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Integrating dial-a-ride and ridesharing services into Curitiba's Public Transport Network (RIT)

Demand responsive and multimodal transport to modify feeder bus lines operation in Curitiba, Brazil

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Integrating dial-a-ride and ridesharing services into Curitiba's Public Transport Network (RIT)

Demand responsive and multimodal transport to improve and complement feeder bus lines operation inside a study area in Curitiba, Brazil

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Abstract

Demand Responsive Transport is regarded by many as key for the future of public transportation and mobility as a service. Nevertheless, recent research shows that more than a half of DRT services provided by start-ups in the microtransit era fail within 7 years of operation.

This degree project is part of the collaboration within the *Smart City Concepts in Curitiba* consortium and focuses on the modelling and assessment of DRT services in Curitiba, Brazil. The goal of DRT services implementation in this degree project is to reduce car ridership and improve the level of service of public transit inside a study area with low public transport demand. Using PTV Visum 2022 and analytical expressions, three scenarios have been coded and compared to a base scenario.

- **Scenario I** introduces a ridesharing service inside the study area.
- **Scenario II** introduces dial-a-ride express shuttles operated by minibuses between the zones inside the study area.
- **Scenario III** focuses on multimodal transport where a dial-a-ride service feeds the main bus lines inside the zone, and some of the existing feeder lines (around 50%) are replaced by demand responsive dial-a-ride minibuses.

A maximum reduction of total system costs of -13,67% (relative difference) is achieved in scenario III with respect to the base scenario. Subsequently, scenario II achieves to reduce the total system costs by -6,04% relative to the base scenario. Finally, for scenario I, the average of multiple simulation runs suggests that a reduction of -1,28% of total system costs is possible by operating a ridesharing fleet of 35 vehicles with high distribution of occupancies inside the vehicles.

The results of this degree project show the benefits of combining conventional collective transport with demand responsive transport in low demand density areas, this combination provides a better level of service to public transport users and could be implement in time periods with low demand or on weekends.

Keywords: DRT, dial-a-ride, ridesharing, feeder lines, multimodal transport, PTV Visum, Curitiba, RIT.

Sammanfattning

Demand Responsive Transport betraktas av många som framtiden för kollektivtrafik och mobilitet som tjänst. Ändå visar ny forskning att mer än hälften av DRT-tjänsterna som tillhandahålls av nystartade företag inom mikrokollektivtrafik misslyckas inom sina första sju år på marknaden.

Detta examensarbete är en del av samarbetet mellan konsortiet *Smart City Concepts in Curitiba* och fokuserar på modellering och bedömning av DRT-tjänster. DRT-tjänsternas syfte är att minska bilåkande och förbättra servicenivån för kollektivtrafik inom ett studieområde med låg efterfrågan på kollektivtrafik. Med hjälp av PTV Visum 2022 har tre scenarion kodats och jämförts med ett basscenario.

- **Scenario I** introducerar en samåkningstjänst inom studieområdet.
- **Scenario II** introducerar expressbussar med dial-a-ride mellan zonerna inne i studieområdet.
- **Scenario III** fokuserar på multimodala transporter där dial-a-ride-tjänster matar huvudbusslinjerna inom zonen, och några av de befintliga matarlinjerna (cirka 50 %) ersätts av efterfrågestyrda dial-a-ride minibussar.

En maximal minskning av de totala systemkostnaderna på -13,67 % (relativ skillnad) uppnås i scenario III jämfört med basscenariot. I scenario II sänks de totala systemkostnaderna med -6,04 % i förhållande till basscenariot. För scenario I tyder genomsnittet av flera simuleringskörningar på att en minskning med -1,28 % av de totala systemkostnaderna är möjlig genom att driva en samåkningsflotta på 35 fordon med hög fördelning av beläggning i fordonen.

Resultaten av detta examensarbete visar fördelarna med att kombinera konventionella kollektiva transporter med efterfrågekänsliga transporter i områden med låg efterfrågan. Denna kombination ger en bättre servicenivå till kollektivtrafikanvändare och skulle kunna implementeras under tidsperioder med låg efterfrågan, eller på helger.

Nyckelord: DRT, dial-a-ride, samåkning, matarlinjer, multimodala transporter, PTV Visum, Curitiba, RIT.

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This journey has only been possible with the help of my family, friends, supervisors, representatives of Curitiba, colleagues, and the scholarship provided to me by the European Union under the EIT Urban Mobility Master School.

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I would like to continue by expressing how honored I feel to be granted an opportunity to start my first transportation related job at a great consulting company like **Sweco**, this is really a dream come true. I would like to thank my boss **Martin Holmstedt**, who trusted me and welcomed me in the ***Traffic Analysis*** **group**. At **Sweco** I have learnt a lot and feel at home even after a short time. I would also like to thank the rest of my friends and colleagues in other groups of the ***Trafik och Samhällsplanering (Region Nordöst)*** with whom I have shared amazing moments.

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Stockholm, 15th of June 2022

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1 Introduction

1.1 Background and motivation

According to the WRI (World Resources Institute) Brazil was the seventh country responsible for the largest GHG emissions globally in the world during 2018, contributing to 2,19% of the global total emissions. After agriculture, the second sector generating more GHG emissions was transportation which accounted for more than 191.7 Mt CO_2 emitted contributing therefore to 0,4% of global greenhouse gas emissions (Friedrich et al., 2020). Road based transport is the biggest contributor to the previously mentioned transport sector emissions.

The motivation for writing this degree project arises from the growing importance of reliable and sustainable public transport in cities as the backbone of mobility of cities, and a principal alternative to private car ridership. Public transport ridership has reportedly been decreasing in many regions around the world such as California, USA (Manville et al., 2018) or entire countries (Graehler et al., 2019). Moreover, due to the recent pandemic situation in some countries, densely populated regions have shown decreases in public transportation ridership ranging in some cases to up to 40% and 60% (Jenelius & Cebecauer, 2020). These previous dynamics threatening public transport ridership, as well as unsustainable financial operation, worsening quality of service, and the increasing attractiveness of private car are pressing issues to pay more attention to provide better quality public transportation. At the same time, many countries and cities need to lower their dependance on private car in urban centers, this latter can also be in large extent achieved by providing good quality public transportation.

To achieve optimal and reliable public transport supply, a careful design and planning of the public transportation network should be carried out at a strategic, tactical, and operational level. However, planning, design and implementation of new lines are not static processes since cities are constantly changing. The continuous growth and change of activities in cities create room for new services that are added to the public transport network supply (corridors and routes). Generally, while the planning for these new services is well-structured and their implementation is carefully carried out, in many cases, there is not enough attention paid to how new services will affect other existing lines in terms of ridership, and, more importantly, if some of previous existing lines should be modified, or should continue operating at all.

The modifications made to the supply in a public transport network affects the assignment of trips in the network. While the supply for public transport tends to remain static over time, the demand changes within different time spans.

Curitiba

Curitiba is the eight largest city in Brazil with an estimated population of 1.963.726 inhabitants and a demographic density of 4.027 hab/km² (seventh most densely populated city in Brazil) (*IBGE, 2022*). Curitiba was the first city to introduce a BRT system in the world, and remains a leader in innovative urban planning (Lindau et al., 2010). Nevertheless, Curitiba is not only a leader in public transport and urban planning innovations, but with 1.665.540 registered private vehicles (IBGE, 2022) it is the city with the highest private vehicle share in Brazil. However, Curitiba has set ambitious goals with respect to GHG emissions and is committed to becoming 100% carbon neutral by year 2050. One of the sectors with most ambitious goals is the transportation sector. (See Figure 1).

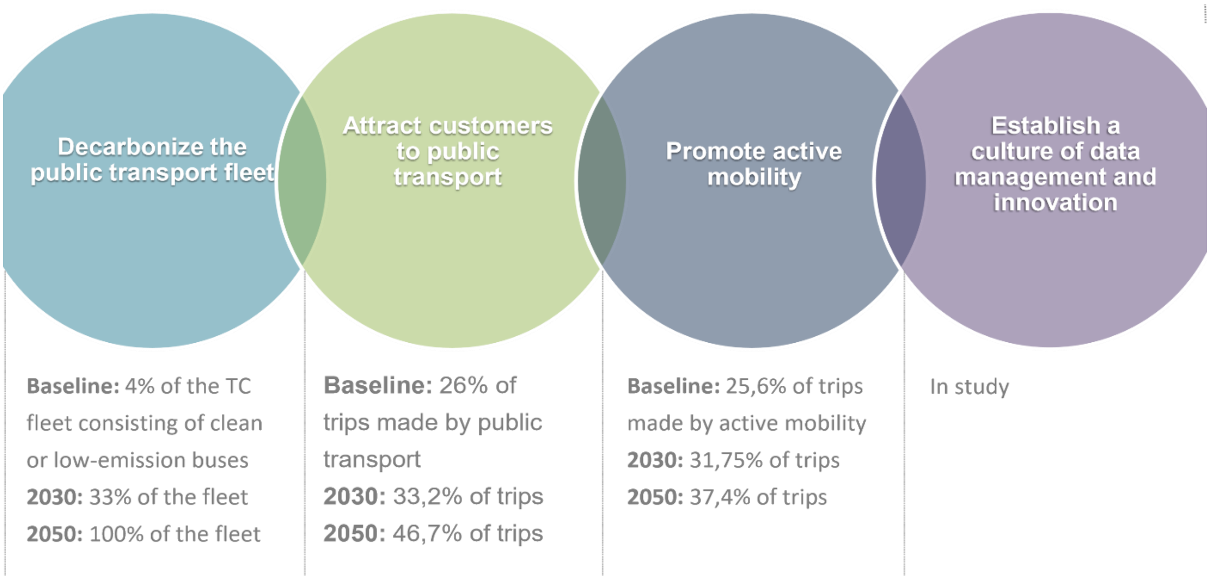


Figure 1. Transportation goals for Curitiba to years 2030 and 2050. Source: Investment ambitions for integrated solutions. (Curitiba, 2020) (IPPUC, 2020).

Figure 1 shows Curitiba's sustainable transportation related goals. The second most important goal in the agenda of Curitiba´s roadmap to sustainable transportation within the next 30 years is to increase more public transport ridership.

The current degree project studies the introduction of demand responsive transport services to serve a study area with low public transport ridership in Curitiba. The goal of this degree project is to analyze the effects of the introduction of different DRT services and evaluate how they can serve as means to increase public transport ridership and reduce private car dependence inside the study are. Three scenarios have been coded into a pre-existing PTV Visum Curitiba Region model (courtesy of IPPUC) featuring ridesharing and dial-a-ride services. The outputs of each scenario have been evaluated by means of global system costs functions which evaluate the cost of one hour of operation of the system in R$/h. Consequently, all previous scenarios are compared to the base scenario, and the system costs are assessed by comparing the relative difference between system costs and metrics of consumption generated by the introduced new services.

1.2 Objective and commitment

The objective of this degree project is to analyze whether the introduction of new DRT services inside a selected study area could improve the performance of the system and produce modal shifts from private modes to public transportation. Since the public transport system has many involved actors, which in turn incur costs while interacting in the system, before developing global cost functions to evaluate the whole performance of the system, in a first instance, the objective is to develop analytical expressions by making assumptions about the involved actors in the operation of the system, and then build global cost functions which allow to evaluate total system costs. In such a way, the positive and negative effects of modifications in the system and how they affect each involved actor are possible. Our approach is to hold accountability and look for causality between the system variables as much as possible. To develop analytical expressions that make sense, this degree project aims to develop own analytical expressions which are in some way supported on literature review or basic knowledge.

Furthermore, to achieve this objective and be able to trust the obtained results there are two main aspects to consider:

- To get a clear understanding of the system global costs, it is necessary to make reasonable assumptions about the characteristics of the area of study, the population, and the public transport services inside it. All the assumptions made during the assessment of the system costs must be reasonable and if possible, supported by actual evidence.
- The costs assumed for the system operation and value of time of users should be unbiased and not modified to give priority to any preferred solution.

The current degree project aims to combine a theoretical framework based on analytical expressions, DRT desirable system characteristics from literature revie, and continuous approximation models with a professional transport planning tool used by practitioners in the transport planning professional arena. The chosen tool is PTV Visum 2022 which serves as demand modelling tool and simulation at macroscale. More specifically, the degree project aims to firstly propose alterations in a base scenario through the introduction of new mobility service with respect to the performance of the feeder lines inside the study area, and eventually under the last scenario, evaluate if it would be possible to replace some feeder lines with low ridership by DRT services.

The second main objective of this degree project is to reduce the total system cost of the Integrated Transport Network of Curitiba (RIT) by proposing changes in the bus feeder lines operated inside the study area. In this way, considering base scenario A and alternative scenario B, the second main objective of the present degree project is thus better expressed by:

$$TC_{system_A} > TC_{system_B}$$

At the highest level, the total cost of the system is composed by the cost incurred by the public transport users and the cost incurred by the operator(s) of the system; in this case the without loss of generality, the aim is to achieve configurations of the system such that:

$$TC_{operator_A} + TC_{users_A} > TC_{operator_B} + TC_{users_B}$$

Nevertheless, a will be show in the next sections, the interest of operator and users is conflicting in some ways. Therefore, it is not only necessary to achieve the above reduction in system costs, but to establish how the new modifications to the network affect positive or negatively the above presented actors. There will be specific sections for developing the perspectives and costs of the above actors, as well as private car users, and environmental cost.

1.3 Research questions, and objective

The main research questions for this degree project are related to the system costs of the introduced DRT services, and how the characteristics of these affect particularly the operator and user cost.

1.3.1 Simulation outputs questions

- Are the mean travel times inside the areas of study significantly improved by the proposed scenario?
- Are the obtained simulation outputs in accordance with the preliminary findings of the literature review?
- Are the link travel times inside the area of study shorter?
- How does the introduction of the new DRT services affect the ridership of feeder lines?

1.3.2 Global cost function questions

With respect to the implementation of new DRT services, there is a set of basic research questions to answer regarding the costs of the system under the new scenario.

- Does the implementation of the new DRT service minimize the system total cost with respect to the base scenario?
- If the cost is minimized, who is more benefitted by this? The user? The operator? The environment? All the previous ones?
- Does the travel times (total and average) decrease?
- Does the access and egress time decrease?
- Do the operator costs tend to increase by introducing the new service?
- Do the fares collected by feeder line decrease by the introduction of the new service?
- Do the environmental costs of the system increase?

1.4 Scope of the project

The scope of the project in first instance was to propose the redesign of a selected number of feeder lines of the RIT to optimize the performance of the network. Initially, the set of lines was unclear, and comprehended the total set of feeder lines shown in Figure 2. After dialog with representants of IPPUC and URBS, the study area of Campo Comprido was chosen as area of study. The scope of the current degree project is to test different configuration of demand responsive transport services to serve a study are portrayed in yellow in Figure 2. There is a total number of 16 feeder lines operating inside the study area. The costs and characteristics of other lines operating inside the area of study have not been assessed. The degree project focuses on the effects of the introduction of different DRT services when compared to the performance of the mentioned set of feeder line within the study area. Three scenarios have been coded into a pre-existing PTV Visum Curitiba Region model (courtesy of IPPUC) featuring ridesharing and dial-a-ride services. The outputs of each scenario have been evaluated by means of global system costs functions which evaluate the cost of one hour of operation of the system in R$/h. Consequently, all previous scenarios are compared to the base scenario, and the system costs are assessed by comparing the relative difference between system costs and metrics of consumption generated by the introduced new services.

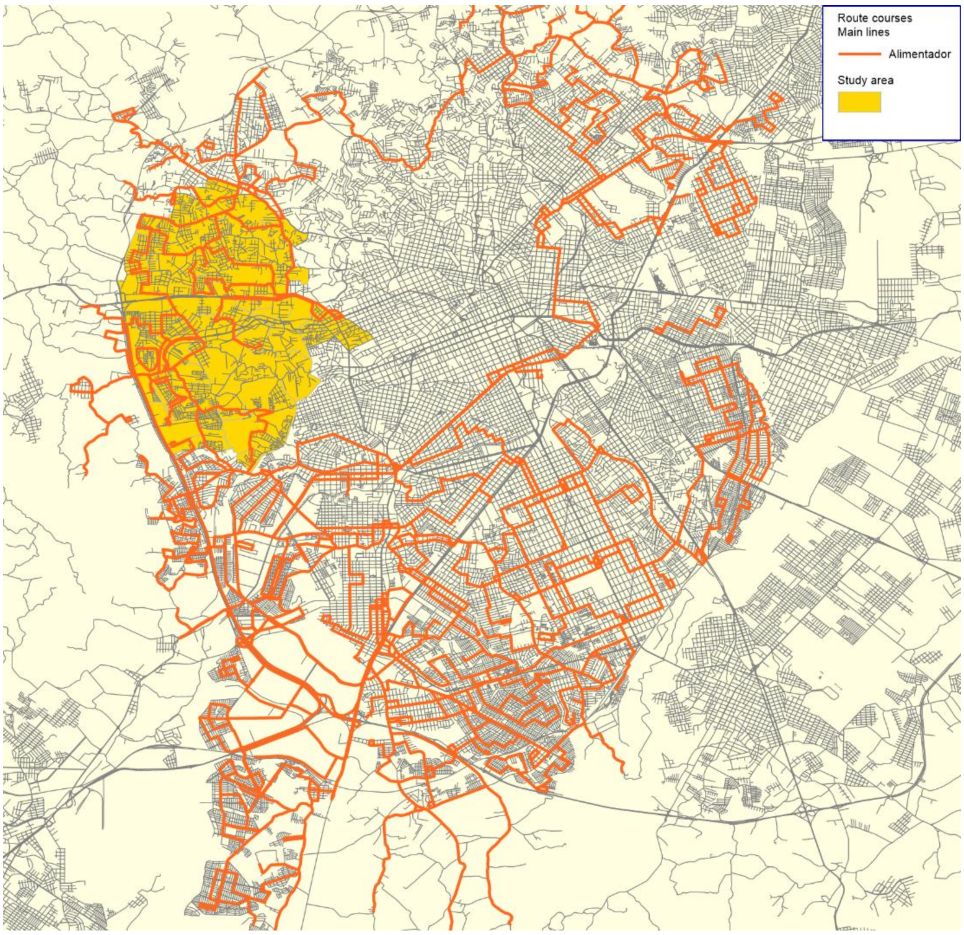


Figure 2. Total number of feeder lines operating in the RIT (126) and final area of study (16 feeder lines inside the study area have been analyzed and their operational costs have been estimated). Made by the author using PTV Visum 2022.

