (veh.hr)	Total Passenger Time (pass.hr)	Total Travel Distance (veh.km)	Speed (Km/h)
40007	4000		Constituição	Ant. Quental . R.Salgueiros	84	1512	10	1042	1032	3			11	404	3,2	154,5	4,1	86,70	27,5
40007	4000	9931	Constituição					1042	1032	0	1	0,29							
40004	9931		Constituição	R.Salgueiros . Constituição	122	1634	15	1242	1225	5			16	420	5,5	159,9	7,1	149,4	27,5
40004	9931	4000	Constituição					1242	1225	0	1	0,34							
99316	4000		Constituição	Constituição . A.Leote Rego	50	1684	6	1242	1225	2			19	439	6,5	166,4	8,4	61,26	9,5
99316	4000	4000	Constituição					1058	1044	0	13	4,42							
40003	4000		Constituição	A.Leote Rego . R.Rib.	90	1774	13	1092	1078	4			14	453	4,2	170,6	5,5	97,04	23,1
40003	4000	9931	Constituição					1092	1078	0	1	0,30							
40009	9931		Constituição	R.Rib. Sousa . Constituição	40	1814	4	1306	1292	1			5	458	1,8	172,4	2,3	51,66	28,8
40009	9931	3001	Constituição					1306	1292	0	1	0,36							
99319	3001		Constituição	Constituição . Pad.Pach.Mte	50	1864	6	1306	1292	2			19	477	6,8	179,2	8,9	64,58	9,5
99319	3001	9931	Constituição					1293	1279	0	13	4,66							
30011	9931		Constituição	Pad.Pach.Mte . Constituição	318	2182	38	1332	1317	14			39	516	14,3	193,5	18,6	418,8	29,4
30011	9931	3001	Constituição					1332	1317	0	1	0,37							
99318	3001		Constituição	Constituição . Serpa Pinto	50	2232	6	1332	1317	2			25	541	9,2	202,6	11,9	65,85	7,2
99318	3001	4700	Constituição					780	771	0	19	6,95							
30013	4700		Constituição	Serpa Pinto . Ol.Monteiro	356	2588	32	807	798	7			200	741	44,3	246,9	57,6	284,0	6,4
30013	4700	4700	Constituição					689	682	0	168	37,23							
47007	4700		Constituição	Constituição .Av.França	191	2779	17	1014	972	5			17	758	4,6	251,5	6.0	185,6	40,4
				TOTAL	**2779**	**2779**	**312**			**111**	**446**	**140**	**758**		**252**	**252**	**327**	**3447**	**13,7**

Table D.2: SATURN: CAR corridor results for the Scenario BL0

								BL0											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
26009	26001		C. M. Dias	C. M. Dias . B. J. Caraça	334	334	30	1444	1444	12,0			131,0	131	52,5	52,5	68,3	482,3	9,2
26009	26001	24001	C. M. Dias					961	961		101,0	40,5							
26001	24001		Constituição	B. J. Caraça . R. Alegria	176	510	16	1164	1148	5,1			414,0	545	132,1	184,6	171,7	202,1	1,5
26001	24001	99321	Constituição					856	844		398,0	127,0							
24001	99321		Constituição	R. Alegria . Constituição	256	766	23	1115	970	6,2			568,0	1113	153,0	337,6	198,9	248,2	1,6
24001	99321	24337	Constituição					1115	970		545,0	146,8							
99321	24337		Constituição	Constituição . Costa Cabral	50	816	5	1175	781	1,1			220,0	1333	47,7	385,3	62,0	39,1	0,8
99321	24337	36337	Constituição					1175	781		215,0	46,6							
24337	36337		Pr.Marquês	Costa Cabral . Pr.Marquês	48	864	12	2133	1424	4,7			185,0	1518	73,2	458,5	95,1	68,3	0,9
24337	36337	36437	Pr.Marquês					1456	972		173,0	68,4							
36337	36437		Constituição	Pr.Marquês . Vi. Setubal	60	924	9	1456	919	2,3			197,0	1715	50,3	508,8	65,4	55,2	1,1
36337	36437	99314	Constituição					1456	919		188,0	48,0							
36437	99314		Constituição	Vi. Setubal . Constituição	94	1018	11	1819	1148	3,5			126,0	1841	40,2	549,0	52,2	107,9	2,7
36437	99314	36537	Constituição					1819	1148		115,0	36,7							
99314	36537		Constituição	Constituição . Faria Guima	50	1068	7	1819	1113	2,2			151,0	1992	46,7	595,6	60,7	55,6	1,2
99314	36537	36637	Constituição					1464	895		144,0	44,5							
36537	36637		Constituição	Faria Guima . R.S.Brás	197	1265	29	1464	864	7,0			271,0	2263	65,0	660,7	84,6	170,2	2,6
36537	36637	99315	Constituição					1162	686		242,0	58,1							
36637	99315		Constituição	R.S.Brás . Constituição	113	1378	16	1368	826	3,7			19,0	2282	4,4	665,0	5,7	93,4	21,4
36637	99315	40007	Constituição					1368	826		3,0	0,7							
99315	40007		Constituição	Constituição . Ant. Quental	50	1428	7	1368	826	1,6			66,0	2348	15,1	680,2	19,7	41,3	2,7
99315	40007	40004	Constituição					867	524		59,0	13,5							

Table D.2: SATURN: CAR corridor results for the Scenario BL0 (cont.)

								BL0											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
40007	40004		Constituição	Ant. Quental . R.Salgueiros	84	1512	10	1042	692	1,9			12,0	2360	2,3	682,5	3,0	58,1	25,2
40007	40004	99316	Constituição					1042	692		2,0	0,4							
40004	99316		Constituição	R.Salgueiros . Constituição	122	1634	15	1242	876	3,7			17,0	2377	4,1	686,6	5,4	106,9	25,8
40004	99316	40003	Constituição					1242	876		2,0	0,5							
99316	40003		Constituição	Constituição . A.Leote Rego	50	1684	6	1266	900	1,5			42,0	2419	10,5	697,1	13,7	45,0	4,3
99316	40003	40009	Constituição					1083	770		36,0	9,0							
40003	40009		Constituição	A.Leote Rego . R.Rib. Sousa	90	1774	13	1093	787	2,8			81,0	2500	17,7	714,8	23,0	70,8	4,0
40003	40009	99319	Constituição					1093	787		68,0	14,9							
40009	99319		Constituição	R.Rib. Sousa . Constituição	40	1814	4	1306	999	1,1			91,0	2591	25,2	740,1	32,8	39,9	1,6
40009	99319	30011	Constituição					1306	999		87,0	24,1							
99319	30011		Constituição	Constituição . Pad.Pach.Mte	50	1864	6	1306	983	1,6			143,0	2734	39,0	779,1	50,7	49,1	1,3
99319	30011	99318	Constituição					1294	973		137,0	37,4							
30011	99318		Constituição	Pad.Pach.Mte . Constituição	318	2182	38	1333	977	10,3			41,0	2775	11,1	790,2	14,5	310,6	27,9
30011	99318	30013	Constituição					1333	977		3,0	0,8							
99318	30013		Constituição	Constituição . Serpa Pinto	50	2232	6	1357	1001	1,7			21,0	2796	5,8	796,1	7,6	50,0	8,6
99318	30013	47007	Constituição					792	584		15,0	4,2							
30013	47007		Constituição	Serpa Pinto . Ol.Monteiro	356	2588	32	807	604	5,4			81,0	2877	13,6	809,7	17,7	215,1	15,8
30013	47007	47005	Constituição					690	516		49,0	8,2							
47007	47005		Constituição	Constituição .Av.França	191	2779	17	1014	777	3,7			17,0	2894	3,7	813,3	4,8	148,4	40,4
				TOTAL	**2779**	**2779**	**312**			**83**	**2582**	**730**	**2894**		**813**	**813**	**1057**	**2657**	**3,3**