1.5 Limitations

There are multiple limitations with respect to the methodology used for assessing the costs and performance of the system. Firstly, it should be noted that the scope of the project only considered the costs of operation of the previously mentioned set of 16 feeder lines and the set of remaining lines operated inside the study area have not been assessed. Furthermore, many of the calculations introduced in the methodology section rely on average headways and average commercial speeds, while headways and commercial speeds vary greatly in real life. Moreover, the methodology used to compare the environmental costs (CORINAIR) (EEA, 2007) is based on approximation of bulk emissions of categories of vehicles. Finally, it is important to mention that for the calculation of the costs associated to rolling distances for both private car and public transport, assumptions about the composition of the fleet have been made, and average vehicles have been assumed to circulate in the network. Finally, the values of times of uses have been also assessed based on statistics and can be considered as limitations and source to error.

From the modelling point of view, the model can portrait behavior different to real world public transport users. For example, the model may assign lower demand to particular lines because the impedance calculated for the connection using Public Transport may be too high. Nevertheless, in real life, the behavior of user could vary with respect to the assignment obtained by the model. Finally, the introduction of the new public transport services affects the route choices of the users, this latter effect is correctly modelled by the current model, such that the route choice and ridership of public transport lines inside the area of study is modified. Nevertheless, the model does not evaluate possible demand shifts and increasing public transport demand with respect to the base scenario, this could in principle be done by applying choice models and PTV Visum in future research.

2 Curitiba’s transit network (RIT) Integrated Transit Network

2.1 Public transit network

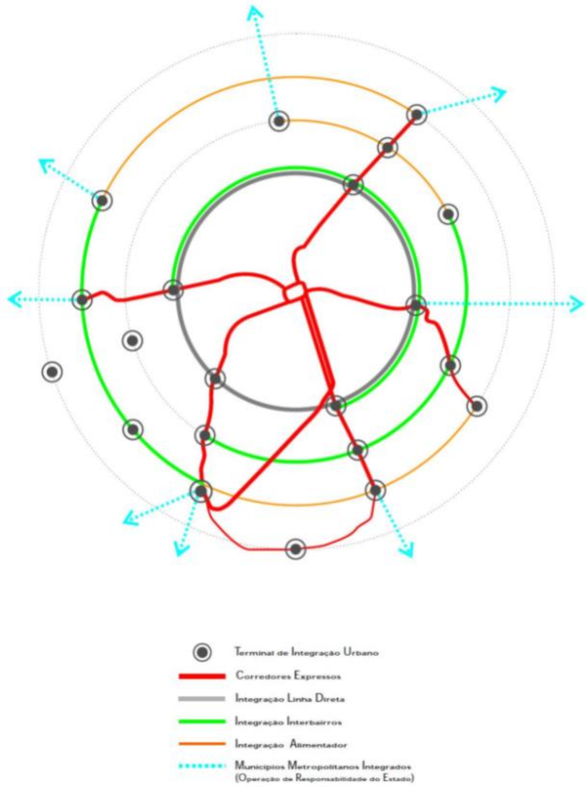


Figure 3. RIT (Integrated Transport Network). Source (URBS,2017)

The RIT allows users to travel between different lines of the network by a single fare payment. To access the different lines of the network (without having to pay again) the user makes use of the integration terminals, which allow change between lines. In the above figure, the integration terminals are represented by the circle round point. In these stations, the system allows users to alight/board to access other lines in the network without need of new payment (URBS, 2020).

Through COMEC (Coordination of the Metropolitan Region of Curitiba) Curitiba’s RIT is available to supply public transportation to 13 adjacent municipalities at a regional level. The metropolitan region users travel with feeder lines to the integration terminals and then continue their journey using the RIT (URBS, 2020). Nevertheless, it should be noted that there is a small number of cases for which the metropolitan integration of fare is not available. However, the previous scheme is not followed by many feeder lines in the network.

One of the focus areas of this project is on how to provide good connection to the RIT and assess the operation of feeder lines operating in the network. To succeed in this task, background knowledge about

2.1.1 Historical context and background

Regarding the development of the RIT and bus transit in time, Lindau et al. (2010) identify three periods in the history of modern Curitiba which were decisive for the development of the RIT.

1. 1943 to 1970
   Planning principles and vision of the city were forged.
2. 1972 to 1988
   Plan execution that led to the consolidation of a city-wide integrated bus transit system (RIT)
3. 1988 to Present
   Metropolitan expansion and improvements to the network.

2.1.2 Category of Lines

The characteristics of the lines that compose the RIT differ according to the commercial speed, the capacity of the vehicles, the operational headway between services, and the average number of stops per km traveled by the line.

Main lines

The lines of the RIT are listed hereunder in order of descendent hierarchy (Source: URBS).

1. ***Expresso Ligeirão (BRT)***

The Expresso Ligeirão (EL) lines are operated by biarticulated vehicles in segregated exclusive bus lanes (right of way type A) and a reduced number of stops. The EL lines provide smaller travel times to the users, and the boarding and alighting operations for these lines are done in the terminals or in the tube stations.

2. ***Expresso (Express line)***

The Expresso lines are operated by biarticulated vehicles that connect the integration terminals with the city center. Furthermore, the expresso lines have segregated bus lanes and the boarding and alighting operations are done in the terminals or in the tube stations of the routes.

3. ***Linha Direta (Direct line- "Ligerinho")***

These are complementary lines to the express and Interbarrios lines. The boarding and alighting operations are done at tube stations. On average the stops of the routes under this category are located each 3 km.

4. ***Interbairros (Between neighborhoods)***

These are operated by articulated vehicles that connect the different neighborhoods and terminals without passing through the center of the city.

5. ***Alimentador (Feeder)***

These connect the neighborhoods of each region to the integration terminals and are operated by microbuses, regular buses, or articulated buses.

6. ***Troncal***

These lines connect the integration terminals to the center of the city. They operate in shared lanes with private cars.

Special lines

There is a restricted number of lines which are considered special lines see Figure 4. These lines are listed here:

- ***Circular Centro***

This line is operated by micro-ônibus, and supply origins and destinations of high demand (public facilities). This line has a different fare established.

- ***Convencional***

These lines are operated by regular buses or microbuses that connect the different neighborhoods of the city to the city center without fare-integration.

- ***Linha Turismo***

Departs form the center and passes though the principal touristic attractions of the city. This line has a different fare established.

Categoria de Linhas	Tipos de Veículo	Capacidade dos Veículos	Frota Operante Subtotal	Frota Operante Total	Quantidade de Linhas
EXPRESSO LIGEIRÃO	BIARTICULADO	250	44	44	03
EXPRESSO	BIARTICULADO	230/250	97	128	05
	ARTICULADO	170	31		
LINHA DIRETA	ARTICULADO	150	38	219	15
	PADRON	110	181		
INTERBAIRROS	ARTICULADO	140	91	102	08
	PADRON	100	1		
	HÍBRIDO	79	10		
ALIMENTADOR	ARTICULADO	140	71	425	129
	COMUM	85	325		
	MICRO ESPECIAL	70	29		
TRONCAL	ARTICULADO	140	5	77	15
	COMUM	85	59		
	HÍBRIDO	79	10		
	MICRO ESPECIAL	70	3		
CONVENCIONAL	COMUM	85	102	217	74
	HÍBRIDO	79	10		
	MICRO ESPECIAL	70	102		
	MICRO	40	3		
CIRCULAR	MICRO	40	5	5	01
TURISMO	DOUBLE-DECK	65	12	12	01
		TOTAL	1.229		251

Figure 4. Fleet composition of the RIT. URBS (2017)

3 Literature review

The literature review focuses firstly on a brief introduction to the planning and operation of bus transport systems where the Network Transit Planning (TNP) problem is introduced. This first stage is based mainly on the research done by Ibarra-Rojas et al. (2015) and introduces basic concepts such as the trade-off between level-of-service (LOS) provided to the user and the system operation costs. In a second and more detailed stage, the literature review will focus mainly on flexible transit and more specifically on demand responsive transport (DRT). The second stage is motivated by the fact that in some areas with low demand density, the critical demand threshold required for conventional public transit to be beneficial for society, is not reached. When the effect of economies of scale is present, flexible collective transportation (FCT) and more particularly demand responsive transport (DRT) are available options to meet the mobility needs of users in low demand density areas. In a third, and final stage, the literature review focuses on the failure and success of DRT systems.

3.1 Planning and operation of bus transport systems

An extensive literature review of bus transport systems, their planning and efficiency has been conducted by Ibarra-Rojas et al. (2015). As the authors argue, the planning, operation and control of a public transport system is quite complex. Firstly, because there are many involved actors taking place in the process such as: authorities, users, non-users, and operators. Secondly, because these actors usually have different goals different socioeconomic characteristics (which determines their mobility needs and choices across time). And thirdly, because the distribution of these actors in space and time is a dynamic process spreading over continuous time, which leaves room for different time windows of analysis and decision making (hours, days, months, seasons, and years).

The primary trade-off that must be addressed when planning and operating a transport system is that of the level of service faced by the user, and the operating costs for the agencies (Ibarra-Rojas et al., 2015)(Daganzo & Ouyang, 2019a). This trade-off is easily understood by the following statement "Users desire an excellent service preferably at a low price, while agencies look to have a profitable system with low costs" this previous quote already allows to understand the main problem: it is difficult to provide an excellent service at low price, in a first instance. Additionally, it is even more complex to provide such quality of service when the cost of operation of the system are very high. This previous tradeoff between provided level of service and cost of operator is show in *Figure 5*.

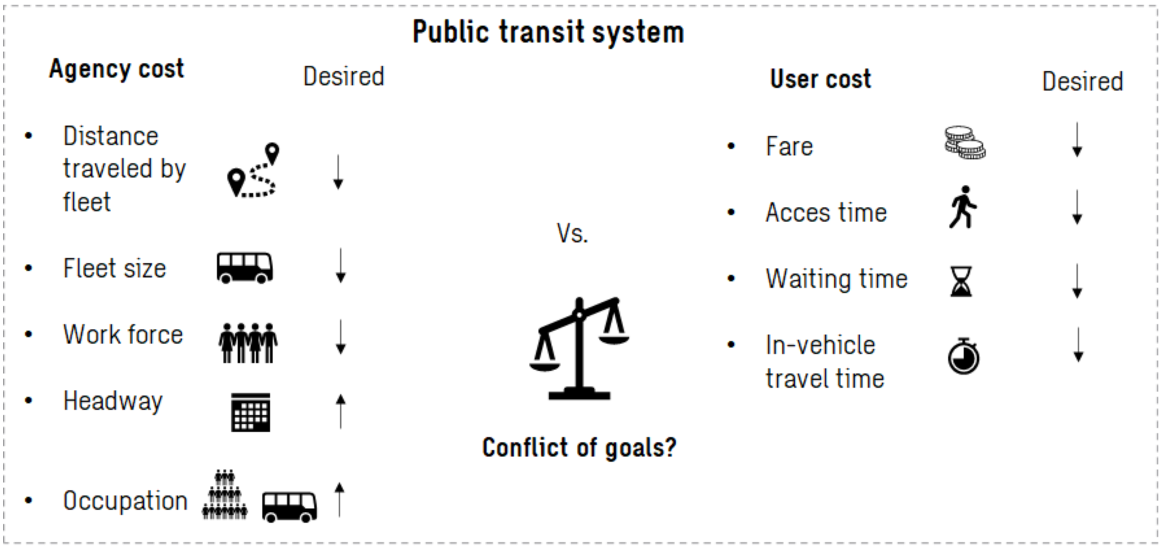


Figure 5. Trade-off between provided level of service and operating costs. Made by the author.

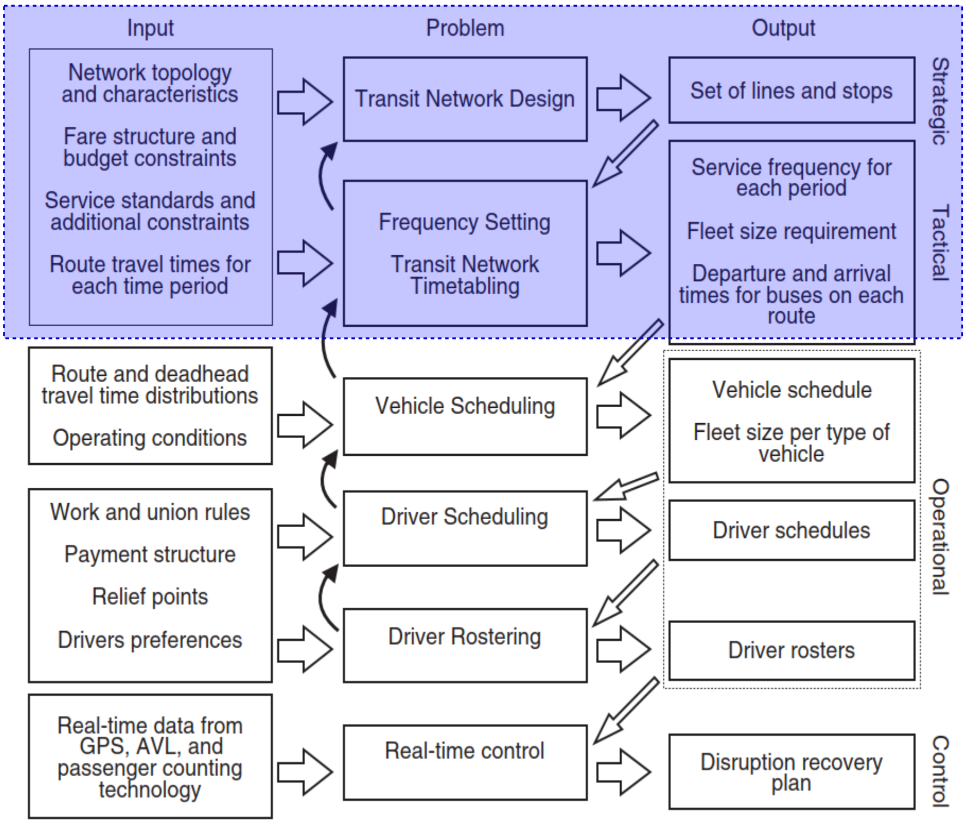


Figure 6. Interaction between stages of the planning process and real-time control strategies. (Ibarra-Rojas et al., 2015)

The planning process spans across all the decisions that should be made before the operation of the system (Ibarra-Rojas et al., 2015) the planning process also called the Transit Network Planning problem (TNP) is subdivided into the following stages or problems due to its complexity:

- Transit Network Design (TND)
- Frequency Setting (FS)
- Transit Network Timetabling (TNT)
- Vehicle scheduling problem (VSP)
- Driving Scheduling problem (VSP)

Ibarra-Rojas et al. (2015) remark that each one of these problems is at the same time dependent on the previous stage problem. Figure 6 shows the sub-problems of the TNP and their correspondent inputs and outputs. For this degree project, the focus will be mainly on analyzing the output of the strategical and tactical phases of the TNP (blue-shaded area) in Figure 6, these outputs are given by the existing feeder lines analyzed inside the study area, and to a secondary degree also analyze the second stage of the operational level of the TNP problem which concerns the fleet size per type of vehicle, these system characteristics will be the input to calculate the system costs by applying the simplified analytical expressions introduced in section 5.5 (the network layout, and fleet determine the system costs).

3.2 Flexible transit

In contrast to public transit with fixed schedules and routes, flexible transit provides adaptive routes and schedules. To have an organized way to systematically assess the different type of services of flexible transit, it is good to **classify them depending on how people share rides and vehicles**. (Daganzo & Ouyang, 2019).

Daganzo & Ouyang (2019) classify public transportation services depending on the way how people share rides and vehicles. On the one side of the spectrum, there is conventional mass transit which presents economies of scale and is operated with large capacity vehicles, fixed routes, and fixed schedules (Daganzo & Ouyang, 2019). On the other side of the spectrum, there is conventional private travel, where one passenger travels in a privately owned vehicle (Daganzo & Ouyang, 2019). On the first way of transit passengers share large vehicles and have the same departure time, on the latter the trip maker is free to choose the route and the departure time desired. Between these two extremes of travel types, there is a space for what is usually known as flexible transit (Daganzo & Ouyang, 2019).