Table D.3: SATURN: CAR corridor results for the Scenario BL1

								BL1											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
26009	26001		C. M. Dias	C. M. Dias . B. J. Caraça	334	334	30	1444	1444	12			73	73	29	29	38,1	482	16,5
26009	26001	24001	C. M. Dias					961	961		43	17,2							
26001	24001		Constituição	B. J. Caraça . R. Alegria	176	510	16	1163	1163	5			34	107	11	40	14,3	205	18,6
26001	24001	99321	Constituição					855	855		18	5,82							
24001	99321		Constituição	R. Alegria . Constituição	256	766	23	1114	1114	7			24	131	7	48	9,7	285	38,4
24001	99321	24337	Constituição					1114	1114		1	0,3							
99321	24337		Constituição	Constituição . Costa Cabral	50	816	5	1144	1144	2			69	200	22	70	28,5	57	2,6
99321	24337	36337	Constituição					1144	1144		64	20,3							
24337	36337		Pr.Marquês	Costa Cabral . Pr.Marquês	48	864	12	1869	1850	6			14	214	7	77	9,4	89	12,3
24337	36337	36437	Pr.Marquês					903	894		2	1,03							
36337	36437		Constituição	Pr.Marquês . Vi. Setubal	60	924	9	903	894	2			18	232	4	81	5,8	54	12,0
36337	36437	99314	Constituição					903	894		9	2,2							
36437	99314		Constituição	Vi. Setubal . Constituição	94	1018	11	1266	1257	4			110	342	38	120	49,9	118	3,1
36437	99314	36537	Constituição					1266	1257		99	34,6							
99314	36537		Constituição	Constituição . Faria Guima	50	1068	7	1266	1227	2			150	492	51	171	66,5	61	1,2
99314	36537	36637	Constituição					925	896		143	48,7							
36537	36637		Constituição	Faria Guima . R.S.Brás	197	1265	29	925	866	7			271	763	65	236	84,7	171	2,6
36537	36637	99315	Constituição					745	697		242	58,2							
36637	99315		Constituição	R.S.Brás . Constituição	113	1378	16	985	866	4			19	782	5	241	5,9	98	21,4
36637	99315	40007	Constituição					985	866		3	0,7							
99315	40007		Constituição	Constituição . Ant. Quental	50	1428	7	985	866	2			73	855	18	258	22,8	43	2,5
99315	40007	40004	Constituição					615	541		66	15,9							

Table D.3: SATURN: CAR corridor results for the Scenario BL1 (cont.)

								BL1											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
40007	40004		Constituição	Ant. Quental . R.Salgueiros	84	1512	10	777	700	2			13	868	3	261	3,29	59	23,3
40007	40004	99316	Constituição					777	700		3	0,58							
40004	99316		Constituição	R.Salgueiros . Constituição	122	1634	15	976	890	4			18	886	4	265	5,79	109	24,4
40004	99316	40003	Constituição					976	890		3	0,74							
99316	40003		Constituição	Constituição . A.Leote Rego	50	1684	6	1000	914	2			35	921	9	274	11,55	46	5,1
99316	40003	40009	Constituição					807	738		29	7,36							
40003	40009		Constituição	A.Leote Rego . R.Rib. Sousa	90	1774	13	816	749	3			16	937	3	277	4,33	67	20,3
40003	40009	99319	Constituição					816	749		3	0,62							
40009	99319		Constituição	R.Rib. Sousa . Constituição	40	1814	4	1030	962	1			8	945	2	279	2,78	38	18,0
40009	99319	30011	Constituição					1030	962		4	1,07							
99319	30011		Constituição	Constituição . Pad.Pach.Mte	50	1864	6	1030	962	2			99	1044	26	306	34,40	48	1,8
99319	30011	99318	Constituição					1017	951		93	24,86							
30011	99318		Constituição	Pad.Pach.Mte . Constituição	318	2182	38	1145	1064	11			42	1086	12	318	16,14	338	27,3
30011	99318	30013	Constituição					1145	1064		4	1,18							
99318	30013		Constituição	Constituição . Serpa Pinto	50	2232	6	1169	1088	2			22	1108	7	325	8,65	54	8,2
99318	30013	47007	Constituição					742	691		16	4,84							
30013	47007		Constituição	Serpa Pinto . Ol.Monteiro	356	2588	32	787	735	7			141	1249	29	354	37,44	262	9,1
30013	47007	47005	Constituição					706	660		109	22,27							
47007	47005		Constituição	Constituição .Av.França	191	2779	17	1014	960	5			17	1266	5	358	5,89	183	40,4
				TOTAL	**2779**	**2779**	**312**			**90**	**954**	**269**	**1266**		**358**	**358**	**466**	**2868**	**8,0**

Table D.4: SATURN: CAR corridor results for the Scenario BL2

								BL2											
Node A	Node B	Node C	Street	Section	Distance (m)	Distance accumul. (m)	Free flow time (sec)	Demand Flows (veh/h)	Actual Flows (veh/h)	Link Cruise Time (veh.hr)	Delays (sec)	Total Delays (veh.hr)	Travel Time (sec)	Travel Time accumul. (sec)	Total Travel Time (veh.hr)	Total Travel Time accumul. (veh.hr)	Total Passenger Time (pass.hr)	Total Travel Distance (veh.km)	Speed (Km/h)
26009	26001		C. M. Dias	C. M. Dias . B. J. Caraça	334	334	30	1441	1441	12			73	73	29	29	37,99	481	16,5
26009	26001	24001	C. M. Dias					945	945		43	17,21							
26001	24001		Constituição	B. J. Caraça . R. Alegria	176	510	16	1153	1153	5			34	107	11	40	14,16	203	18,6
26001	24001	99321	Constituição					823	823		18	5,77							
24001	99321		Constituição	R. Alegria . Constituição	256	766	23	1099	1099	7			24	131	7	47	9,53	281	38,4
24001	99321	24337	Constituição					1099	1099		1	0,31							
99321	24337		Constituição	Constituição . Costa Cabral	50	816	5	1129	1129	2			63	194	20	67	25,69	56	2,9
99321	24337	36337	Constituição					1129	1129		58	18,19							
24337	36337		Pr.Marquês	Costa Cabral . Pr.Marquês	48	864	12	1891	1877	6			13	207	7	74	8,81	90	13,3
24337	36337	36437	Pr.Marquês					1027	1020		1	0,52							
36337	36437		Constituição	Pr.Marquês . Vi. Setubal	60	924	9	1027	1020	3			18	225	5	79	6,63	61	12,0
36337	36437	99314	Constituição					1027	1020		9	2,55							
36437	99314		Constituição	Vi. Setubal . Constituição	94	1018	11	1286	1278	4			20	245	7	86	9,23	120	16,9
36437	99314	36537	Constituição					1286	1278		9	3,20							
99314	36537		Constituição	Constituição . Faria Guima	50	1068	7	1286	1278	2			31	276	11	97	14,31	64	5,8
99314	36537	36637	Constituição					826	822		24	8,52							
36537	36637		Constituição	Faria Guima . R.S.Brás	197	1265	29	826	822	7			162	438	37	134	48,07	162	4,4
36537	36637	99315	Constituição					678	674		133	30,36							
36637	99315		Constituição	R.S.Brás . Constituição	113	1378	16	924	889	4			19	457	5	139	6,10	101	21,4
36637	99315	40007	Constituição					924	889		3	0,74							
99315	40007		Constituição	Constituição . Ant. Quental	50	1428	7	924	889	2			69	526	17	156	22,16	44	2,6
99315	40007	40004	Constituição					554	533		62	15,32							

Table D.4: **S**ATURN: CAR corridor results for the Scenario BL2 (cont.)

Cont.