Flexible transit can thus have the characteristics of both individual travel and collective travel. If a trip in flexible transit presents more characteristics of individual travel, then the trip falls under the category of individual public transportation (IPT) here the occupancy of the vehicles is low, and users share a common vehicle without requiring significant passenger detours, typical examples of IPT are shared taxis or carpooling services (Daganzo & Ouyang, 2019). On the other hand, if a trip resembles more the behavior of collective travel, it falls under the category of flexible collective transit (FCT) where more passengers are carried in the vehicle (higher occupancy) and the routes and schedules of the services are adaptive, typical examples of FCT are jitneys and dial-a-ride services. Generally, in FCT passengers may be significantly detoured on the way to their destinations (Daganzo & Ouyang, 2019), therefore, the capacity of the vehicles should not be above a certain threshold because the in-vehicle travel time (IVTT) of the users inside the vehicles increases each time a new detour is introduced in the route. Increasing the IVTT means that the cost of the user increases dramatically if there are many passengers inside the vehicle (high occupancy), because the more passengers that are detoured and travel longer, the more the total user costs increase. Finally, Daganzo and Ouyang (2019a) note that while in general FCT provides a more desirable solution from a sustainable point of view (less vehicles and associated externalities) the difficulty of sharing and waiting is still a reality, the authors also argue that the main promise of FCT is that it could improve the level-of-service of conventional transit and still remain cost competitive due to the sharing of rides (Daganzo & Ouyang, 2019a).

This degree project focuses mainly on two services of flexible transit: one service of FCT (Dial-a-ride) and one service of IPT (Ridesharing). Therefore, a further development into the nature and dynamics of these services is provided in future sections, but first a definition and introduction to DRT (Demand responsive transport) is required in the next section. Finally, after introducing DRT, an introduction and description of the previously mentioned services will be provided.

3.2.1 Demand Responsive Transport (DRT)

A definition of DRT is provided by Brake et al. (2004) as "*an intermediate form of public transport, somewhere between a regular service route that uses small low floor buses and variably routed, highly personalized transport services offered by taxis".* This previous definition still leaves room for several types of services and configurations. Therefore, this section will handle the description of DRT developed by Daganzo & Ouyang (2019a) which focuses more in general DRT characteristics and cites some examples.

In DRT Users share vehicles that offer door-to-door service with **adaptive route and no schedule** (Daganzo & Ouyang, 2019a). Typical examples of these type of services are dial-a-ride paratransit and ridesharing services, it is important to notice that under this type of FCT **passengers may endure significant detours** (Daganzo & Ouyang, 2019a). Therefore, the capacity of the vehicles composing the fleet should be carefully chosen when planning this type of service since by introducing one additional passenger in the tour, the unit cost total cost per passenger in the system would increase due to the detour. Other authors have reported this same system behavior e.g. LAYOUT service proposed by Estrada et al. (2021). Moreover, the principal difference between dial-a-ride and ridesharing services like Uber Pool, is that dial-a-ride emphasizes low cost (users prefer longer in-vehicle travel times with less expensive fares) while the latter prioritizes short waits and has therefore higher fares (Daganzo & Ouyang, 2019). Furthermore, shared taxis differ from ride matching in the way that they allow longer detours. DRT services can be offered as "many-to-many" services, meaning that the trip can have multiple origins and destinations, or "many-to-one" where the goal is to connect many destinations to a single specific (Daganzo & Ouyang, 2019a).

3.3 DRT studied services and analytical modelling foundations

This section introduces different continuous approximation models for design and evaluation of performance of various types of DRT services. Most of the formulations presented in this section were introduced by Daganzo & Ouyang (2019) in the form of analytical simplified formulas which consider the performance of the system with respect to the decision variable fleet size.

3.3.1 Dial- a ride

Daganzo & Ouyang (2019) formulate the simplified problem of DAR services. DAR trips can be spontaneous, or reservation based, this means that the booking of the service can occur until up to a maximum time before the trip desired departure time in order to be pre-booked, otherwise the trip will be assigned to the spontaneous category (Daganzo & Ouyang, 2019a). Furthermore, the performance of the matching algorithms of DAR services should be more efficient when passenger trips are known before-hand(Daganzo & Ouyang, 2019a).

Daganzo & Ouyang (2019)argue that although simplistic, their algorithm introduced in (Daganzo & Ouyang, 2019a) is capable of predicting what type of operations are possible with DAR systems. The authors focus particularly on two questions:

- What is the fleet size required for providing a target level of service (constrained by a maximum target waiting T_0)?
- How does DAR compare to other modes?

Daganzo & Ouyang (2019) consider an area of analysis R in steady state, with a demand density λ [pax/km2-h], and uniformly distributed origins and destinations. Furthermore, the authors specify that the fleet size m is more limited than in the case of taxis such that the passengers that request

DAR services will not be immediately assigned to an specific vehicle, and will therefore have to wait at their origin stops (or "homes")(Daganzo & Ouyang, 2019a).

For modelling DAR services Daganzo & Ouyang (2019) consider the theoretical conceptualization of reservoir bins in which they assign relevant objects of interest in a determined state. In this case, the objects of interest are the passengers who request the service (Daganzo & Ouyang, 2019a). More specifically, a passenger can be found in one of the two following states:

1. Waiting: those waiting at home and not yet assigned to a vehicle (Daganzo & Ouyang, 2019a).

2. Occupants: those already assigned to a vehicle or riding in it (Daganzo & Ouyang, 2019a).

Consequently, each passenger is to be collected in one of the two bins and the evolution of the passengers in the DAR system follows the described sequence (Daganzo & Ouyang, 2019a). The expected number of passengers of the first group (waiting group) is denoted by n_w, and the expected number of passengers in the second group (occupants of the bus) is denoted by n_r. Finally, Daganzo & Ouyang (2019) note that when a passenger is assigned to a bus, even if the passenger is not physically inside the bus, the passenger counts as being in the group of occupants.

The matching algorithm designed by Daganzo & Ouyang (2019) follows three rules:

- **"*After achieving a desired passenger loaded buses alternate between pickups and drop-offs*"**(Daganzo & Ouyang, 2019a).
- "*After each pick-up, a bus chooses to drop-off the onboard passenger whose destination is the closes to the current bus location*"(Daganzo & Ouyang, 2019a).
- *"After each drop-off, a bus chooses to pick up the unassigned waiting customer who is the closest to the current bus location. Said customer is immediately assigned to the bus, considered to be an occupant, and include in n_r*"(Daganzo & Ouyang, 2019a).

Daganzo & Ouyang (2019) note that with this algorithm, the **buses' passenger load is a decision variable that can be optimized** as it can be deduced from the first of the previously introduced rules. If $n_r = 1$ the system operates as a taxi service serving one passenger per bus and few number of buses.

3.3.2 Ridesharing

As stated by Daganzo & Ouyang (2019a) and (Daganzo & Ouyang, 2019b) in contrast to DAR services, shared taxis or ridesharing composed by services such as Uber or Lyft**, act in a competitive environment, such that the customers that request a service in the system are not hold waiting in order to be assigned a service**. Customers are assigned a vehicle directly because otherwise they would be lost to other competitors. More specifically, for our purposes this means that the previously defined buffer of unassigned calls n_w introduced in section 3.3.1 will be equal to zero $n_w = 0$ (Daganzo & Ouyang, 2019b). A direct effect of this competition phenomenon is that direct vehicles can be idle or only carrying one passenger(Daganzo & Ouyang, 2019a).

Furthermore, Daganzo & Ouyang (2019a) remark that the assignment of vehicles to customers is done by algorithms that define the system performance, and therefore are the best kept secrets of each operator. Nevertheless, the authors note that most of these algorithms rely on similar facsimiles of the same concepts. In section 3.3.3 a generalized model for DRT services is developed, this model allows for comparison between different DRT services and offers first insights into what could be the best service to serve a specific demand give a target level-of-service, and which fleet size should be provided to meet the demand for each service. For this section, it is noteworthy to mention the statement made by Daganzo & Ouyang (2019a) which can be seen in Figure 7. **"Shared taxi fills a niche in the transportation ecosystems somewhere between DAR and taxi"**. Furthermore, it should be noted that the dotted part of the lines in Figure 7. represent the unfeasible solutions for meeting the demand of each service, since the target travel times f can be provided by a lower demand (solid line of the series).

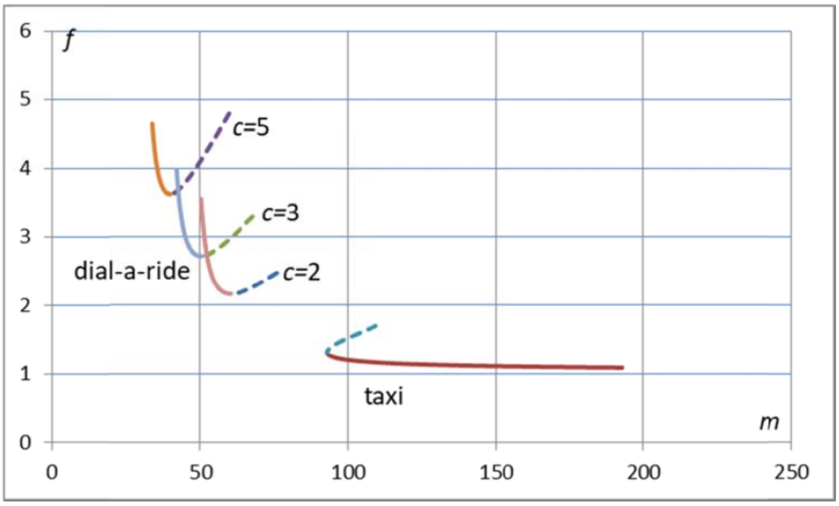


Figure 7. User travel time vs. fleet size (proxy for system cost). Source: Daganzo & Ouyang (2019b). The void between dial-a-ride and taxi is the niche for shared-taxi.

Note: a more detailed description for the quantity f which portraits the user travel time is motivated in the next section.

3.3.3 A general model for DRT comparison of Urban Transportation modes

(Daganzo & Ouyang, 2019b) obtain a generalized model for DRT services ranging from induvial taxi to dial-a-ride services by noting principally that **a system of DRT services can be expressed by a vector $\boldsymbol{n}$ which denotes the current status of the transit system** and is tracked over time with a set of differential equations. Expression (1) describes the change in time of the system vector n, which is dependent on three functions dynamic functions, namely: $\boldsymbol{a}(\boldsymbol{n}), \boldsymbol{p}(\boldsymbol{n})$, and $\boldsymbol{d}(\boldsymbol{n})$.

The vector $\boldsymbol{n}$ is composed by the number of vehicles under different workloads but without reference to their spatial position(Daganzo & Ouyang, 2019b). More specifically, a vehicle's workload is given by a couple of tuples (i, j) the first denoting the amount of passenger inside the vehicle, and the second one denoting the passengers assigned for pick-up. So that the number of vehicles under workload level (i, j) is n =$\{n_{ij}\}$. Daganzo & Ouyang (2019b) remark that although being a deterministic and spaceless model, the model is suitable for policy analysis.

$$d\boldsymbol{n}/dt = \boldsymbol{a}(\boldsymbol{n})\boldsymbol{A} + \boldsymbol{p}(\boldsymbol{n})\boldsymbol{P} + \boldsymbol{d}(\boldsymbol{n})\boldsymbol{D} \quad (1)$$

Expression (1) describes the change of number of vehicles in state n as a function of time, and its correspondent solution according to flow conservation equations i.e. $dn/dt = 0$ (Daganzo & Ouyang, 2019b) is given by (2).

$$\boldsymbol{a}(\boldsymbol{n})\boldsymbol{A} + \boldsymbol{p}(\boldsymbol{n})\boldsymbol{P} + \boldsymbol{d}(\boldsymbol{n})\boldsymbol{D} = \boldsymbol{0} \quad (2)$$

Furthermore, a vehicle can change workload in three ways (Daganzo & Ouyang, 2019b):

Table 1. Workload level of a DRT vehicle.Made by the author based on(Daganzo & Ouyang, 2019b)

(i) An assignment: (*i, j*) changes to (*i, j*+1). The rate at which this occurs is denoted a_{ij} [veh/hr].
(ii) A pickup: (*i, j*) changes to (*i*+1*, j*−1). The rate at which this occurs is denoted p_{ij} [veh/hr].
(iii) A delivery: (*i, j*) changes to (*i*−1*, j*). The rate at which this occurs is denoted d_{ij} [veh/hr].

Such that a vehicle's workload and its correspondent evolution in time is characterized by the processes described in Table 1. Note that the processes in this previous table refer to the variables $(\boldsymbol{n}), \boldsymbol{p}(\boldsymbol{n})$, and $\boldsymbol{d}(\boldsymbol{n})$ in (1) i.e., the rate at which the vehicles change their workloads in time given in units of [veh/hr]. Vehicles are assigned customers which they pick up and then deliver at their desired destination. (Daganzo & Ouyang, 2019b) portrait the information of the network graphically as shown in Figure 8, where the nodes represent the workload states (*i, j*), the double arrows the assignments, the dotted arrows the deliveries, and the slanted arrows pointing upward represent the collections of passenger (pick-ups) (Daganzo & Ouyang, 2019b).

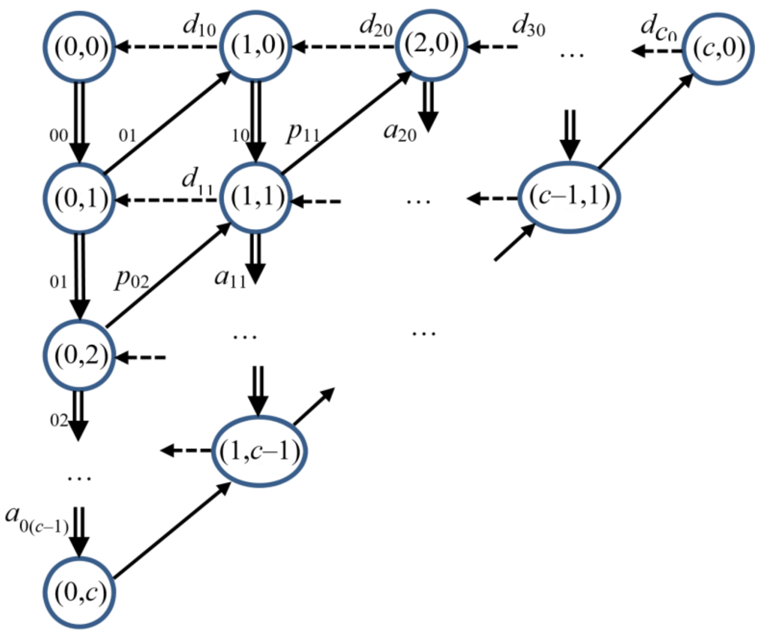


Figure 8. Workload transition network of the general model for DRT. Source: (Daganzo & Ouyang, 2019b)

Daganzo & Ouyang (2019b) remark that the control algorithm of the system determines how the vectors, ***a*={*a_{ij}*}**, ***p*={*p_{ij}*}**, ***d*={*d_{ij}*}** depend on ***n***, i.e., how he vector functions {***a***(***n***), ***p***(***n***), ***d***(***n***)} depend on the current status of the system which is given by vector ***n***, so that by using row vector notation for {*a*(*n*), *p*(*n*), *d*(*n*)} and denoting the link-node incidence matrices ***A*, *P*** and ***D***, the dynamic expression in **(1)** is obtained, this expression **is suitable for assessing the performance of any control algorithm for any given level of demand** (Daganzo & Ouyang, 2019b).

Furthermore, the constant *c* is introduced by Daganzo & Ouyang (2019a) for modelling DAR as a dimensionless proxy for demand that could be understood as the number of requests that the system takes in the time it takes a bus to travel the service area (Daganzo & Ouyang, 2019a). (Daganzo & Ouyang, 2019b) obtains a similar proxy for the generalized case of all DRT services as $\pi = \lambda R^{3/2}/v$, which now is conceptualized as the number of calls that arrive in the time it takes a vehicle of the fleet to cross the region R (as described in previous sections). Daganzo & Ouyang (2019b) continue their analysis motivating that (1) and (2) can be used to assess the performance of all the systems of configurations (λ, R, v, m) and that **if the units of distance and time are set so that $R = 1$ and $v = 1$, the degrees of freedom of the problem is only two** namely the **fleet size m and the rescaled demand density π** (Daganzo & Ouyang, 2019b). Daganzo & Ouyang (2019b) motivate that the formulation of the problem with this intrinsic system of units is useful. For example, the authors note that the minimum fleet size to serve the demand of an algorithm is a function $m_c = m_c(\pi)$ such that the solution can always be expressed in an arbitrary system of units by rescaling the solution *a posteriori* (Daganzo & Ouyang, 2019b), for example by rescaling $m_c = m_c(\lambda R^{3/2}/v)$. This previous approach can be used for any other measure of the form $f(\pi, m)$.