								BL2											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
40007	40004		Constituição	Ant. Quental . R.Salgueiros	84	1512	10	729	707	2			12	538	2	158	3,06	59	25,2
40007	40004	99316	Constituição					729	707		2	0,39							
40004	99316		Constituição	R.Salgueiros . Constituição	122	1634	15	932	900	4			18	556	5	163	5,85	110	24,4
40004	99316	40003	Constituição					932	900		3	0,75							
99316	40003		Constituição	Constituição . A.Leote Rego	50	1684	6	956	924	2			36	592	9	172	12,02	46	5,0
99316	40003	40009	Constituição					768	742		30	7,70							
40003	40009		Constituição	A.Leote Rego . R.Rib. Sousa	90	1774	13	777	752	3			15	607	3	175	4,07	68	21,6
40003	40009	99319	Constituição					777	752		2	0,42							
40009	99319		Constituição	R.Rib. Sousa . Constituição	40	1814	4	988	963	1			7	614	2	177	2,43	39	20,6
40009	99319	30011	Constituição					988	963		3	0,80							
99319	30011		Constituição	Constituição . Pad.Pach.Mte	50	1864	6	988	963	2			107	721	29	206	37,20	48	1,7
99319	30011	99318	Constituição					979	955		101	27,01							
30011	99318		Constituição	Pad.Pach.Mte . Constituição	318	2182	38	1081	1039	11			42	763	12	218	15,75	330	27,3
30011	99318	30013	Constituição					1081	1039		4	1,15							
99318	30013		Constituição	Constituição . Serpa Pinto	50	2232	6	1105	1063	2			21	784	6	224	8,06	53	8,6
99318	30013	47007	Constituição					658	633		15	4,43							
30013	47007		Constituição	Serpa Pinto . Ol.Monteiro	356	2588	32	707	681	6			112	896	21	245	27,56	243	11,4
30013	47007	47005	Constituição					653	630		80	15,14							
47007	47005		Constituição	Constituição .Av.França	191	2779	17	998	968	5			17	913	5	250	5,94	185	40,4
				TOTAL						**89**	**601**	**160**	**913**		**250**	**250**	**325**	**2845**	**11,4**

Table D.5: SATURN: BUS Corridor results for the Base Scenario

								Base scenario											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
26009	26001		C. M. Dias	C. M. Dias . B. J. Caraça	334	334	30	13	13	0,11			42	42	0,15	0,15	7,57	4,34	28,7
26009	26001	24001	C. M. Dias					9	9		12	0,04							
26001	24001		Constituição	B. J. Caraça . R. Alegria	176	510	16	9	9	0,04			28	70	0,07	0,22	3,52	1,58	22,5
26001	24001	99321	Constituição					9	9		12	0,03							
24001	99321		Constituição	R. Alegria . Constituição	256	766	23	15	15	0,10			24	94	0,10	0,32	4,92	3,84	39,1
24001	99321	24337	Constituição					15	15		1	0,00							
99321	24337		Constituição	Constituição . Costa Cabral	50	816	5	15	15	0,02			69	163	0,29	0,61	14,38	0,75	2,6
99321	24337	36337	Constituição					15	15		64	0,27							
24337	36337		Pr.Marquês	Costa Cabral . Pr.Marquês	48	864	12	33	33	0,10			14	177	0,13	0,74	6,38	1,58	12,3
24337	36337	36437	Pr.Marquês					12	12		3	0,03							
36337	36437		Constituição	Pr.Marquês . Vi. Setubal	60	924	9	12	12	0,03			22	199	0,07	0,81	3,65	0,72	9,8
36337	36437	99314	Constituição					12	12		14	0,05							
36437	99314		Constituição	Vi. Setubal . Constituição	94	1018	11	12	12	0,04			13	212	0,04	0,85	2,16	1,12	26,0
36437	99314	36537	Constituição					12	12		2	0,01							
99314	36537		Constituição	Constituição . Faria Guima	50	1068	7	12	12	0,02			20	232	0,07	0,92	3,32	0,60	9,0
99314	36537	36637	Constituição					12	12		13	0,04							
36537	36637		Constituição	Faria Guima . R.S.Brás	197	1265	29	12	12	0,09			53	285	0,18	1,09	8,80	2,35	13,4
36537	36637	99315	Constituição					12	12		25	0,08							
36637	99315		Constituição	R.S.Brás . Constituição	113	1378	16	12	12	0,06			18	303	0,06	1,15	2,97	1,34	22,6
36637	99315	40007	Constituição					12	12		1	0,00							
99315	40007		Constituição	Constituição . Ant. Quental	50	1428	7	12	12	0,02			51	354	0,17	1,32	8,42	0,59	3,5

Table D.5: SATURN: BUS Corridor results for the Base Scenario (cont.)

Cont.								**Base scenario**											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
99315	40007	40004	Constituição					12	12		44	0,15							
40007	40004		Constituição	Ant. Quental . R.Salgueiros	84	1512	10	12	12	0,03			11	365	0,04	1,36	1,82	1,00	27,5
40007	40004	99316	Constituição					12	12		1	0,00							
40004	99316		Constituição	R.Salgueiros . Constituição	122	1634	15	12	12	0,05			16	381	0,05	1,41	2,63	1,44	27,5
40004	99316	40003	Constituição					12	12		1	0,00							
99316	40003		Constituição	Constituição . A.Leote Rego	50	1684	6	12	12	0,02			19	400	0,06	1,47	3,12	0,59	9,5
99316	40003	40009	Constituição					12	12		13	0,04							
40003	40009		Constituição	A.Leote Rego . R.Rib. Sousa	90	1774	13	12	12	0,04			14	414	0,05	1,52	2,30	1,07	23,1
40003	40009	99319	Constituição					12	12		1	0,00							
40009	99319		Constituição	R.Rib. Sousa . Constituição	40	1814	4	12	12	0,01			4	418	0,01	1,53	0,66	0,47	36,0
40009	99319	30011	Constituição					12	12		1	0,00							
99319	30011		Constituição	Constituição . Pad.Pach.Mte	50	1864	6	12	12	0,02			19	437	0,06	1,59	3,13	0,59	9,5
99319	30011	99318	Constituição					12	12		13	0,04							
30011	99318		Constituição	Pad.Pach.Mte . Constituição	318	2182	38	12	12	0,13			39	476	0,13	1,72	6,43	3,77	29,4
30011	99318	30013	Constituição					12	12		1	0,00							
99318	30013		Constituição	Constituição . Serpa Pinto	50	2232	6	12	12	0,02			25	501	0,08	1,81	4,12	0,59	7,2
99318	30013	47007	Constituição					6	6		19	0,06							
30013	47007		Constituição	Serpa Pinto . Ol.Monteiro	356	2588	32	6	6	0,05			65	566	0,11	1,91	5,37	2,11	19,7
30013	47007	47005	Constituição					6	6		33	0,05							
47007	47005		Constituição	Constituição .Av.França	191	2779	17	6	6	0,03			18	584	0,03	1,94	1,44	1,10	38,2
				TOTAL	**2779**	**2779**	**312**			**1,03**	**274**	**0,92**	**584**		**1,94**		**97,08**	**31,57**	**16,3**