Finally, (Daganzo & Ouyang, 2019b) derive the dimensionless estimate of the door-to-door travel time of the users f, as shown in Figure 9 to Figure 11 on the y-axis. This general DRT model developed by Daganzo & Ouyang (2019b) allows to assess how and in which niche each transportation mode is more desirable from a societal point of view as a function of the demand in the area of service R.

Figure 9 to Figure 11 from Daganzo & Ouyang (2019b) assess the door-to-door travel time for different modes as a function of the fleet size. Recalling that the fleet size is a perfect proxy for cost of the operator and that travel time is a proxy for user cost, the curves in Figure 9 to Figure 11 show different configurations of performance that affect both the operator and the user costs depending on which set (f, m) is chosen. However, although the curves display many configurations, some parts of the curves are not desirable i.e., the parts of each curve where the fleet size starts increasing after the minimum fleet size has been reached, these parts can be better visualized in the dotted lines of Figure 7. Furthermore, the most important series shown in Figure 9 to Figure 11 is the **red-dashed line which represents the "Pareto-Optimality Frontier"** or as stated by Daganzo & Ouyang (2019b) "the set of points whose cost-time coordinates are not improved by any other point on any curve ". The previous statement can easily be verified in the following way according to Daganzo & Ouyang (2019b) *"read the diagram in Figure 9 to Figure 11 by entering through the abscissa with an imaginary line (by taking a constant door-to door travel time f) and encountering the first correspondent curve intersecting the line, this point is given by the mode that with the minimum fleet size serves the goal door-to-door travel time"*.

Daganzo & Ouyang (2019b) recall that Figure 9 to Figure 11 are based on proxies an intent to give a qualitative general picture, meaning that for quantitative comparisons, the proxies should be converted into actual costs. Furthermore, Figure 9 to Figure 11 portrait how by increasing demand, conventional transit becomes the most predominant mode. The authors also remark that from the different niches in Figure 9 to Figure 11 is remarkable to see how conventional transit is positioned to serve the low-cost/low-LOS portion of the market, DRT (including shared taxi) the mid-cos/mid-LOS, and Taxi the high end (Daganzo & Ouyang, 2019a).

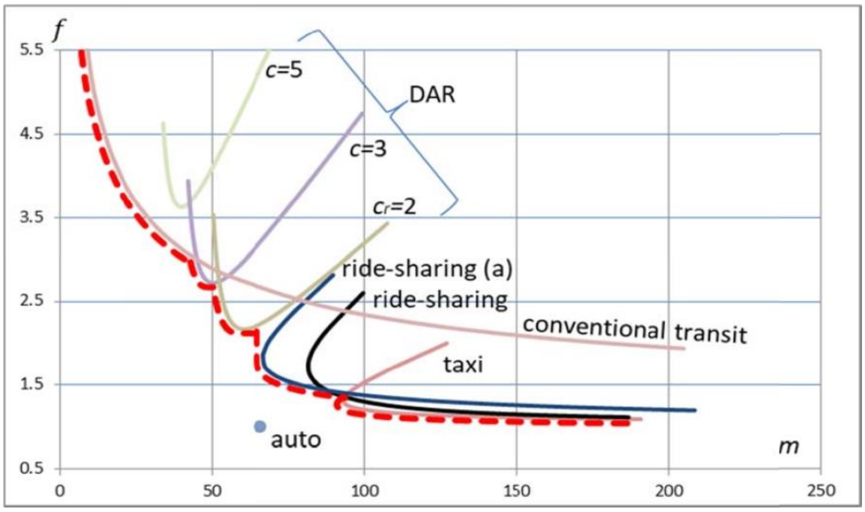


Figure 9.User travel time vs. fleet size for π = 100 (Small, low-density community). Source: (Daganzo & Ouyang, 2019b)

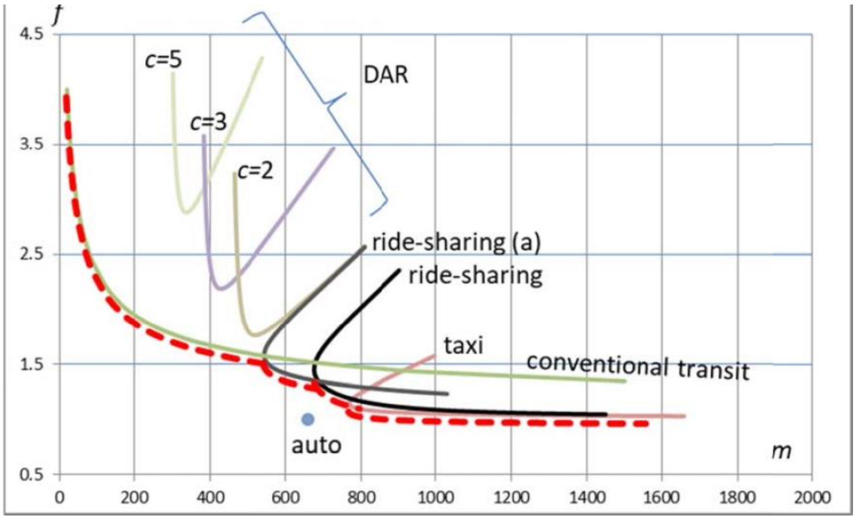


Figure 10.User travel time vs. fleet size for π = 1000 (Small, low-density community). Source: (Daganzo & Ouyang, 2019b)

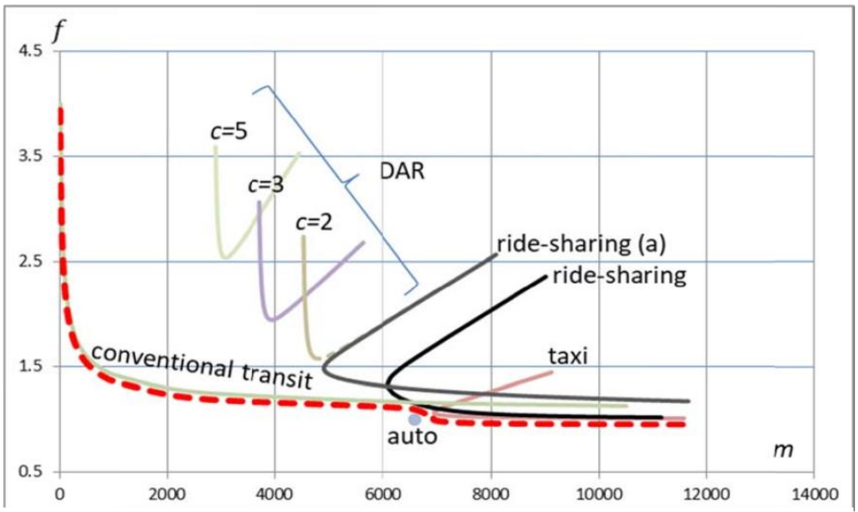


Figure 11. User travel time vs. fleet size for π = 10000 (Small, low-density community). Source: (Daganzo & Ouyang, 2019b)

3.3.4 Continuous approximation models for DRT systems

As documented by Ibarra-Rojas et al. (2015) continuous approximation models for solving the TNP problem develop relationships between the components of the public transportation network by a simplification of the network with idealized structures, and by making some assumptions about the characteristics of the network and its components. Furthermore, Ibarra-Rojas et al. (2015) report that the first studies with continuous approximation models used to solve the TNP problem and focused on the line spacing, stop spacing, and line frequency, assuming uniformly distributed demand. Posteriorly, other studies considered time dependent demand, space dependent demand, and zone based specific demand (Ibarra-Rojas et al., 2015).

Other approaches focused on the design of public transport networks with idealized forms and combining different types of network structures. Examples of these approaches are the works done by Daganzo (2010) where the well-known hybrid-structure concept was introduced by combining grid and hub-and-spoke structures, or the rectangle-shaped continuous approximation model used for the redesign and optimization of the bus network of Barcelona (Estrada et al., 2011).

Continuous approximation models have also been used to design DRT services. This section will focus briefly on showing some examples of continuous approximation models used to design DRT systems, and the key decision variables from the operator´s perspective regarded as fundamental for determining the performance and characteristics of an optimal DRT system.

3.3.4.1 Optimal zone sizes and headways

The key decision variables for design of DRT systems using continuous approximations are the optimal zone size and the operational headway of the service, these latter affect the system performance and costs. Furthermore, the right service area size and operational headway are dependent on the demand density of the zone.

The problem of finding optimal zone size [km2] and optimal headway [h/veh] for DRT services has been studied by different authors including Estrada et al.(2021), Kim et al., 2019), and Badia & Jenelius (2021). Estrada et al. (2021) focuses principally on the design of the characteristics of general DRT services, while Kim et al. (2019) and Badia & Jenelius (2021) develop models for DRT services used as feeder lines. It should be remarked that Badia & Jenelius (2021) extend the case of feeder services with DRT to the era of automated vehicles, but in this section only the cost structure proposed for the base scenario introduced by Badia & Jenelius (2021) will be discussed.

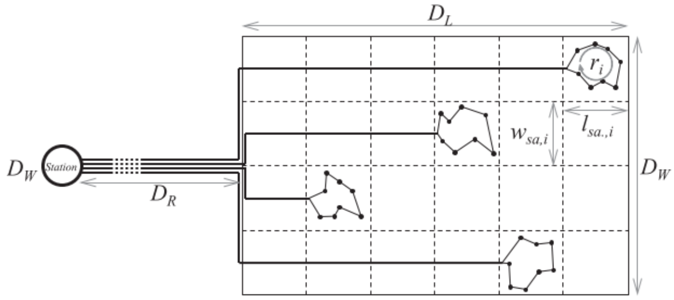


Figure 12. Idealization of service area and configuration of flexible-route bus according to Badia & Jenelius (2021)

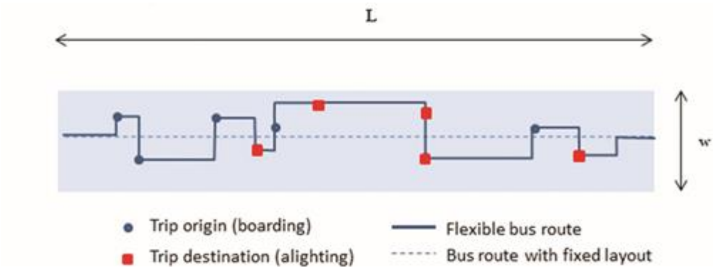


Figure 13. Idealization of service area and configuration of flexible-route bus according to Estrada et al. (2021)

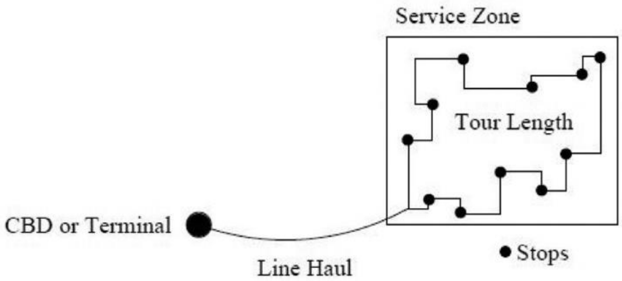


Figure 14. Idealization of service area and configuration of flexible-route bus according to Kim et al. (2019)

All the previously mentioned authors and studies idealize the area of operation i.e. the zone size [km2] as a rectangular or squared shape and assume that the demand density [pax/km2-h] or equivalently [pax/sq. mile] is uniformly distributed over the service area. Furthermore, these studies also assume that the origin and destinations inside the area of services are random and independently distribute in space and time, and that the demand is uniformly distributed inside the service area.

Badia & Jenelius (2021) idealized the service area as rectangular area of width D_w and length D_L , where passengers are fed to the area of service from a station. The same is true for the opposite direction. Furthermore, the DRT service proposed by Badia & Jenelius (2021) is a door-to-door service, where the road infrastructure is represented by an idealized grid, and the area of service R is further subdivided into sub-areas where internal routes are performed to deliver the passengers at their desired destinations (see Figure 12). The decision variables for the case of this door-to-door feeder service, which resembles the characteristics of airport or hub shuttle services, are the headway H_i $[h/veh]$ at which vehicles are dispatched from the station, and the side $l_{sa,i}$[km] and width length $w_{sa,i}$[km] of the correspondent sub-areas by which the area of service D_wx D_L is subdivided.In a similar fashion as Badia & Jenelius (2021), Estrada et al. (2021) idealize the area of service R as a rectangle with width W and length L (see Figure 13).

With respect to this section, it was discussed that for designing DRT services, continuous approximation models can be used and that furthermore two key decision variables for the design of the systems are usually considered:

- The size of the service area (which affects the operating cost in the form of distance-based costs and the accessibility provided to the user).
- The operational headway at which vehicles are dispatched (which affects the operating cost in the form distance-based cost, fleet size required, and level of service provided to the user).

3.4 Failure and success of DRT services

A motivation for this section is the desire for a successful real-life implementation of DRT systems to improve the performance of the transportation system studied inside the area of study. While the previous sections focused on a discussion about the design of DRT systems by mean of analytical models and analytical expressions to determine the physical and operational characteristics of the system, real-world implementations occur in a complex socio-technical system where the success of DRT services is not a straightforward process, and where in many cases there is not a careful design of the system carried out. As a result, several DRT systems have failed to be successful financially and have stopped operation due to extremely high operational costs that cannot be covered by the returns of the system. A popular case of such failures is the finish DRT system Kutsuplus which failed because of too high operational costs, too high subvention (around 80% of the fare was subsidized) and competition from other ride-hailing platforms as UBER (*Science|Bussines, 2016)*, or the incredible case of Bridj's operation in the U.S. which was stopped due to extremely high subsidies, with a subsidy of approximately $1000 per trip (Currie & Fournier, 2020). Therefore, this section is devoted to the failure and success in implementation of DRT services and which traits and conclusions can be drawn from literature review with respect to these.

Papanikolaou et al. (2017) develop a methodological framework for assessing the success of DRT services. Papanikolaou et al. (2017) argue that one of the main reasons for failure of DRT systems arises from the incorrect scale of DRT operations implemented in many cities around the world. The incorrect scale of implementation occurs mainly because DRT services do not match the market conditions to be served. Here, it can be suspected that many operators fail because they do not know which is the market they should serve, the scale of demand, and consequently what are the optimal fleet size and resources required to deploy the service. Recall from section 3.3.3 that DRT services are meant to serve low-to medium demand density zones with mid-cost/mid-LOS users (Daganzo & Ouyang, 2019a). Furthermore, Papanikolaou et al. (2017) identify the lack of a methodological framework to identify the preconditions and requirements for a DRT system to be considered as "successful" which can be linked as a cause to the mismatch of market needs and the therefore financial failure of these systems. Furthermore, Papanikolaou et al. (2017) points out that there is little understanding about the data requirements, and therefore about which should be the socioeconomic assessment when structuring these type of services. Another problem is that of not having an archetypal ideal of what are the strategical objectives and what should be the role of DRT services in the transportation system (Papanikolaou et al., 2017). This last problem can be furthered explained by the many particularities of different contexts where DRT services are deployed. Nevertheless, Papanikolaou et al. (2017) argue that is possible to identify a set of attributes of DRT systems that could be divided into groups and put together to understand the successful implementation of DRT. Papanikolaou et al. (2017) adapt **a business and management-oriented approach to assess two crucial aspects.**

- What is the **role of DRT systems** within the overall transportation market?
- Describe the market niches that could be served better by DRT.

The study conducted by Papanikolaou et al. (2017) also arises new research questions to assess the successful implementation of DRT services and which data is required to answer them (see Figure 16).

Papanikolaou et al. (2017) argue that in contrast to the TNP problem of conventional transit (see section 3.1 and particularly Figure 6. Interaction between stages of the planning process and real-time control) which has been extensively researched and subdivided into subsequential standardized stages and steps, **the problem of design of DRT services has not yet a well-defined step and stage-**

based methodology. While the Transit Network Design problem has a well-defined strategical approach, continues by a tactical stage, and finally handles the operational aspects and the control of the operations of the systems in greater detail (see Figure 6. Interaction between stages of the planning process and real-time control) these standardized stages are not available for the planning of DRT systems, this motivated the study of Papanikolaou et al. (2017) which motivates a framework for the planning of DRT services taking the perspective of the operator and is shown in Figure 15.