Table D.6: SATURN: BUS Corridor results for the Scenario BL0

								BL0											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
26009	26001		C. M. Dias	C. M. Dias . B. J. Caraça	334	334	30	13	13	0,11			42	42	0,2	0,2	7,6	4,3	28,7
26009	26001	24001	C. M. Dias					9	9		12	0,04							
26001	24001		Constituição	B. J. Caraça . R. Alegria	176	510	16	9	9	0,04			28	70	0,1	0,2	3,5	1,6	22,5
26001	24001	99321	Constituição					9	9		12	0,03							
24001	99321		Constituição	R. Alegria . Constituição	256	766	23	15	13	0,08			24	94	0,1	0,3	4,3	3,3	39,1
24001	99321	24337	Constituição					15	13		1	0,00							
99321	24337		Constituição	Constituição . Costa Cabral	50	816	5	15	10	0,01			220	314	0,6	0,9	30,5	0,5	0,8
99321	24337	36337	Constituição					15	10		215	0,60							
24337	36337		Pr.Marquês	Costa Cabral . Pr.Marquês	48	864	12	33	33	0,07			184	498	1,1	2,0	56,3	1,1	0,9
24337	36337	36437	Pr.Marquês					12	8		173	1,06							
36337	36437		Constituição	Pr.Marquês . Vi. Setubal	60	924	9	12	8	0,02			196	694	0,4	2,5	20,6	0,5	1,1
36337	36437	99314	Constituição					12	8		188	0,40							
36437	99314		Constituição	Vi. Setubal . Constituição	94	1018	11	12	8	0,02			12	705	0,0	2,5	1,2	0,7	29,2
36437	99314	36537	Constituição					12	8		1	0,00							
99314	36537		Constituição	Constituição . Faria Guima	50	1068	7	12	7	0,01			14	719	0,0	2,5	1,4	0,4	13,2
99314	36537	36637	Constituição					12	7		7	0,01							
36537	36637		Constituição	Faria Guima . R.S.Brás	197	1265	29	12	7	0,06			37	756	0,1	2,6	3,6	1,4	19,2
36537	36637	99315	Constituição					12	7		9	0,02							
36637	99315		Constituição	R.S.Brás . Constituição	113	1378	16	12	7	0,03			18	773	0,0	2,6	1,8	0,8	23,1
36637	99315	40007	Constituição					12	7		1	0,00							
99315	40007		Constituição	Constituição . Ant. Quental	50	1428	7	12	7	0,01			30	803	0,1	2,7	3,0	0,4	6,1
99315	40007	40004	Constituição					12	7		23	0,05							

Table D.6: SATURN: BUS Corridor results for the Scenario BL0 (cont.)

Cont.

								BL0											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
40007	40004		Constituição	Ant. Quental . R.Salgueiros	84	1512	10	12	8	0,02			11	814	0,0	2,7	1,2	0,7	28,5
40007	40004	99316	Constituição					12	8		1	0,00							
40004	99316		Constituição	R.Salgueiros . Constituição	122	1634	15	12	9	0,04			16	829	0,0	2,7	1,8	1,0	28,2
40004	99316	40003	Constituição					12	9		1	0,00							
99316	40003		Constituição	Constituição . A.Leote Rego	50	1684	6	12	9	0,01			42	871	0,1	2,8	5,0	0,4	4,3
99316	40003	40009	Constituição					12	9		36	0,09							
40003	40009		Constituição	A.Leote Rego . R.Rib. Sousa	90	1774	13	12	9	0,03			14	885	0,0	2,9	1,6	0,8	23,8
40003	40009	99319	Constituição					12	9		1	0,00							
40009	99319		Constituição	R.Rib. Sousa . Constituição	40	1814	4	12	9	0,01			4	888	0,0	2,9	0,5	0,4	40,0
40009	99319	30011	Constituição					12	9		1	0,00							
99319	30011		Constituição	Constituição . Pad.Pach.Mte	50	1864	6	12	9	0,02			12	901	0,0	2,9	1,5	0,5	14,8
99319	30011	99318	Constituição					12	9		6	0,02							
30011	99318		Constituição	Pad.Pach.Mte . Constituição	318	2182	38	12	9	0,09			39	939	0,1	3,0	4,7	2,8	29,7
30011	99318	30013	Constituição					12	9		1	0,00							
99318	30013		Constituição	Constituição . Serpa Pinto	50	2232	6	12	9	0,01			21	960	0,1	3,1	2,6	0,4	8,6
99318	30013	47007	Constituição					6	4		15	0,04							
30013	47007		Constituição	Serpa Pinto . Ol.Monteiro	356	2588	32	6	5	0,04			65	1025	0,1	3,1	4,1	1,6	19,7
30013	47007	47005	Constituição					6	5		33	0,04							
47007	47005		Constituição	Constituição .Av.França	191	2779	17	6	5	0,02			18	1043	0,0	3,2	1,1	0,9	38,2
				TOTAL	**2779**	**2779**	**312**			**0,77**	**733**	**2,39**	**1043**		**3,2**		**157,8**	**24,4**	**7,7**

Table D.7: SATURN: BUS Corridor results for the Scenario BL1

								BL1											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
26009	26001		C. M. Dias	C. M. Dias . B. J. Caraça	334	334	30	13	13	0,11			42	42	0,15	0,15	7,57	4	28,7
26009	26001	24001	C. M. Dias					9	9		12	0,04							
26001	24001		Constituição	B. J. Caraça . R. Alegria	176	510	16	9	9	0,04			28	70	0,07	0,22	3,52	2	22,5
26001	24001	99321	Constituição					9	9		12	0,03							
24001	99321		Constituição	R. Alegria . Constituição	256	766	23	15	15	0,10			24	94	0,10	0,32	4,92	4	39,1
24001	99321	24337	Constituição					15	15		1	0,00							
99321	24337		Constituição	Constituição . Costa Cabral	50	816	5	15	15	0,02			69	163	0,29	0,61	14,38	1	2,6
99321	24337	36337	Constituição					15	15		64	0,27							
24337	36337		Pr.Marquês	Costa Cabral . Pr.Marquês	48	864	12	33	33	0,10			13	176	0,12	0,73	5,90	2	13,3
24337	36337	36437	Pr.Marquês					12	12		2	0,02							
36337	36437		Constituição	Pr.Marquês . Vi. Setubal	60	924	9	12	12	0,03			17	193	0,06	0,78	2,80	1	12,7
36337	36437	99314	Constituição					12	12		9	0,03							
36437	99314		Constituição	Vi. Setubal . Constituição	94	1018	11	12	12	0,04			12	204	0,04	0,82	1,92	1	29,2
36437	99314	36537	Constituição					12	12		1	0,00							
99314	36537		Constituição	Constituição . Faria Guima	50	1068	7	12	12	0,02			14	218	0,04	0,86	2,20	1	13,2
99314	36537	36637	Constituição					12	12		7	0,02							
36537	36637		Constituição	Faria Guima . R.S.Brás	197	1265	29	12	11	0,09			37	255	0,12	0,98	5,76	2	19,2
36537	36637	99315	Constituição					12	11		9	0,03							
36637	99315		Constituição	R.S.Brás . Constituição	113	1378	16	12	11	0,05			18	272	0,05	1,03	2,58	1	23,1
36637	99315	40007	Constituição					12	11		1	0,00							
99315	40007		Constituição	Constituição . Ant. Quental	50	1428	7	12	11	0,02			30	302	0,09	1,12	4,35	1	6,1
99315	40007	40004	Constituição					12	11		23	0,07							

Table D.7: SATURN: BUS Corridor results for the Scenario BL1 (cont.)

Cont.

								BL1											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
40007	40004		Constituição	Ant. Quental . R.Salgueiros	84	1512	10	12	11	0,03			11	313	0,03	1,15	1,59	1	28,5
40007	40004	99316	Constituição					12	11		1	0,00							
40004	99316		Constituição	R.Salgueiros . Constituição	122	1634	15	12	11	0,05			16	328	0,05	1,20	2,37	1	28,2
40004	99316	40003	Constituição					12	11		1	0,00							
99316	40003		Constituição	Constituição . A.Leote Rego	50	1684	6	12	11	0,02			35	363	0,11	1,30	5,33	1	5,1
99316	40003	40009	Constituição					12	11		29	0,09							
40003	40009		Constituição	A.Leote Rego . R.Rib. Sousa	90	1774	13	12	11	0,04			14	377	0,04	1,35	2,08	1	23,8
40003	40009	99319	Constituição					12	11		1	0,00							
40009	99319		Constituição	R.Rib. Sousa . Constituição	40	1814	4	12	11	0,01			4	380	0,01	1,36	0,56	0	40,0
40009	99319	30011	Constituição					12	11		1	0,00							
99319	30011		Constituição	Constituição . Pad.Pach.Mte	50	1864	6	12	11	0,02			12	393	0,04	1,39	1,90	1	14,8
99319	30011	99318	Constituição					12	11		6	0,02							
30011	99318		Constituição	Pad.Pach.Mte . Constituição	318	2182	38	12	11	0,12			39	431	0,12	1,51	5,98	4	29,7
30011	99318	30013	Constituição					12	11		1	0,00							
99318	30013		Constituição	Constituição . Serpa Pinto	50	2232	6	12	11	0,02			22	453	0,07	1,58	3,41	1	8,2
99318	30013	47007	Constituição					6	6		16	0,05							
30013	47007		Constituição	Serpa Pinto . Ol.Monteiro	356	2588	32	6	6	0,05			65	518	0,10	1,68	5,08	2	19,7
30013	47007	47005	Constituição					6	6		33	0,05							
47007	47005		Constituição	Constituição .Av.França	191	2779	17	6	6	0,03			18	536	0,03	1,71	1,42	1	38,2
				TOTAL	**2779**	**2779**	**312**			**0,98**	**226**	**0,73**	**537**		**1,71**		**85,61**	**30,4**	**17,8**