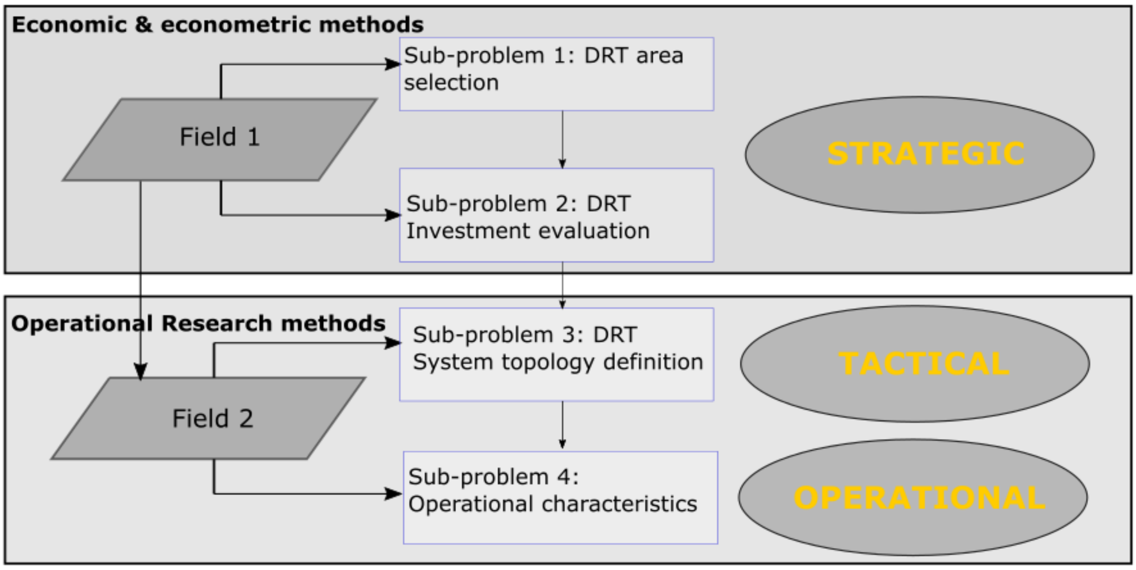


Figure 15. Problems of DRT services and their respective levels of analysis. Made by the author: Based on (Papanikolaou et al., 2017)

Papanikolaou et al. (2017) note that most of the research work published in the field of planning, design, and implementation of DRT can be classified into two categories:

- Strategical level research-> based on econometric and economic modeling tools.
- Tactical & operational research-> based on operations research (OR) and simulations.

Furthermore, Papanikolaou et al. (2017) decompose the intrinsic problems of each one of the previous fields in a subsequent series of sub-problems. Firstly, as shown in Figure 15, the selection of the area and the investments associated to the implementation of DRT services should be assessed. Afterwards, the typology and operational characteristics of the system should be defined. A more detailed set of questions is given in Figure 16 as a continuation of Figure 15, where Papanikolaou et al. (2017) report some of the questions that should be assessed in research when assessing the viability and success of DRT systems from the perspective of the operator.

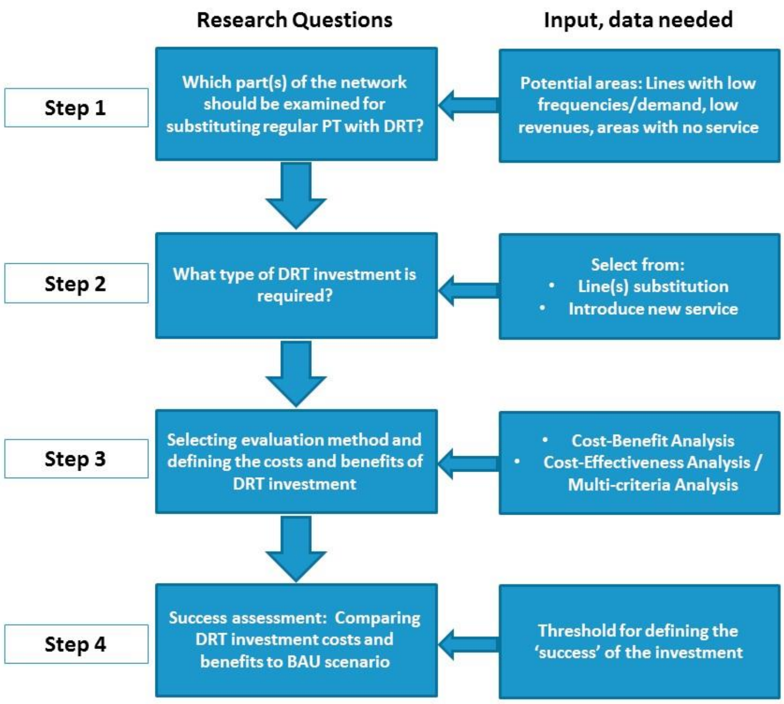


Figure 16. Problems of DRT services and their respective levels of analysis. Source: (Papanikolaou et al., 2017)

On the other hand, leaving aside the formulation of the problem and focusing more on practice, an extensive study focusing on the statistics of failure for DRT operators was conducted by Currie & Fournier(2020). The authors analyze the failure of DRT services across more than 40 years of implementations in the case of 120 DRT implementations around the world. This study shows that while there is a tendence and willing around the world to implement such services, which are discussed to be the "future of transport", reality shows that the survival rates for such services is quite low. **50% of DRT systems fail before 7 years of operation, 40% fail in less than 3 years, and about 25% fail within the first 2 years of operation** (Currie & Fournier, 2020). Nevertheless, the new era advocates of "micro-transit" argue that the accelerated technological development in the way of platforms or apps through which trips can be booked, has reduced the cost of DRT and made it more effective and sustainable, an argument which Currie & Fournier(2020) still question.

Currie & Fournier (2020) categorize each service of the data set as belonging to one of three periods (see Figure 17 and Figure 18):

- Early Dial-a-bus services (1970-1984)
- Paratransit/Community Transport Era (1985-2009)
- ICT Micro-Transit Era (2010-2019)

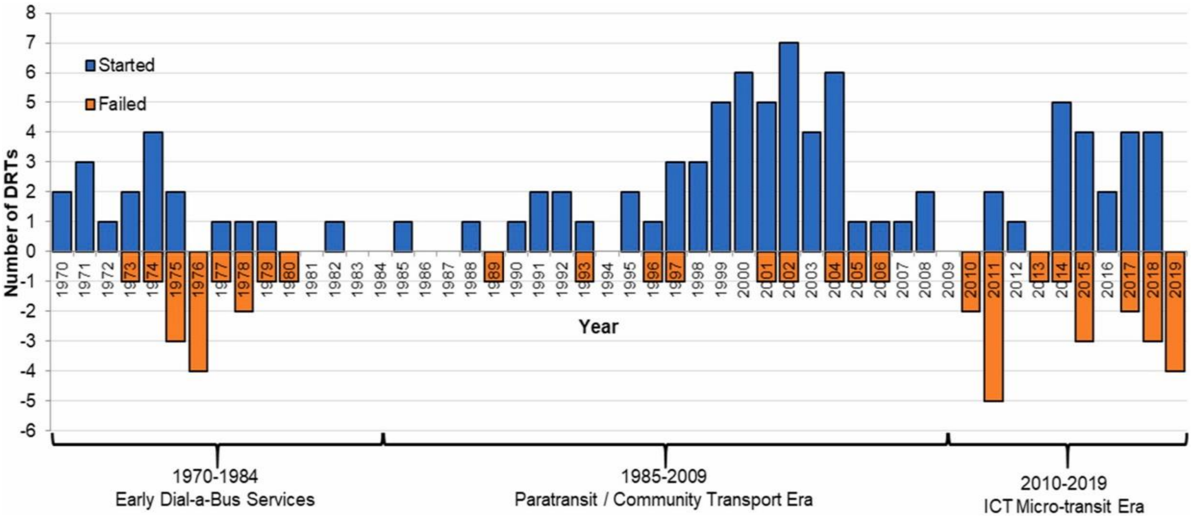


Figure 17. Frequency distribution of DRT start-ups and failures. Source: (Currie & Fournier, 2020)

Each one of the previously described groups is argued to have a characteristic that has changed the development of DRT across time (Currie & Fournier, 2020) such that the first era called by the authors **Early Dial-a-bus services (1970-1984)** refers to the first implementations of the services and was characterized by a **lesser number of new startups, but a higher failure rate**. Another era is the one of **Paratransit/Community Transport Era (1985-2009)** where a further development of DRT services was accomplished through community acts such as the (ADA) Americans with Disability Act, or regulations to provide better accessibility to some characteristic type of users or communities, the **DRT services of this era were strongly subsidized** as charging fares is unfeasible for low and no income social needs based ridership (Currie & Fournier, 2020). Finally, the last era is the **ICT Micro-Transit Era (2010-2019** which has more open start-ups than the early era, but less than the Paratransit/Community era, interestingly enough, by Currie & Fournier(2020) remark that **this era has more failures on annual and total basis.**

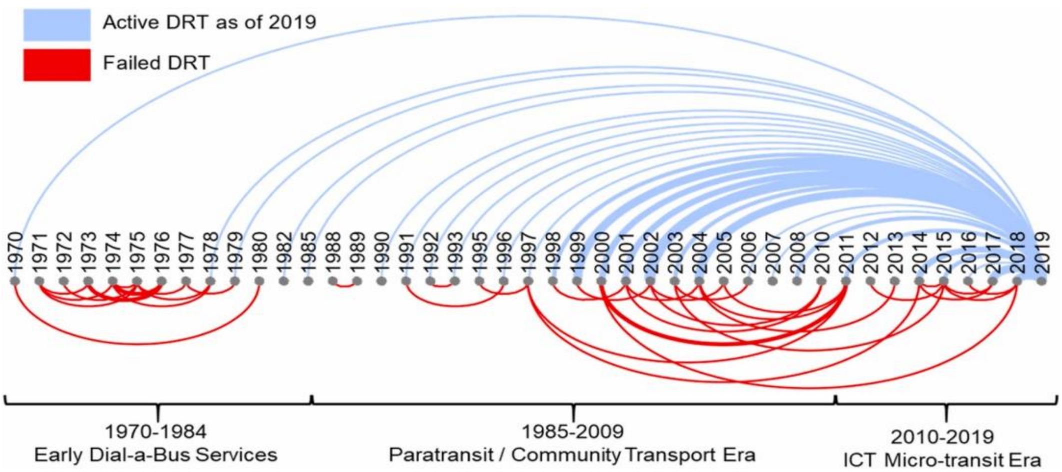


Figure 18. DRT lifespan - startup and failure years. Source: (Currie & Fournier, 2020)

From the available set of 120 DRT services studied by Currie & Fournier(2020), the study developed a more detailed analyses on terms of **cost of operation** based on 33 startups for which operational costs of the services were available, such that a chi-squared test with 95% confidence interval was done to establish if there was **enough evidence to demonstrate the existence of a link between operational cost and DRT failure**, the results of this test are show on Table 2.

Table 2. Chi-squared test for link between cost and DRT failure. Source: (Currie & Fournier, 2020).

Low/High Cost DRTs by Active/Inactive Groups – Chi-squared test.

Relative cost	Service life			Total	X^2 test of independence	
	Active-short	Active-long	Inactive			
Low	2	8	6	*16*	*Df*	*2*
High	1	2	14	*17*	X^2 statistic	0.058
Total	*3*	*10*	*20*	*33*	p-value	**0.029**

The p-value shown in the results on Table 2 suggest that at a 95% confidence interval, carrying out a Chi-squared test, there is significant information to affirm that **there is a link between failure rate and operational costs**. Another important aspect that Currie & Fournier(2020) studies is the **link between type of operational scheme and success rate**, since according to the authors there seems to be a discrepancy in argumentations of some authors such as Travers Morgan (1990) which argues simpler DRT types such as many-to-one operations are more successful, while other authors such as Commission For Integrated Transport (2008) argue that many-to many operations and the eventual achievement of economies of scale thereof are more successful. To assess this previous discrepancy Currie & Fournier(2020) developed a statistical analysis based on the characteristics of 38 DRT services operating in a time span between 1970 and 2019, the results of this analysis are shown in Table 3.

Table 3. DRT type and rate of success. Source: (Currie & Fournier, 2020)

Active, failed DRT service by region (1970–2019).

Operating Types	Active	Inactive	Total	% Active	% Inactive
Route deviation	4	7	11	36%	64%
Many-to-One	0	0	0	–	–
Many-to-Few	5	4	9	56%	44%
Simplified operation (sum of above)	9	11	20	45%	55%
Many-to-Many	5	13	18	28%	72%
Total	**14**	**24**	**38**	**37%**	**63%**

The results of Table 3 have been summarized by Currie & Fournier(2020) in three simple conclusions and observations:

- **Many-to-many DRT (most complex and larger scale DRT) have the highest failure rate (72%)**, therefore large scale and more complex systems may not be advisable (Currie & Fournier, 2020).
- **Many-to-few DRT services has the lowest failure rate (44%)** (Currie & Fournier, 2020).
- **Route deviation and simplified DRT** services demonstrate average failure rates and perform therefore not better or worse than other designs (Currie & Fournier, 2020).

Finally, Currie & Fournier(2020) remark that the overall evidence support the "keep it simple " mantra for DRT design, and that the cost of operation of modern DRT systems on the ICT era is around the double of those for the 1984-2009 era (paratransit), and similar to those of the 1970-1984 era (see Figure 19) Currie & Fournier(2020) speculate that in the case of many startups founded in the ICT era, the developments are made by an injection of private fuel capital, such that a substantial amount of expenditure is done in new vehicles, equipment, employees; these costs are never recovered given low DRT ridership (Currie & Fournier, 2020).

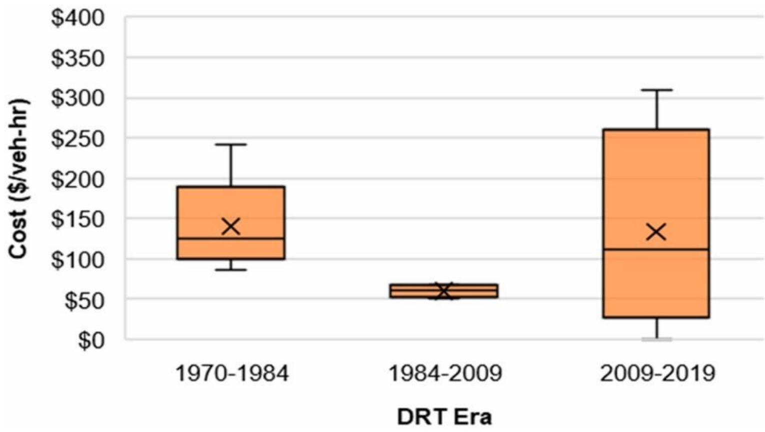


Figure 19. Average and Distribution of Operating Costs per vehicle-hour by era. (Currie & Fournier, 2020).

4 PTV Visum

4.1 Basic PTV Visum objects

This section introduces the basic components and procedures relevant to the degree project when using the macroscopic modeling software tool PTV Visum 2022 developed by PTV Group in Karlsruhe, Germay. PTV Visum is a complex demand and macroscopic modeling tool and a detailed description of it fall outside the scope of this degree project. Therefore, in this section only a brief list of the basic type of objects that one needs to understand a PTV Visum model, and it is intended such that the reader can easily find to which type of element is pointed in next sections. Nevertheless, in each scenario it is explain how the scenario is coded with PTV Visum. Special attention has been paid to section 4.2 since modelling DRT services is the purpose of this degree project.

Note: All PTV Visum objects have attributes, these attributes have several practical applications and establish the characteristics and functionality of objects. In the methodology, several user defined attributes are introduced.

Nodes: are the start or end of links, these are introduced each time there is a relevant change in the modeled link (drop of a lane, capacity restriction, velocity reduction, or blockage for a given mode).

Links: these represent the physical infrastructure in which different modes travel within the network. Along the modeled properties of the links, the volume-delay-function (VDF) that the link has been assigned is crucial since it encodes the capacity of the in-question link.

Zones: represent the origin-destination zoning (TAZ) or zoning at which the demand between OD pairs is modeled.

Connectors: These connect the demand of the zone to the link infrastructure or vice versa. Connectors can be created form node to zone or zone to node.

Stop point: Physical point where the bus/transport vehicle stops

Stop area: Physical area where users wait for the services.

Stop: Conceptual conception of stop point and stop area.

Lines: Lines refer to the characteristics of a particular type of service (line) these should not be confused with line routes.

Line routes: The actual physical route traveled by a bus line.

Demand matrices: matrices that determine the demand between origins and destinations (at zone, or main zone level for example).

Skim matrices: Skim matrices are cost or impedance matrices which calculate/assign transportation costs to connections between origins and destinations depending on a wide variety of factors.

PTV Visum trips assignment

The assignment concerns how the trips will be loaded into the network according to the characteristics of the demand and the available supply in the network in terms of links characteristics, capacity, and the characteristic of the modes using the infrastructure.

4.2 Modelling of DRT services in PTV Visum

As mentioned before, public transit with fixed routes is only optimal from a societal perspective when a certain demand threshold is reached for the operating fixed route lines. In contrast to the fixed supply of public transit, DRT provides a more flexible options for users since the routes do not need to be pre-established, the stops do not need to be fixed, and the schedule of the services flexible.

Many approaches have emerged combining last-mile solutions powered by DRT services in areas with low demand density [pax/h-km2]. According to PTV Group expertise "Only in combination with the conventional public transport, ride sharing systems lead to a sustainable offer in urban transport" (PTV,2021). Therefore, this section is devoted to the task of explaining the theoretical foundation and limitations of modeling DRT services with PTV Visum in a first instance, to then proceed to the modelling of DRT services with conventional public transport (fixed route) lines, this latter is a multimodal assignment and is accessible in PTV Visum. The current section is based on the PTV Visum 2022 User Manual.

When modelling ride-sharing services in PTV Visum, there are some additional components that one must add to the PTV Visum model to generate the trips and evaluate the performance of the system. The main additional components to model DRT-services are:

- Pick-up/ drop-off points (PUDOS)
- Disaggregate demand in space and time (trip request procedure and tour planning)
- Service areas (assigning service areas)

The general idea is that demand must be disaggregate in space and time, meaning that the generation of trips cannot be done in an aggregate way with general OD matrices per zone, but trips must be generated at a specific time t and at a specific node of the in-question service area. A trip is generated from an area i to an area j at a specific time t, and the trip is generated at specific PUDOS (selected nodes) of each zone.

Assignment of DRT trips: Microscopic vs. macroscopic simulations

When introducing DRT services, the assignment of trips in the network becomes multimodal. In this way, trips that were assigned previously with only fixed time-table routes are now to consider the stochastic disaggregation of demand and the vehicle routes generated to serve this demand. The problem thus with the introduction of DRT services is that they cannot be made with only static assignment but require microscopic simulation features, these affect the assignment and its convergence.

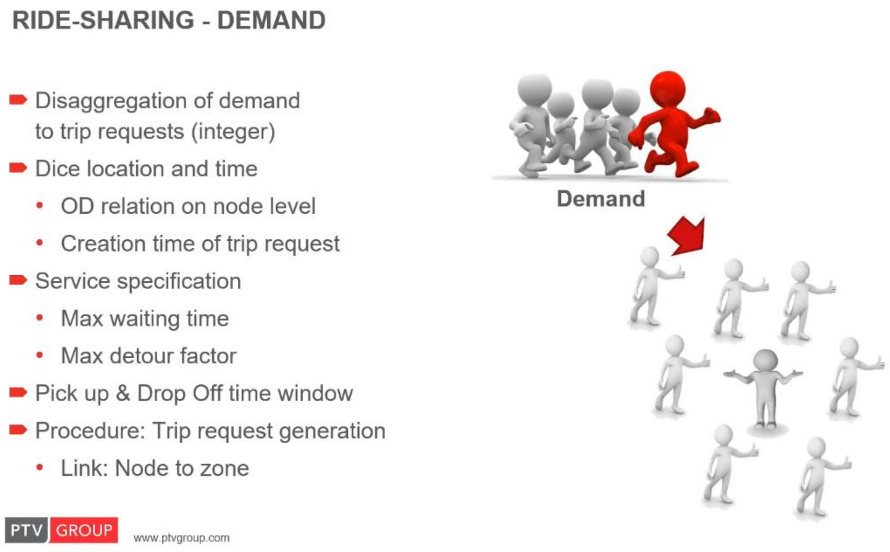


Figure 20. Ridesharing disaggregation of demand. (PTV Group Traffic, 2021)

Size of service areas in PTV Visum

The size of the service areas for DRT services must be defined in PTV Visum in order to assign the trips generated by users in the system. A crucial step is the size and division of the service areas. While smaller areas give more detail about the costs of the routes of the trips assigned in each area, by nature they lead to smaller number of realizations (trip requests) i.e., the smaller the area, the smaller the number of requested trips inside the area (PTV Group Traffic, 2021). This previous fact makes that smaller service areas lead to more stochastic fluctuations, and therefore the convergence of the route search and route choice of the model can be affected. On the other hand, big areas (more aggregation of requests) lead to more stable skim matrices, which is good for the assignment, since the convergence criteria is fulfilled faster, but they also coarsen the result, meaning that they can over or underestimate the costs of the routes inside the area.

Tour Planning Procedure

The tour planning procedure links the demand, i.e. the generated trip requests of DRT services, with the supply, i.e. the vehicle fleet and the pickup and drop-off points (*PTV Visum Help - Tour Planning Procedure*, PTV 2021). There are two types of trips modeled for ridesharing or DRT services, the ones that are known beforehand (pre-book trips) and the ones that occur spontaneously during the day (assignment period).

There are two methods used to solve the planning problem of the routes:

- Dispatcher:

The dispatcher does not know the trips in advance, the trips are generated at a given point and the dispatcher tries to serve the trips with the existing vehicles of the fleet(*PTV Visum Help - Tour Planning Procedure*, PTV 2021) in order to do this, the dispatcher takes into account trips that were reserved beforehand (pre-booked) trips, and modifies the routes of the vehicles which were assigned these trips.

Tour Planning

Figure 21 shows the case in which two vehicles (red and blue) have a predefined route, and one of them must be assigned an additional "spontaneous" passenger P3 who was a destination D3. In these cases, PTV Visum calculates the additional cost of adding P3 to the tour of each vehicle and assigns the passenger to the vehicle which yields the minimum cost (red vehicle in Figure 22).Nevertheless, the number of possible routes can grow extremely when more candidate vehicles are analyzed. Therefore, to not affect the running times of the model dramatically, PTV introduces grids that restrict the number of possible candidates available to pick up the new passenger as shown in

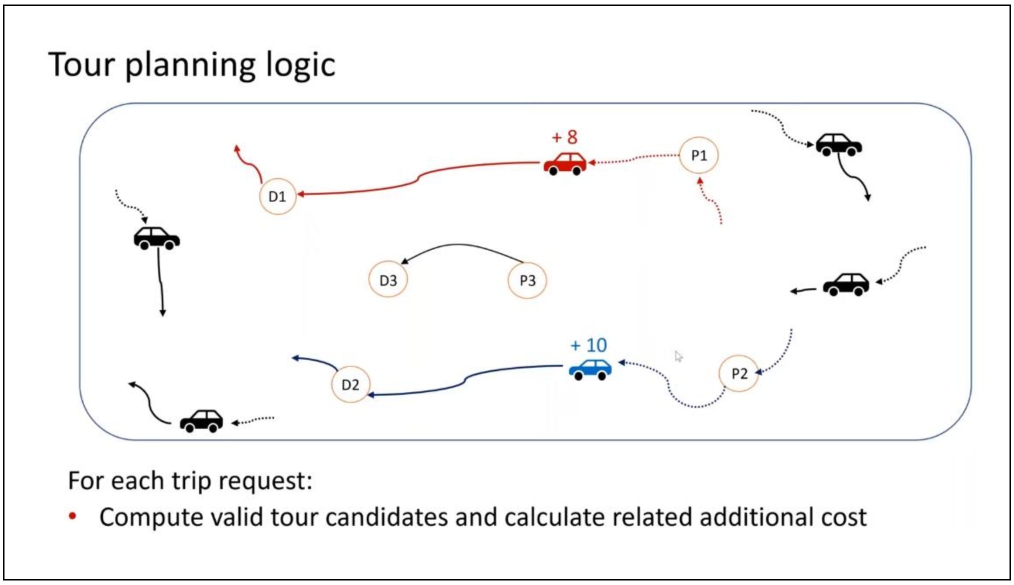


Figure 21.Tour planning logic I. (PTV Group Traffic, 2021).

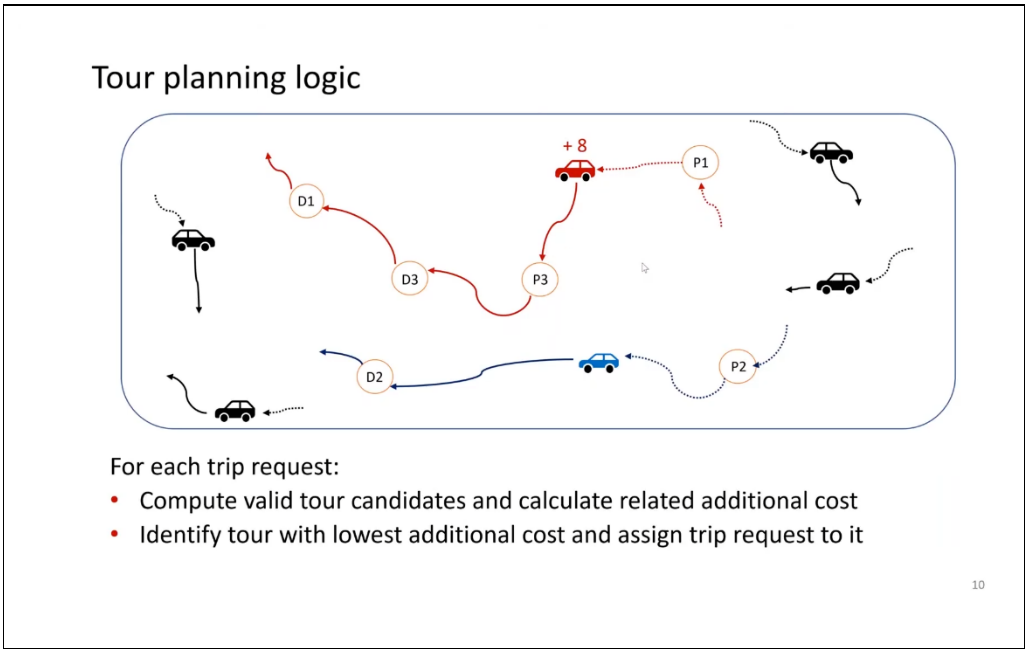


Figure 22.Tour planning logic II.(PTV Group Traffic, 2021)

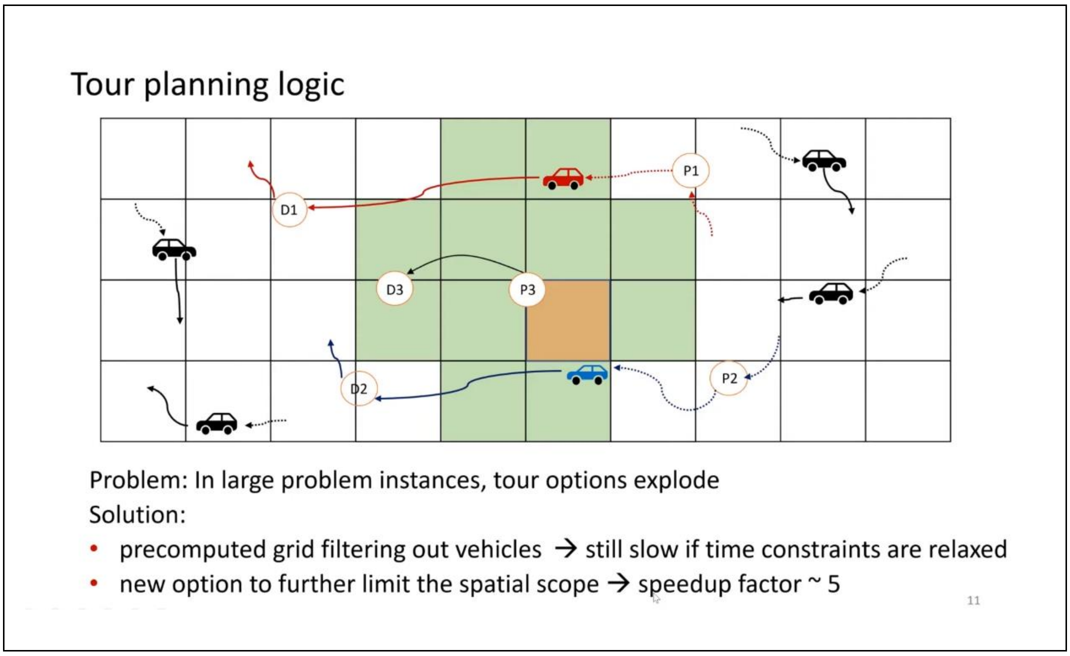


Figure 23. Tour planning logic III.(PTV Group Traffic, 2021)

5 Methodology

Based on information about the study area and the transportation system operating within it, this section will motivate the methodology and modelling decisions made during the project. The socioeconomic characteristics of the population, and the performance of public and private transport modes inside the study area are discussed here. Consequently, this information serves as a mean to base the modelling decisions and assumptions carried out during this degree project. Furthermore, the previously mentioned information motivated the coded scenarios in the model and the chosen values attributed to different costs in the total cost functions.

5.1 Area of analysis and characteristics

One of the main goals of this degree project is to provide better accessibility to the RIT in areas with low passenger demand. By doing so, a higher ridership in public transport can be achieved and there will be more willingness to shift from private modes to ride-sharing and public transport. In this context, several discussions were conducted with representatives of IPPUC, who proposed different desired areas of study and described the characteristics of these. Finally, after more in depth analysis, the Campo Comprido zone was prioritized. In this zone Public Transport Users experience very long travel times when compared to Private Car users. Furthermore, an increase of PuT ridership is expected due to the introduction of the new station CIC which will enlarge the West corridor 1,5km further after the station Campo Comprido and further investments in the West Corridor. Nevertheless, after suggestion of IPPUC, the area of analysis was enlarged to include neighboring zones inside 7 additional neighbor neighborhoods. The area of analysis thus comprehends the partially and/or totally, the zones inside Campo Comprido, Campina do Siqueira, Mossungue, Santo Inácio, Santa Felicidade, Orleans, SaoBraz, and Cidade Industrial de Curitiba.

The area of analysis comprehends 54 zones of Curitiba's PTV Visum model in the south and north surroundings of the west BRT corridor (Leste) of the RIT and covers an extension of 33 km2 (see Figure 24). There are 55 bus lines operating inside or on the borders of the study area. Considering most of the lines operate in 2 directions, there is a total of 109 Line Course Routes (PTV Visum objects) coded in the model with are relevant to the study area. It should be noted that inside these previous line courses, several lines are metropolitan lines (not show in Figure 24). There are 16 feeder lines inside the area of study operating in 2 directions accounting for 32 line route courses coded in the PTV Visum base model.

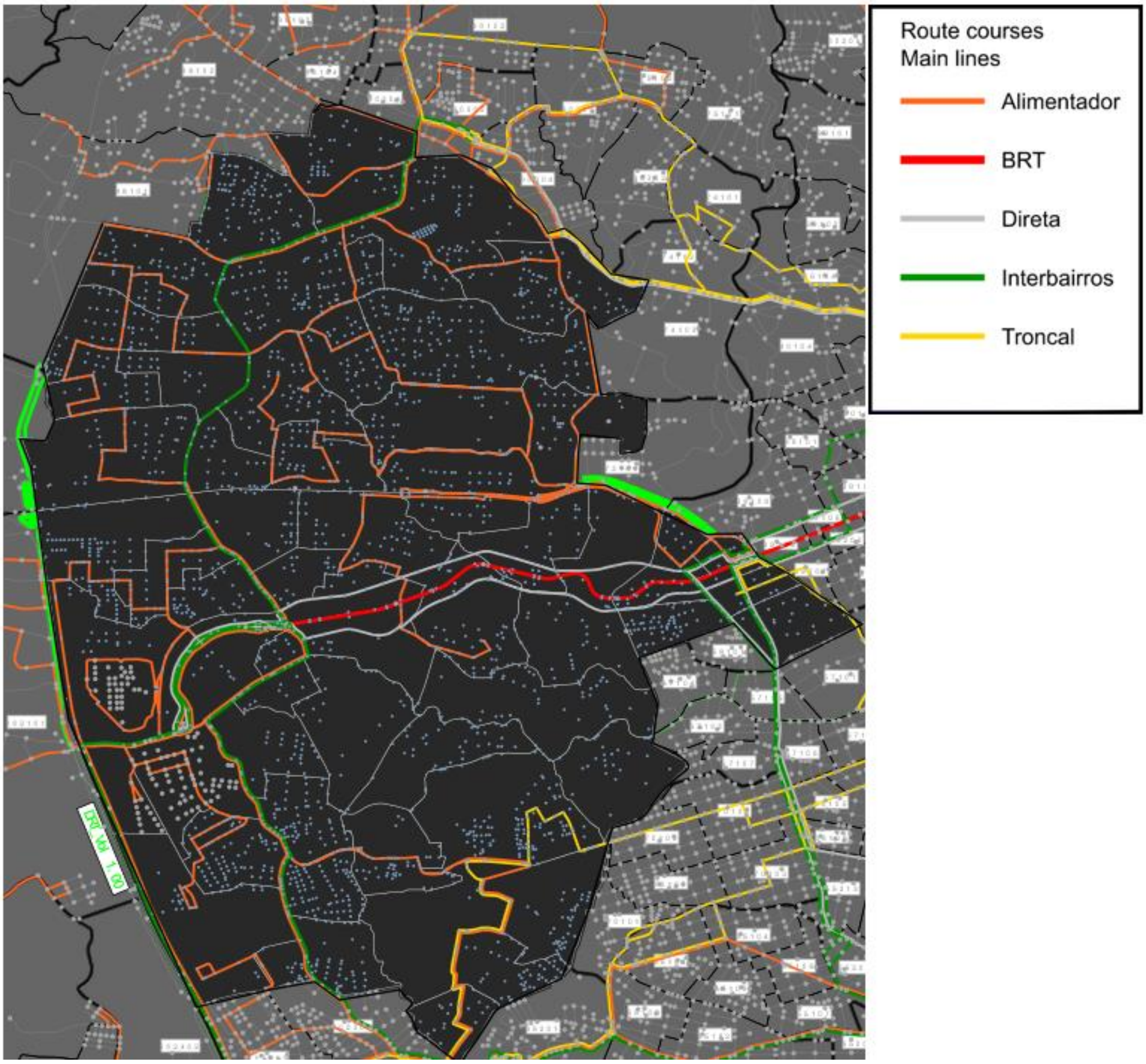


Figure 24. Study area and main transit lines. Source: made by the author.

Comparison of Public and Private modes

Table 4. Comparison of private and public transport inside the zones. Made by the author based on the OD survey of Curitiba Great Region IPPUC (2018).