Table D.8: SATURN: BUS Corridor results for the Scenario BL2

								BL2												
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
26009	26001		C. M. Dias	C. M. Dias . B. J. Caraça	334	334	30	13	13	0,11			42	42	0,15	0,15	7,57	4	28,7
26009	26001	24001	C. M. Dias					9	9		12	0,04							
26001	24001		Constituição	B. J. Caraça . R. Alegria	176	510	16	9	9	0,04			28	70	0,07	0,22	3,52	2	22,5
26001	24001	99321	Constituição					9	9		12	0,03							
24001	99321		Constituição	R. Alegria . Constituição	256	766	23	15	15	0,10			24	94	0,10	0,32	4,92	4	39,1
24001	99321	24337	Constituição					15	15		1	0,00							
99321	24337		Constituição	Constituição . Costa Cabral	50	816	5	15	15	0,02			63	157	0,26	0,58	13,13	1	2,9
99321	24337	36337	Constituição					15	15		58	0,24							
24337	36337		Pr.Marquês	Costa Cabral . Pr.Marquês	48	864	12	33	33	0,10			12	169	0,11	0,69	5,44	2	14,4
24337	36337	36437	Pr.Marquês					12	12		1	0,01							
36337	36437		Constituição	Pr.Marquês . Vi. Setubal	60	924	9	12	12	0,03			17	186	0,06	0,75	2,80	1	12,7
36337	36437	99314	Constituição					12	12		9	0,03							
36437	99314		Constituição	Vi. Setubal . Constituição	94	1018	11	12	12	0,04			12	197	0,04	0,79	1,92	1	29,2
36437	99314	36537	Constituição					12	12		1	0,00							
99314	36537		Constituição	Constituição . Faria Guima	50	1068	7	12	12	0,02			14	211	0,04	0,83	2,20	1	13,2
99314	36537	36637	Constituição					12	12		7	0,02							
36537	36637		Constituição	Faria Guima . R.S.Brás	197	1265	29	12	11	0,09			37	248	0,12	0,95	5,76	2	19,2
36537	36637	99315	Constituição					12	11		9	0,03							
36637	99315		Constituição	R.S.Brás . Constituição	113	1378	16	12	11	0,05			18	265	0,05	1,00	2,58	1	23,1
36637	99315	40007	Constituição					12	11		1	0,00							
99315	40007		Constituição	Constituição . Ant. Quental	50	1428	7	12	11	0,02			30	295	0,09	1,08	4,35	1	6,1
99315	40007	40004	Constituição					12	11		23	0,07							

Table D.8: SATURN: BUS Corridor results for the Scenario BL2 (cont.)

Cont.

								BL2											
Node A	**Node B**	**Node C**	**Street**	**Section**	**Distance (m)**	**Distance accumul. (m)**	**Free flow time (sec)**	**Demand Flows (veh/h)**	**Actual Flows (veh/h)**	**Link Cruise Time (veh.hr)**	**Delays (sec)**	**Total Delays (veh.hr)**	**Travel Time (sec)**	**Travel Time accumul. (sec)**	**Total Travel Time (veh.hr)**	**Total Travel Time accumul. (veh.hr)**	**Total Passenger Time (pass.hr)**	**Total Travel Distance (veh.km)**	**Speed (Km/h)**
40007	40004		Constituição	Ant. Quental . R.Salgueiros	84	1512	10	12	11	0,03			11	306	0,03	1,12	1,59	1	28,5
40007	40004	99316	Constituição					12	11		1	0,00							
40004	99316		Constituição	R.Salgueiros . Constituição	122	1634	15	12	11	0,05			16	321	0,05	1,16	2,37	1	28,2
40004	99316	40003	Constituição					12	11		1	0,00							
99316	40003		Constituição	Constituição . A.Leote Rego	50	1684	6	12	11	0,02			36	357	0,11	1,27	5,49	1	5,0
99316	40003	40009	Constituição					12	11		30	0,09							
40003	40009		Constituição	A.Leote Rego . R.Rib. Sousa	90	1774	13	12	11	0,04			14	371	0,04	1,31	2,08	1	23,8
40003	40009	99319	Constituição					12	11		1	0,00							
40009	99319		Constituição	R.Rib. Sousa . Constituição	40	1814	4	12	11	0,01			4	374	0,01	1,33	0,56	0	40,0
40009	99319	30011	Constituição					12	11		1	0,00							
99319	30011		Constituição	Constituição . Pad.Pach.Mte	50	1864	6	12	11	0,02			12	387	0,04	1,36	1,90	1	14,8
99319	30011	99318	Constituição					12	11		6	0,02							
30011	99318		Constituição	Pad.Pach.Mte . Constituição	318	2182	38	12	11	0,12			39	425	0,12	1,48	5,98	4	29,7
30011	99318	30013	Constituição					12	11		1	0,00							
99318	30013		Constituição	Constituição . Serpa Pinto	50	2232	6	12	11	0,02			21	446	0,07	1,55	3,26	1	8,6
99318	30013	47007	Constituição					6	6		15	0,05							
30013	47007		Constituição	Serpa Pinto . Ol.Monteiro	356	2588	32	6	6	0,05			65	511	0,10	1,65	5,08	2	19,7
30013	47007	47005	Constituição					6	6		33	0,05							
47007	47005		Constituição	Constituição .Av.França	191	2779	17	6	6	0,03			18	529	0,03	1,68	1,42	1	38,2
				TOTAL	**2779**	**2779**	**312**			**0,98**	**219**	**0,69**	**529**		**1,68**		**83,90**	**30,4**	**18,1**

APPENDIX E: DRACULA AGGREGATE RESULTS

Table E.1: DRACULA: Total changes in performance within the study area

Absolute Totals		Without BL				With BL												Difference		
		Base				BL0				BL1				BL2				BL0	BL1	BL2
		Average	Stand. Deviation	Confidence interval (α=0,0025; N=30)		Average	Stand. Deviation	Confidence interval (α=0,0025; N=30)		Average	Stand. Deviation	Confidence interval (α=0,0025; N=30)		Average	Stand. Deviation	Confidence interval (α=0,0025; N=30)		Average		
Queuing Delay	veh-hr	852	31	840	863	1310	55	1290	1331	1021	44	1004	1037	956	68	931	982	54%	20%	12%
Cruising Time	veh-hr	552	4	550	553	490	8	487	493	515	6	513	517	529	10	526	533	-11%	-7%	-4%
Total Travel Time	veh-hr	1403	28	1393	1414	1801	48	1783	1818	1535	39	1521	1550	1486	59	1464	1507	28%	9%	6%
Total Passenger Time	pass-km	2766	92	2731	2800	3344	97	3308	3380	2993	89	2960	3027	2941	96	2905	2977	21%	8%	6%
Total Travel Distance	pcu-km	20411	184	20343	20480	18778	314	18661	18896	20194	223	20111	20278	20202	279	20098	20306	-8%	-1%	-1%
Total Passenger Distance	pass-km	38035	262	37937	38133	35805	422	35648	35963	37621	325	37500	37742	37679	372	37540	37818	-6%	-1%	-1%
Passenger Speed	km/hr	14	2,8	12,7	14,8	11	4,4	9,1	12,3	13	3,7	11,2	13,9	13	3,9	11,4	14,3	-22%	-9%	-7%
Overall Average Speed	km/hr	15	1,2	14,1	15,0	10	1,0	10,1	10,8	13	1,0	12,8	13,5	14	1,0	13,2	14,0	-28%	-10%	-7%
Average Total	pcu/hr	15962				15962				15927				15899						

Table E.2: DRACULA: Changes in BUS performance within the study area

Bus Totals		Without BL				With BL												Difference		
		Base				BL0				BL1				BL2				BL0	BL1	BL2
		Average	Stand. Deviation	Confidence interval (α=0,0025; N=30)		Average	Stand. Deviation	Confidence interval (α=0,0025; N=30)		Average	Stand. Deviation	Confidence interval (α=0,0025; N=30)		Average	Stand. Deviation	Confidence interval (α=0,0025; N=30)		Average		
Queuing Delay	veh-hr	13	2	13	14	145	1,6	14	15	145	1,5	14	15	15	1,3	14	15	11%	11%	12%
Cruising Time	veh-hr	6	0,1	6	6	6	0,1	6	6	6	0,1	6	6	6	0,1	6	6	-3%	-5%	-4%
Total Travel Time	veh-hr	19	2	19	20	21	1,48	20	21	21	1,5	20	21	21	1,2	20	21	7%	6%	7%
Total Passenger Time	pass-km	967	85	935	998	1030	74,2	1002	1058	1024	73,1	997	1052	1037	58,6	1015	1058	7%	6%	7%
Total Travel Distance	pcu-km	236	2	235	237	234	2,1	233	235	233	2,9	232	235	234	1,7	234	235	-1%	-1%	-1%
Total Passenger Distance	pass-km	11807	107	11767	11847	11698	105,3	11658	11737	11672	146,3	11617	11727	11721	86,3	11689	11753	-1%	-1%	-1%
Overall Average Speed	km/hr	12	1	12	13	11	0,9	11	12	12	0,9	11	12	11	0,7	11	12	-7%	-7%	-8%

Table E.3: DRACULA: Changes in CAR performance within the study area

Car Totals		**Without BL**				**With BL**											
		Base				**BL0**				**BL1**				**BL2**			
		Average	**Stand. Deviation**	**Confidence interval (α=0,0025; N=30)**		**Average**	**Stand. Deviation**	**Confidence interval (α=0,0025; N=30)**		**Average**	**Stand. Deviation**	**Confidence interval (α=0,0025; N=30)**		**Average**	**Stand. Deviation**	**Confidence interval (α=0,0025; N=30)**	
Queuing Delay	veh-hr	839	31	827	850	1296	56	1275	1316	1006	434	990	1022	941	68	916	967
Cruising Time	veh-hr	545	4	544	547	484	8	481	487	509	6	507	511	524	10	520	527
Total Travel Time	veh-hr	1384	28	1374	1394	1780	48	1762	1798	1515	39	1500	1529	1465	59	1443	1487
Total Passenger Time	pass-km	1799	36	1786	1813	2314	62	2291	2337	1969	51	1950	1988	1904	76	1876	1933
Total Travel Distance	pcu-km	20175	184	20107	20244	18544	314	18427	18662	19961	223	19877	20044	19968	279	19864	20072
Total Passenger Distance	pass-km	26228	239	26139	26317	24108	409	23955	24260	25949	290	25841	26057	25958	362	25823	26093
Overall Average Speed	km/hr	14,6	0,4	14,4	14,7	10,4	0,4	10,3	10,6	13,2	0,4	13,0	13,4	13,7	0,7	13,4	13,9

APPENDIX F: DRACULA CORRIDOR RESULTS

Table F.1: DRACULA: CAR corridor results for the Base Scenario

Anode	Bnode	Distance (m)	Accumulated Distance (m)	Free flow time (sec)	Performed Flow (veh/hr.)	Average time (sec)	Standard Deviation (sec)	Maximum Time (sec)	Average Speed Km/h)	Accumulated Average Time (sec)	Total Travel Time (veh.hr)	Delay (sec)	Accumulated Total Delay (veh.hr)	Accumulated Total Travel Distance (veh.km)
26009	26001	334	334	30	1081	103	44	242	12	103	30,9	73	21,9	361
26001	24001	176	510	16	866	34	15	66	17	137	39,2	18	26,4	514
24001	99321	256	766	23	796	32	7	61	28	169	46,2	8	28,2	717
99321	24337	50	816	5	797	30	21	74	4	199	52,9	26	33,9	757
24337	36337	48	864	12	1380	13	3	27	9	212	58,0	2	34,6	823
36337	36437	60	924	9	985	16	12	46	11	228	62,3	7	36,6	883
36437	99314	94	1018	11	1291	15	5	45	21	243	67,7	4	37,9	1004
99314	36537	50	1068	7	1290	15	12	52	9	258	73,1	8	40,8	1068
36537	36637	197	1265	28	1036	48	20	94	14	307	87,0	20	46,5	1272
36637	99315	113	1378	16	942	26	12	89	14	332	93,8	10	49,0	1379
99315	40007	50	1428	7	938	32	24	71	4	365	102,2	25	55,5	1426
40007	40004	84	1512	10	687	12	2	23	23	377	104,4	2	55,9	1483
40004	99316	122	1634	15	813	18	4	41	24	394	108,4	3	56,6	1583
99316	40003	50	1684	6	811	14	10	37	11	409	111,6	8	58,4	1623
40003	40009	90	1774	13	723	15	2	27	20	423	114,6	2	58,7	1688
40009	99319	40	1814	4	876	8	5	35	15	431	116,5	5	59,9	1723
99319	30011	50	1864	6	880	9	9	32	10	441	118,8	3	60,7	1767
30011	99318	318	2182	38	883	52	16	154	22	492	131,6	14	64,0	2048
99318	30013	50	2232	6	880	20	18	114	7	512	136,4	14	67,4	2092
30013	47007	356	2588	32	508	77	27	151	16	590	147,3	45	73,8	2273
47007	47005	191	2779	17	577	20	2	29	33	610	150,5	3	74,3	2383

Table F.2: DRACULA: CAR corridor results for the Scenario BL0

Anode	Bnode	Distance (m)	Accumulated Distance (m)	Free flow time (sec)	Performed Flow (veh/hr.)	Average time (sec)	Standard Deviation (sec)	Maximum Time (sec)	Average Speed Km/h)	Accumulated Average Time (sec)	Total Travel Time (veh.hr)	Delay (sec)	Accumulated Total Delay (veh.hr)	Accumulated Total Travel Distance (veh.km)
26009	26001	334	334	30	898	165	140	815	7	165	41,1	135	33,6	300
26001	24001	176	510	16	710	34	57	222	8	240	47,9	18	37,3	425
24001	99321	256	766	23	548	278	139	482	3	518	90,2	255	76,1	565
99321	24337	50	816	5	540	90	41	270	1	608	103,8	86	89,0	592
24337	36337	48	864	12	683	72	59	430	2	681	117,5	61	100,5	625
36337	36437	60	924	9	514	99	27	189	2	780	131,6	90	113,4	656
36437	99314	94	1018	11	798	32	15	81	10	811	138,6	20	117,9	731
99314	36537	50	1068	7	798	19	16	67	8	830	142,9	12	120,6	771
36537	36637	197	1265	28	690	66	24	127	10	897	155,6	38	127,9	906
36637	99315	113	1378	16	648	29	14	81	13	926	160,8	13	130,1	980
99315	40007	50	1428	7	648	33	24	70	4	959	166,7	26	134,7	1012
40007	40004	84	1512	10	478	12	1	16	23	970	168,3	2	135,0	1052
40004	99316	122	1634	15	609	17	3	34	25	987	171,1	2	135,3	1127
99316	40003	50	1684	6	606	19	14	80	8	1006	174,3	13	137,5	1157
40003	40009	90	1774	13	546	16	3	32	18	1022	176,7	3	138,0	1206
40009	99319	40	1814	4	700	9	6	33	14	1031	178,5	5	139,0	1234
99319	30011	50	1864	6	700	14	10	36	11	1045	181,1	8	140,5	1269
30011	99318	318	2182	38	715	52	13	98	22	1097	191,5	14	143,3	1496
99318	30013	50	2232	6	714	16	14	58	9	1112	194,6	10	145,2	1532
30013	47007	356	2588	32	408	69	25	117	18	1181	202,3	37	149,3	1677
47007	47005	191	2779	17	499	20	2	27	34	1201	205,1	3	149,7	1773