Neighborhood	Average travel time (min)			Modal share (%)	
	PuT	Car	Extra travel time (%)	PuT	Car
Campina do Siqueira	36	21	71,43%	22	64
Campo Comprido	42	22	90,91%	35	43
Mossungue	45	27	66,67%	22	64
Santo Inácio	43	20	115,00%	25	67
Orleans	40	25	60,00%	29	53
Santa Felicidade	52	21	147,62%	18	67
Sao Braz	53	20	165,00%	25	51
CIC	55	25	120,00%	27	38
Average	46	23	**102,21%**	25	56

Table 4 summarizes the comparison between the characteristics of the two principal modes inside the zones of study. The average travel times are much higher for Public Transport users than for Private Car users inside all the zones. On average, a user travelling with Public Transport inside the area of study will experience a travel time that is two times higher than the average travel time of Private Car user (see dashed series in Figure 25). Furthermore, the calculated percentual differences between travel times for private and public modes shown in Table 4 suggest that there are large variances depending on within which zone the trip is performed. While In zones such as Mossungue, Campina do Siqueira, or Orleans a Public Transport user would experience on average 60%-70% longer travel times compared to private mode, on other zones, such as Santo Inácio, Santa Felicidade, Sao Braz, or Cidade Industrial de Curitiba, the user would experience longer travel times ranging between 115% and 165%. The previous information is shown in Figure 25, where the dashed series show the average travel times for each mode.

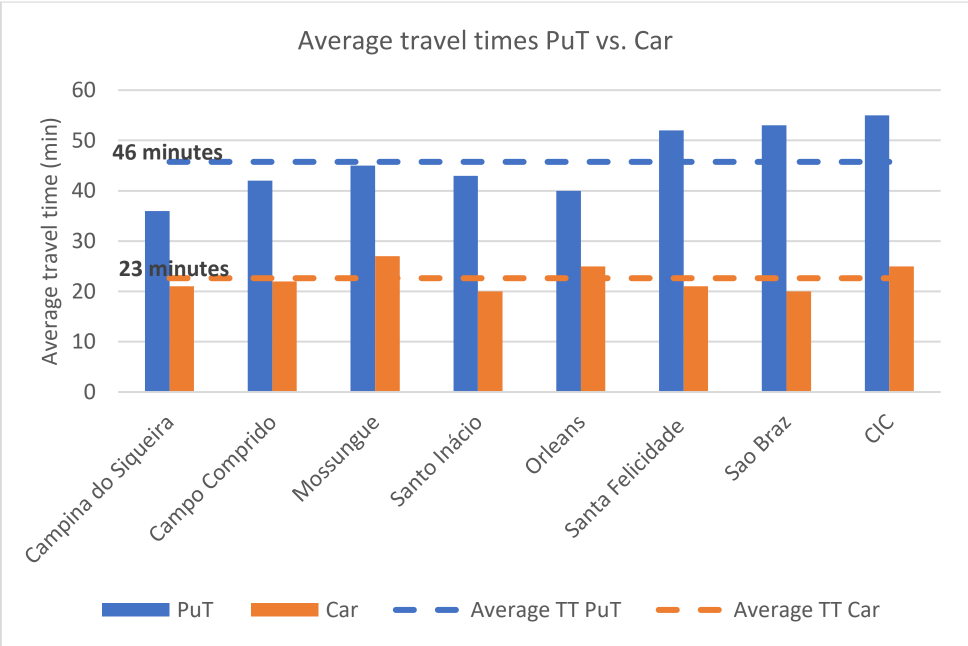


Figure 25. Comparison of average travel times for neighborhoods inside the study zone. Made by the author based on statistics of IPPUC (2018).

Figure 26 shows the modal share of the most predominant modes inside the study area i.e., Private Car and Public Transport. The shorter average travel times of Figure 25 (23 minutes for private car to 46 minutes for public transport) result in a much higher percent of mode share for Private Car travel inside the study area which can be seen in Figure 26.

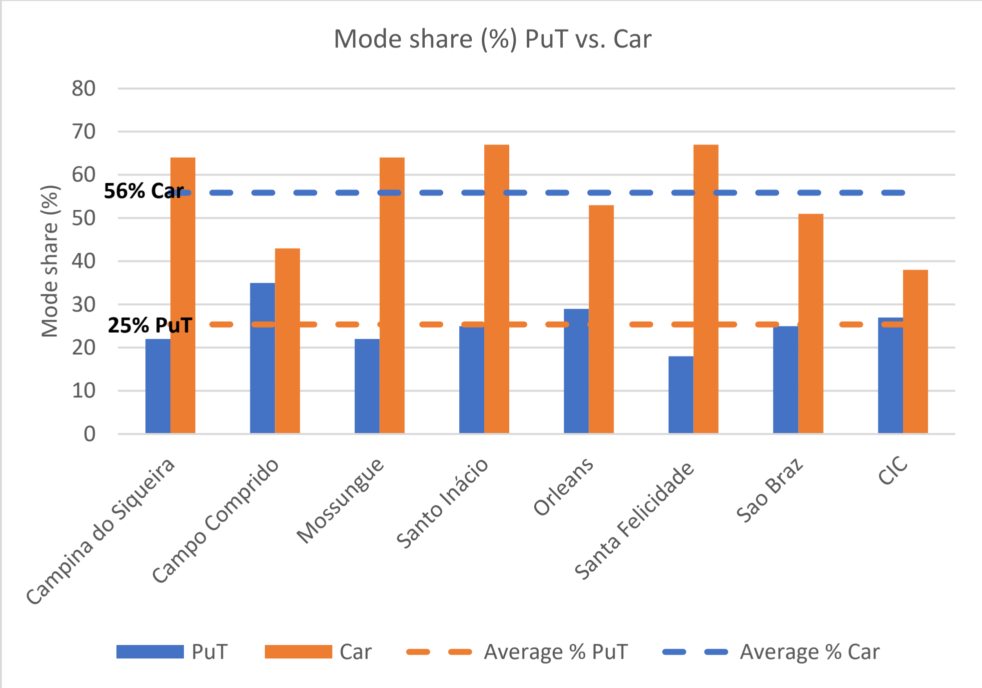


Figure 26. Comparison of modal share for neighborhoods inside the study zone. Made by the author based on statistics of IPPUC (2018).

Socioeconomic characteristic of the zones

The considered socioeconomic characteristics of the study area will be principally the welfare deduced form the average income that a household inside the study area reported in 2017 when the socioeconomic data for the origin-destination survey for Great Curitiba was collected.

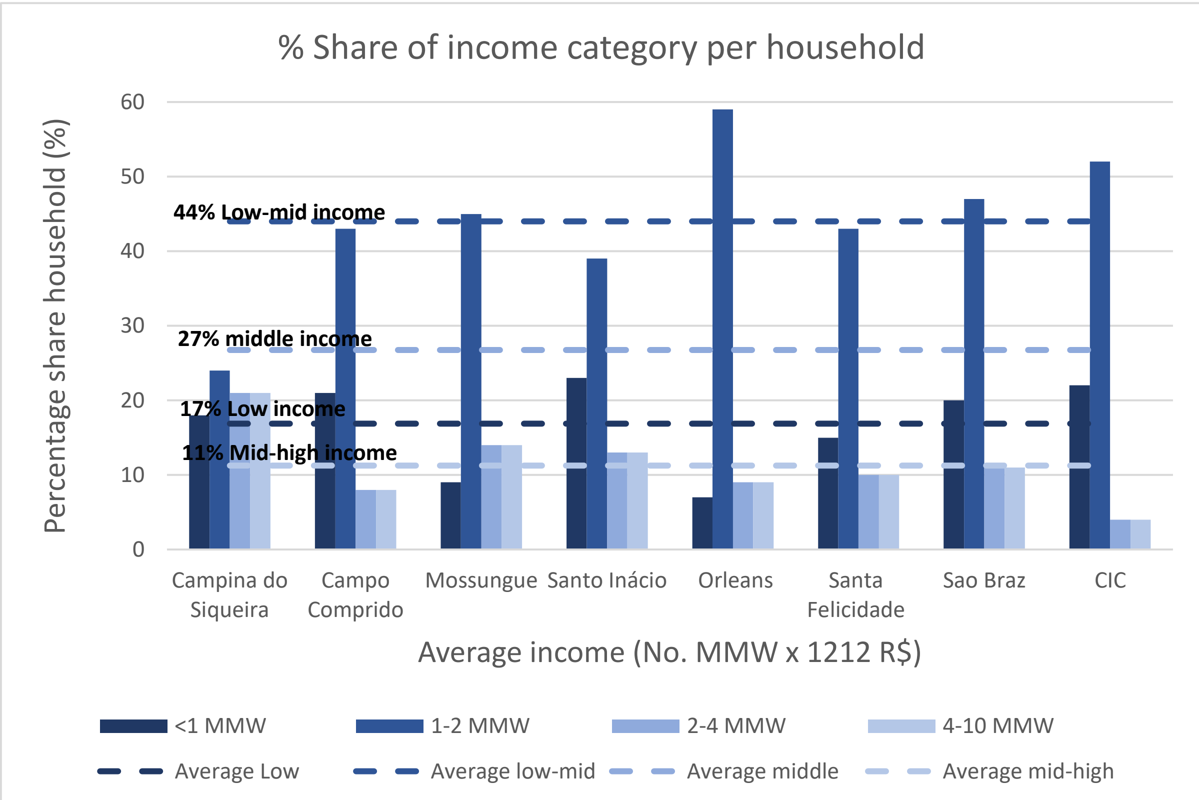


Figure 27. Percentage share of number of minimum monthly wages (income) per household. Made by the author based on statistics of IPPUC (2018).

This socioeconomic data served as input for the development of Curitiba's PTV Visum model. As a metric of welfare, the average income inside the study area is reported, this latter is inferred from the amount of monthly minimum wages that a household reported during the origin-destination survey for Great Curitiba region.

Possible market share for DRT

The possible market share for DRT systems will be based on the socioeconomic characteristics of the users of each service. Section 3.3.3 discussed a general model to assess which type of services fills better the needs of customers based on the demand density, the target travel times set by the operator, and the values of time of users.

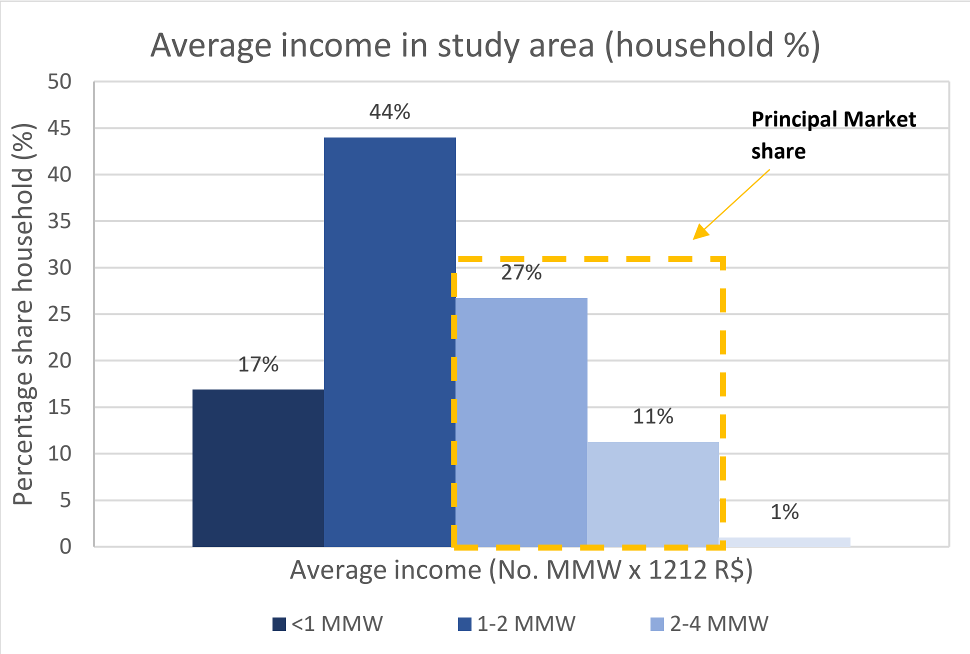


Figure 28. Average income per household in area of study and possible target markets. Made by the author based on statistics of IPPUC (2018).

Figure 28 shows the average income characteristics of the study area, earlier in section 3.3.3 when comparing how different DRT service compared to other modes, and which would be the possible markets for these type of services regarding the costs structure components analytically assessed by Daganzo & Ouyang (2019b), It was discussed that DAR services and ridesharing services would better fit the needs of a market composed by middle-income users principally. Therefore, Figure 28 shows the dashed yellow line which captures the targeted principal market shared of 38% of the residents inside the zone.

An adoption of DRT services as considered in this degree project can occur from a modal shift in either three ways:

- Shift from private Car to DRT services (Scenario I- ridesharing).
- Shift from Public Transport feeder lines to dial-a-ride intrazonal shuttle services inside the study area (Scenario II).
- Shift from Public Transport feeder lines to a combination of public transport and DRT (multi-modal transport: Scenario III).

If the income of the PuT users demand is assumed to follow the same distribution as the average income in Figure 28, it could be argued that a demand shift of 38% from PuT users to a combination of PuT and DRT services could be considered for scenario II and III. However, considering 38% of adoption from the total demand for Public Transport in order to design and dimension the characteristic of the dial-a-ride system may be in first instance inaccurate and in second instance undesirable for the design of the system. Firstly, an adoption of 38% of the total demand for PuT is quite high for a DRT system, since it would represent a total of around 6310 pax/h based on 38% of the total OD Demand Matrix in the study area for peak commuting period 07:00-11:00 h (8338 trips/h as origin, and 8266 trips/h as destination), this demand of 6310 pax/h is equivalent to a demand density of 180 pax/km^2-h, which exceeds greatly a recommended low demand density for DRT services with low capacity vehicles of around 92 pax/km^2-h (Estrada et al., 2021). Furthermore, such a high demand ignores the nature of customers towards diffusion of innovations. Rogers (2003) argues that when new innovations (products/services) are introduced in a market, there is a process by which they are adapted in the market, this process depends on the characteristics of the customers (adopters), such that the rate at which the new product is adapted in the marked is a function of the composition of the market share and the proportion of early and later adopters.

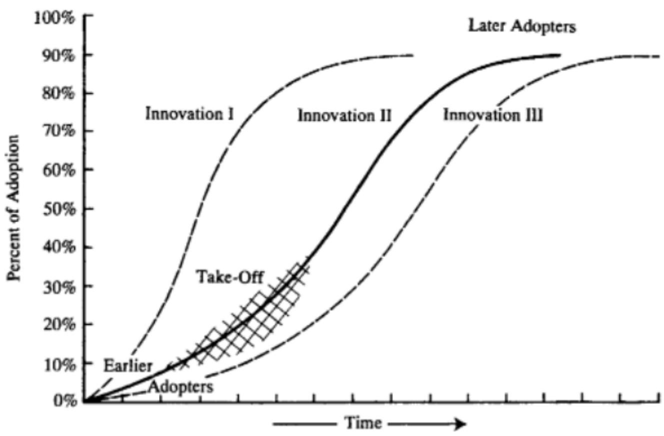


Figure 29. Diffusion of innovations curve. Rogers (2003)

It is therefore more suitable to consider that in principle, an initial maximum demand density of nearly 80 pax/km^2-h inside the study area could be achieved, this demand is equivalent to approximately 2625 pax/h in the area service of 33 km^2.

Private vehicles characteristics inside the area of study

Table 5. Fleet of Private Vehicle characteristics and ownership. Made by the author based on statistics of IPPUC (2018).

Neighborhood	Average age of vehicle fleet (years)	No. Vehicles/household			
		0 (No)	1 vehicle	2 vehicles	3 or more vehicles
Campina do Siqueira	10	22%	52%	19%	7%
Campo Comprido	10	36%	46%	17%	2%
Mossungue	9	24%	39%	34%	3%
Santo Inácio	10	12%	53%	31%	3%
Orleans	10	6%	59%	32%	3%
Santa Felicidade	10	26%	49%	21%	4%
Sao Braz	11	37%	44%	13%	6%
CIC	11	35%	52%	11%	3%
Average	10	25%	49%	22%	4%

Table 5 Summarizes the characteristics of private vehicle ownership and the average old of the vehicle fleet inside the area of study. In 2017 on average a household owned a vehicle that was 10 years old, and at least 75% of the surveyed households reported to own one private vehicle (see Figure 30).