Table F.3: DRACULA: CAR corridor results for the Scenario BL1

Anode	Bnode	Distance (m)	Accumulated Distance (m)	Free flow time (sec)	Performed Flow (veh/hr.)	Average time (sec)	Standard Deviation (sec)	Maximum Time (sec)	Average Speed Km/h)	Accumulated Average Time (sec)	Total Travel Time (veh.hr)	Delay (sec)	Accumulated Total Delay (veh.hr)	Accumulated Total Travel Distance (veh.km)
26009	26001	334	334	30	1088	110	45	236	11	110	33,1	79	24,0	363
26001	24001	176	510	16	875	34	15	66	17	144	41,5	19	28,6	518
24001	99321	256	766	23	789	46	27	154	20	190	51,5	23	33,5	720
99321	24337	50	816	5	780	38	26	134	3	228	59,8	34	40,8	759
24337	36337	48	864	12	1166	22	18	129	6	250	66,8	10	44,1	814
36337	36437	60	924	9	551	57	40	183	3	307	75,6	49	51,6	848
36437	99314	94	1018	11	835	27	15	91	11	334	81,8	16	55,2	926
99314	36537	50	1068	7	830	18	15	69	8	352	86,1	11	57,8	968
36537	36637	197	1265	28	599	72	32	170	9	425	98,1	44	65,1	1086
36637	99315	113	1378	16	631	37	18	92	10	461	104,6	21	68,7	1157
99315	40007	50	1428	7	630	33	25	71	4	495	110,4	26	73,3	1188
40007	40004	84	1512	10	485	12	1	16	23	506	111,9	2	73,5	1229
40004	99316	122	1634	15	615	16	2	27	26	523	114,7	2	73,8	1304
99316	40003	50	1684	6	613	18	12	62	8	541	117,8	12	75,8	1335
40003	40009	90	1774	13	527	15	2	28	19	556	120,0	2	76,1	1382
40009	99319	40	1814	4	680	8	6	31	15	564	121,6	5	77,0	1409
99319	30011	50	1864	6	681	13	10	35	11	578	124,1	7	78,4	1443
30011	99318	318	2182	38	759	49	9	80	23	626	134,4	11	80,7	1685
99318	30013	50	2232	6	759	15	13	51	9	641	137,6	9	82,5	1723
30013	47007	356	2588	32	491	73	25	137	17	714	147,4	41	88,1	1897
47007	47005	191	2779	17	583	20	2	28	34	734	150,7	3	88,5	2009

Table F.4: DRACULA: CAR corridor results for the Scenario BL2

Anode	Bnode	Distance (m)	Accumulated Distance (m)	Free flow time (sec)	Performed Flow (veh/hr.)	Average time (sec)	Standard Deviation (sec)	Maximum Time (sec)	Average Speed Km/h)	Accumulated Average Time (sec)	Accumulated Total Delay (veh.hr)	Accumulated Total Travel Distance (veh.km)	Accumulated Total Delay (veh.hr)	Accumulated Total Travel Distance (veh.km)
26009	26001	334	334	30	1086	99	44	233	12	99	29,9	69	20,9	363
26001	24001	176	510	16	864	34	15	68	17	133	38,0	18	25,2	515
24001	99321	256	766	23	786	42	17	107	22	175	47,2	19	29,3	716
99321	24337	50	816	5	778	38	24	110	4	213	55,4	34	36,6	755
24337	36337	48	864	12	1238	21	11	89	6	234	62,6	9	39,8	814
36337	36437	60	924	9	667	55	24	123	3	289	72,8	46	48,4	854
36437	99314	94	1018	11	878	19	8	51	16	308	77,5	8	50,3	937
99314	36537	50	1068	7	875	16	13	57	9	324	81,3	9	52,4	981
36537	36637	197	1265	28	567	58	27	136	12	382	90,5	29	57,1	1092
36637	99315	113	1378	16	624	33	17	91	12	414	96,1	16	59,9	1163
99315	40007	50	1428	7	623	32	24	69	4	447	101,7	25	64,2	1194
40007	40004	84	1512	10	476	12	1	16	23	458	103,2	2	64,4	1234
40004	99316	122	1634	15	612	17	3	35	25	475	106,1	2	64,8	1309
99316	40003	50	1684	6	610	19	13	69	8	494	109,3	13	67,0	1339
40003	40009	90	1774	13	518	16	4	34	18	510	111,6	3	67,4	1386
40009	99319	40	1814	4	672	9	6	34	14	518	113,2	5	68,3	1413
99319	30011	50	1864	6	672	14	10	36	11	532	115,7	8	69,7	1446
30011	99318	318	2182	38	737	50	11	96	22	582	126,0	12	72,2	1681
99318	30013	50	2232	6	736	15	13	55	9	598	129,1	9	74,1	1718
30013	47007	356	2588	32	474	76	27	141	16	674	139,1	44	79,9	1886
47007	47005	191	2779	17	588	20	2	29	33	694	142,4	3	80,4	1999

Table F.5: DRACULA: BUS corridor results for the Base Scenario

Anode	Bnode	Distance (m)	Accumulated Distance (m)	Free flow time (sec)	Performed Flow (veh/hr.)	Average time (sec)	Standard Deviation (sec)	Maximum Time (sec)	Average Speed Km/h)	Accumulated Average Time (sec)	Total Travel Time (veh.hr)	Delay (sec)	Accumulated Total Delay (veh.hr)	Accumulated Total Travel Distance (veh.km)
26009	26001	334	334	30	8	84	63	197	14	84	0,19	54	0,1	2,7
26001	24001	176	510	16	6	62	15	92	9	146	0,29	46	0,2	3,7
24001	99321	256	766	23	10	61	10	80	14	207	0,46	38	0,3	6,3
99321	24337	50	816	5	10	29	21	65	5	236	0,54	25	0,4	6,8
24337	36337	48	864	12	22	13	2	19	9	250	0,62	2	0,4	7,8
36337	36437	60	924	9	8	10	1	13	17	260	0,65	2	0,4	8,3
36437	99314	94	1018	11	8	15	4	23	21	275	0,68	4	0,4	9,1
99314	36537	50	1068	7	8	10	6	25	15	285	0,70	3	0,4	9,5
36537	36637	197	1265	28	10	83	12	96	8	368	0,92	55	0,5	11,4
36637	99315	113	1378	16	10	45	8	64	8	413	1,05	29	0,6	12,5
99315	40007	50	1428	7	10	56	14	67	3	469	1,20	49	0,8	13,0
40007	40004	84	1512	10	10	12	1	12	23	481	1,23	2	0,8	13,8
40004	99316	122	1634	15	10	41	7	59	10	522	1,35	27	0,8	15,0
99316	40003	50	1684	6	10	15	9	31	10	537	1,39	9	0,9	15,5
40003	40009	90	1774	13	10	14	1	16	21	551	1,43	1	0,9	16,4
40009	99319	40	1814	4	9	30	5	41	4	581	1,50	26	0,9	16,8
99319	30011	50	1864	6	8	14	10	31	7	595	1,54	8	1,0	17,2
30011	99318	318	2182	38	8	76	13	102	15	671	1,71	38	1,0	19,8
99318	30013	50	2232	6	8	14	10	35	11	685	1,74	8	1,1	20,2
30013	47007	356	2588	32,04	4	127	10	141	10	812	1,88	95	1,2	21,6
47007	47005	191	2779	17,19	4	20	1	22	33	832	1,90	3	1,2	22,4

Table F.6: DRACULA: BUS corridor results for the Scenario BL0

Anode	Bnode	Distance (m)	Accumulated Distance (m)	Free flow time (sec)	Performed Flow (veh/hr.)	Average time (sec)	Standard Deviation (sec)	Maximum Time (sec)	Average Speed Km/h)	Accumulated Average Time (sec)	Total Travel Time (veh.hr)	Delay (sec)	Accumulated Total Delay (veh.hr)	Accumulated Total Travel Distance (veh.km)
26009	26001	334	334	30	8	87	61	195	14	87	0,2	57	0,13	2,7
26001	24001	176	510	16	6	79	23	114	7	166	0,3	63	0,23	3,7
24001	99321	256	766	23	10	71	14	99	12	236	0,5	48	0,36	6,3
99321	24337	50	816	5	10	119	36	189	1	355	0,8	114	0,68	6,8
24337	36337	48	864	12	22	44	38	122	3	399	1,1	32	0,88	7,9
36337	36437	60	924	9	9	82	16	116	2	481	1,3	74	1,07	8,4
36437	99314	94	1018	11	10	15	4	26	21	496	1,4	4	1,08	9,3
99314	36537	50	1068	7	10	19	15	47	8	515	1,4	12	1,11	9,8
36537	36637	197	1265	28	9	71	15	96	9	586	1,6	43	1,22	11,6
36637	99315	113	1378	16	8	55	17	93	7	641	1,7	38	1,30	12,5
99315	40007	50	1428	7	8	45	22	69	3	686	1,8	38	1,39	12,9
40007	40004	84	1512	10	8	11	1	12	24	698	1,9	1	1,39	13,6
40004	99316	122	1634	15	8	42	5	53	10	739	1,9	27	1,45	14,5
99316	40003	50	1684	6	8	21	13	42	7	760	2,0	15	1,49	14,9
40003	40009	90	1774	13	8	13	0	14	22	774	2,0	1	1,49	15,7
40009	99319	40	1814	4	8	30	5	41	4	804	2,1	27	1,55	16,0
99319	30011	50	1864	6	8	18	9	32	9	822	2,1	12	1,57	16,4
30011	99318	318	2182	38	8	90	14	114	12	912	2,3	52	1,69	18,9
99318	30013	50	2232	6	8	13	10	32	11	925	2,4	7	1,70	19,3
30013	47007	356	2588	32	4	109	25	143	11	1035	2,5	77	1,79	20,7
47007	47005	191	2779	17	4	20	1	22	34	1054	2,5	3	1,79	21,5

Table F.7: DRACULA: BUS corridor results for the Scenario BL1

Anode	Bnode	Distance (m)	Accumulated Distance (m)	Free flow time (sec)	Performed Flow (veh/hr.)	Average time (sec)	Standard Deviation (sec)	Maximum Time (sec)	Average Speed Km/h)	Accumulated Average Time (sec)	Total Travel Time (veh.hr)	Delay (sec)	Accumulated Total Delay (veh.hr)	Accumulated Total Travel Distance (veh.km)
26009	26001	334	334	30	8	83	61	194	14	83	0,2	53	0,1	2,7
26001	24001	176	510	16	6	62	15	93	10	146	0,3	47	0,2	3,7
24001	99321	256	766	23	10	61	10	79	14	207	0,5	38	0,3	6,3
99321	24337	50	816	5	10	34	23	74	4	241	0,6	30	0,4	6,8
24337	36337	48	864	12	22	22	18	76	6	263	0,7	11	0,5	7,8
36337	36437	60	924	9	8	55	30	105	4	318	0,8	46	0,6	8,3
36437	99314	94	1018	11	8	16	4	26	20	334	0,8	5	0,6	9,1
99314	36537	50	1068	7	8	16	13	42	10	350	0,9	9	0,6	9,5
36537	36637	197	1265	28	9	73	14	95	9	423	1,1	45	0,7	11,2
36637	99315	113	1378	16	10	56	17	94	7	479	1,2	40	0,8	12,3
99315	40007	50	1428	7	10	46	23	68	3	525	1,3	39	0,9	12,8
40007	40004	84	1512	10	9	11	1	12	24	536	1,4	1	0,9	13,6
40004	99316	122	1634	15	8	41	5	51	10	577	1,5	26	1,0	14,6
99316	40003	50	1684	6	8	23	15	46	7	600	1,5	17	1,0	15,0
40003	40009	90	1774	13	8	13	0	14	22	613	1,5	0	1,0	15,8
40009	99319	40	1814	4	8	29	3	36	4	642	1,6	26	1,1	16,1
99319	30011	50	1864	6	8	17	9	31	10	659	1,6	11	1,1	16,5
30011	99318	318	2182	38	8	86	14	114	13	745	1,8	47	1,2	19,0
99318	30013	50	2232	6	8	16	12	35	9	760	1,9	10	1,2	19,4
30013	47007	356	2588	32	4	108	20	136	11	868	2,0	76	1,3	20,9
47007	47005	191	2779	17	4	20	1	21	34	888	2,0	2	1,3	21,6

Table F.8: DRACULA: BUS corridor results for the Scenario BL2

Anode	Bnode	Distance (m)	Accumulated Distance (m)	Free flow time (sec)	Performed Flow (veh/hr.)	Average time (sec)	Standard Deviation (sec)	Maximum Time (sec)	Average Speed Km/h)	Accumulated Average Time (sec)	Total Travel Time (veh.hr)	Delay (sec)	Accumulated Total Delay (veh.hr)	Accumulated Total Travel Distance (veh.km)
26009	26001	334	334	31	8	83	61	192	14	83	0,2	53	0,1	2,7
26001	24001	176	510	16	6	62	15	92	9	145	0,3	46	0,2	3,7
24001	99321	256	766	23	10	63	11	84	14	208	0,5	40	0,3	6,3
99321	24337	50	816	5	10	37	21	69	4	245	0,6	32	0,4	6,8
24337	36337	48	864	12	22	22	13	51	6	267	0,7	10	0,5	7,8
36337	36437	60	924	9	8	52	17	76	4	319	0,8	44	0,6	8,3
36437	99314	94	1018	11	8	14	3	20	21	333	0,8	3	0,6	9,1
99314	36537	50	1068	7	8	14	11	38	11	347	0,9	7	0,6	9,5
36537	36637	197	1265	28	10	75	16	96	9	423	1,1	47	0,7	11,3
36637	99315	113	1378	16	10	60	22	107	6	482	1,2	43	0,8	12,5
99315	40007	50	1428	7	10	43	25	68	3	525	1,4	36	0,9	13,0
40007	40004	84	1512	10	10	11	1	12	24	537	1,4	1	0,9	13,8
40004	99316	122	1634	15	9	42	6	56	10	579	1,5	27	1,0	14,9
99316	40003	50	1684	6	9	26	15	52	6	604	1,6	20	1,0	15,4
40003	40009	90	1774	13	9	13	1	14	22	618	1,6	0	1,0	16,2
40009	99319	40	1814	4	8	30	4	41	4	648	1,7	27	1,1	16,5
99319	30011	50	1864	6	8	18	10	32	8	666	1,7	12	1,1	16,9
30011	99318	318	2182	38	8	90	14	111	12	756	1,9	52	1,3	19,5
99318	30013	50	2232	6	8	15	11	36	9	772	1,9	9	1,3	19,9
30013	47007	356	2588	32	4	115	22	146	11	887	2,1	83	1,4	21,3
47007	47005	191	2779	17	4	20	1	21	34	907	2,1	3	1,4	22,1