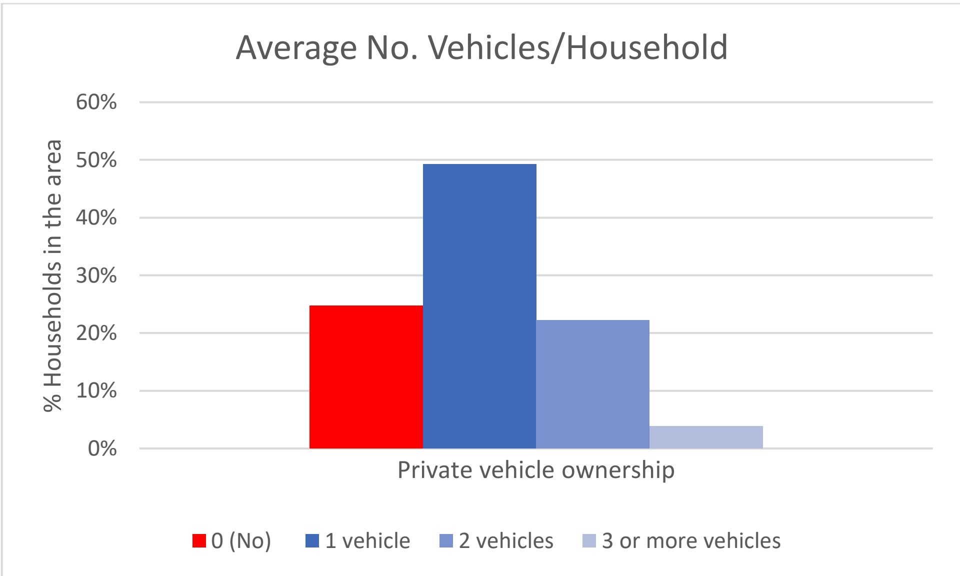


Figure 30. Average private vehicle ownership inside the area of study. Made by the author based on statistics of IPPUC (2018).

The car ownership inside the area is high, with as much of 75% of the households owning at least 1 private vehicle, this previous fact combined with much more competitive travel times of Private Car to Public Transport (see Figure 25) results in the previously shown low share for Public Transport mode inside the study area (see Figure 26). Finally, the results shown Table 5 will serve as means to base future decisions made when an assessment of the environmental costs of road based transport inside the zone of study will be made in sections 5.7 and 5.9.

5.2 Modelling procedures

5.2.1 Update and preparation of the model

The only significant update (not considering defining new user defined attributes) made to the existing model for the base scenario is the introduction of timetables to all the PuT lines of the model. After revision of the model and discussion with a PTV Visum expert, a Timetable- based assignment for the model was preferred instead of a Headway-based assignment (original model) due to the long operational headways of some of the lines coded in the model.

Furthermore, a simplification has been made to generate timetables for metropolitan lines with too long operational headways i.e., all the lines with $H > 30\ min$. The timetables for these lines (190 Line routes in total) have been assigned to the median value of the population $H = 2700\ s = 45\ min$.

5.3 Defining the stop points

This degree project aims to evaluate the introduction of ridesharing and DRT services inside the previously discussed study area by means of macroscopic simulation with the professional demand transport modelling software PTV Visum 2022. In PTV Visum, ridesharing and DRT services can be requested by users at PUDOs (pickup and drop off points) as explained in 4.2, PUDOs provide therefore accessibility to the offered services. This section discusses the methodology followed to allocate the PUDOs of each coded scenario.

Accessibility is increased when users can reduce their effort to access the system, this latter can be mainly achieved by providing shorter access or waiting times. Nevertheless, as for all other transportation modes, accessibility in DRT always comes with a cost. The detour factors are crucial when assessing DRT success since they modify greatly the travel times of the passenger inside the vehicle, since longer detour factors to pick up an additional passenger increment the operating cost of the system for both users and operators. Consequently, the detour factors (accepted and perceived) are also one of the important factors in the modeling of ride-sharing services in practice and therefore in PTV Visum.

Nevertheless, there remains a main question with respect to the possible stop points in the network of DRT services: **What is an acceptable density of DRT PUDOs to provide enough accessibility and simultaneously not increment greatly the operating costs? What is the right trade-off between accessibility and operating cost?**

In the case of scenarios II and III, as it will be discussed later, the introduced DRT services inside the study area aim to serve as complement to the existing supply of public transportation. Since accessibility is provided to users by creating more available stops, or in this case by allowing users to request the trips in a larger number of available PUDOs, a natural further question to ask with respect to accessibility is: **What is the desired maximum walking distance that users are willing to walk to access public transport services?**

Daniels & Mulley (2013) studied walking distances to public transport in Sydney, Australia. The study reports that the overall average walking distance to public transport was 573 m, with 25 percent of the trips being performed with a walking distance within 235 m, and 75 percent of walking trips being within less than 824 meters. Furthermore, the same decreasing willingness to walk when access distances increase was studied by Pongprasert & Kubota (2019) and Pongprasert & Kubota (2017), these latter study more specifically the attitude of TOD residents towards accessing transit stations in a radius of 1 km in Bangkok, Thailand. Although in this case, our interest is not centered on the accessibility to the main corridors of the RIT, the characteristics of the previous studies are considered to portrait a similar behavior to the case of accessing the PUDOs. In both studies, Pongprasert and Kubota (2019, 2017) note that:

- *"The share of walking for accessing the stations dramatically reduces from 76% to 25% when the walking distance varies from a walking distance within 500 m to a walking distance between 500 and 1000m"* (Pongprasert & Kubota, 2017) see Figure 31.

Finally, other authors claim that good accessibility is provided by having a walking distance between 400 to 800 meters form the stop point, or equivalently 10 to 15 minutes of walking time is often acceptable (Wibowo & Olszewski, 2005).

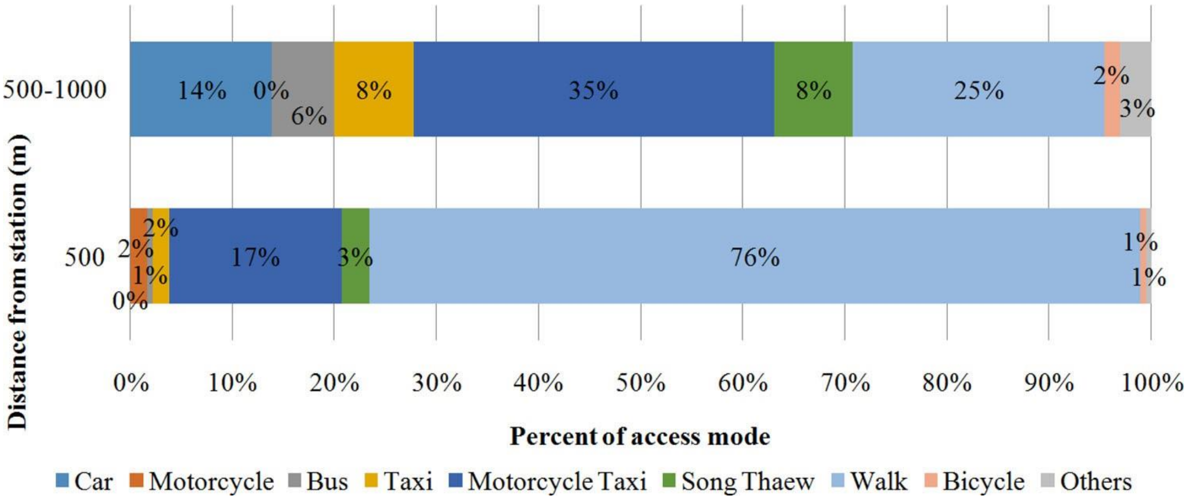


Figure 31. Access modal share of residents living near transit station within 1 km. Pongprasert and Kubota (2019).

Considering the previously mentioned studies, a first step to provide accessible DRT services to the area of study under scenarios II and III will be to distribute enough pick-up and drop off points such that most of the nodes in the study area have a PUDO within a walking distance of 500 meters. Nevertheless, in order reduce the computational times to obtain the public transport assignment in PTV Visum, for scenario II, the dial-a-ride service was coded such that each connector for private mode inside the study was enabled as a PUDO. Finally, in the case of scenario III, the creation of PUDOs includes additional PUDOs at selected locations, this latter is done because the intermodal combination of dial-a-ride and conventional collective transportation in PTV Visum requires that the stop areas at which the transfers take place need to be enabled as PUDOs.

Scenario I

For this scenario a high number of available pick-up and drop off points has been coded, this feature resembles the dynamics of trips booking with modern ride-hailing platforms where a user can be picked up or dropped off at virtually any location in the network. Figure 32 show the nodes inside the study area which serve as PUDOs for scenario I.

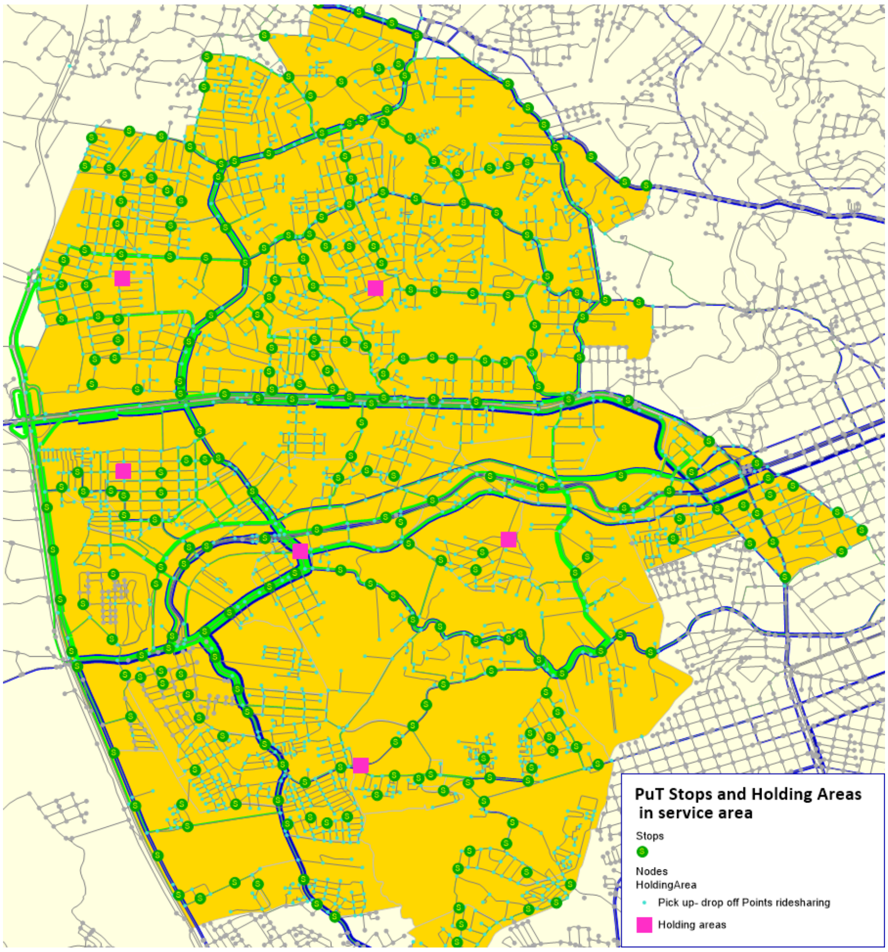


Figure 32. PuT Stops, Pick-up and Drop-off points and Holding areas inside the DRT (ridesharing) service area. Made by the author.

NOTE: The allocation of PUDOS for scenario II and scenario III is handled in sections 6.2 and 6.3 respectively.

5.4 Cost functions to compare scenarios

To compare the results of the base scenario to the alternative scenario(s), a generalized cost function will be used. The generalized cost function will have a common unit [R$/h], which stands for the required cost to operate the system in one hour of operation (peak hour in our case) and will be a sum of the costs that each involved actor in the system incurs by the proposed alternative. The costs considered in the cost function for this degree project are:

- Operator cost (feeder lines operation)
- Public Transport User Cost
- Private Car User Cost
- Environmental costs

The total cost of the system is given by a sum of the above listed costs inside the area of study during one hour of operation of the system. To have more clarity about the components of the cost function and the simplifications and assumptions made, the next sections will develop a more detailed explanation about the units and assumptions made when building the cost function.

Note: Although a much more detailed assessment of the costs of the model could be obtained by a more rigorous use of PTV Visum tools, this degree project´s emphasis will focus on developing simplifications based on averages and analytical expressions to translate the outputs of the PTV Visum model assignments in terms of metrics and monetary costs, such that the outputs of each scenario can be compared in a simplified way and more understanding about the outputs of the model is achieved. By linking the outputs of the model with the analytical expressions developed more traceability is possible and the outputs of the model can be examined carefully.

5.5 Operator cost

The operator cost will be simplified and will be given by the distance-rolling cost, and the workforce cost required to provide the operation of the feeder lines of the public transport system inside the area of study.

Fundamental expressions for public transport system metrics

In a simplified form, the number of kilometers traveled by a line i of a transportation system during one hour of operation can be approximately given by the ratio between the length of the line l [km] i.e. the route course of the line (including all the distance performed from start to end stop) and the average operational target headway provided between consecutive services of the line [h/veh] i.e. how much time is expected to pass between two consecutive services of the line. Such that the distance traveled by one hour of operation of line i is given by (3).

[km-h/veh] $$K_i = \frac{l_i}{H_i} \tag{3}$$

Furthermore, if instead of analyzing one line, the consideration developed considers a set of n lines operating during 1 hour of operation in the service area, then an approximation to the total number of kilometers performed by the set of n lines serving the area of interest is given by simply adding the contribution of each line to the distance travelled by the whole fleet, this total distance traveled by the fleet in one hour of operation is given by (4).

[km-h/veh] $$K = \sum_{i}^{n} K_i = \sum_{i}^{n} \frac{l_i}{H_i} \tag{4}$$

Considering that the number of kilometers travelled by the fleet in one hour given by (4) must be performed by a fleet with commercial speed (speed including boarding, alighting, acceleration, and other operations involved in the operation of the line) and assuming that this commercial speed can be approximated to a constant average given by the PTV Visum model, then fleet size for one hour of operation of the system is approximately the sum of the required number of vehicles for the n lines operating inside the zone, this total fleet size is given by (5).

[veh/h] $$m = \sum_{i}^{n} \frac{K_i}{v_{c_i}} \tag{5}$$

It will be assumed that each vehicle of the fleet of size m in (5) will be operated by an individual driver, such that the number of drivers equals the fleet size.

The previous expressions (3) and (5) are the base for the cost function of the operator which is composed by the number of kilometers travelled by the fleet K multiplied by the corresponding vehicle distance-rolling cost C_d [R$/km] (see section 5.8), and the fleet size m multiplied by the average cost of one hour driver's wage C_m [R$/h] (see section 5.8). Such that the operator cost in a general form is given by (6).

[R$/h] $$C_O = K \cdot C_d + m \cdot C_{m\ R\$/h} \tag{6}$$

It should be noted that K in (4) which accounts for the total distance travelled by the fleet in one hour (without considering the from/to depot and other rebalancing operations) is a fixed quantity obtained by the timetables of the lines or equivalent headways.

While the variable m (fleet size) will be held constant for the base scenario for each lines, the fleet size of dial-a-ride service (minibus) will take different values performing an grid search focused in the area of analysis between $m = 30$ to $m = 40$ vehicles (this analysis is furthered developed in section 6.2) and maximum waiting times varying between 10 and 25 minutes. In the case of scenario I, the fleet of ride sharing vehicles is constant and equal to $m = 35$ vehicles with the characteristics described in section 5.8.

Finally, each scenario will have different vehicle types with varying vehicle costs C_d and different fleet sizes for each type of vehicle. Therefore, there is a need to develop specific cost functions for each scenario in sections 5.5.1 to 5.5.3, and then assess the monetary costs of each specific type of vehicle involved in the operation of the system (see section 5.8).

5.5.1 Base scenario

In the base scenario, the operation of the existing feeder lines is made by the orange buses in Figure 4. It is assumed that the operation is made by two types of vehicles: "Comum" and "Micro Especial" due to the low ridership of feeder lines inside the zone (see section 6.2 and Table 20), this assumption can hold for all the feeder lines inside the area of study except for lines U_826, and U_816 which carry a larger proportion of passengers based on the assignment (see PTripsUnlinked(AP) attribute in Table 20 available in the Annex). Due to higher ridership and occupancies (more than 150 pax/veh based on the assignment), lines U_826, and U_816 should be operated (at least in peak hour) by an articulated bus "Articulado" based on the results of the assignment. Nevertheless, for this degree project it is assumed that the vehicle type "Articulado" is not operated by the selected feeder lines of the model. Furthermore, the assumption holds also with the way how the lines have been coded by Engimind (consulting group which built the base model) this can be seen in the attributes of the Line routes (VehCombNo in Table 20), and the vehicle units coded for the model (see Table 21).

Vehicle type "Comum" has a capacity of $85 pax/veh$ and a rolling cost C_{d_C} (see section 5.8) and the vehicle type "Micro Especial" has a capacity of $70\ pax/veh$ and a rolling cost C_{d_M} (see section 5.8). Both vehicles are assumed to have an average commercial speed v_c of 14 km/h based on average commercial speeds and evidence discussed earlier. The cost of the operator in the base scenario for the operation of the feeder fleet is given by (7), where the subscripts C, and M denote the type of vehicle "Comum", or "Micro Especial" respectively as show in Figure 4. K_C and K_M denote the total distance traveled in kilometers by each type of vehicle type, and the quantity m denotes the total fleet size which is operated by a workforce of m drivers earing an average $C_{m\ R\$/h}$(see section 5.8).

$$C_O = K_C \cdot C_{d_C} + K_M \cdot C_{d_M} + m \cdot C_{m\ R\$/h} \tag{7}$$

5.5.2 Scenario I (Ridesharing)

Under this scenario a modal shift of 5% from private car to ride-sharing services will be assumed. The modal shift under this scenario assumes that no intermodal transport PuT-DRT or DRT-Put is possible. This last assumption implies that the new ridesharing mode introduced in the model and offered to users by a ride-haling or ridesharing company does not affect the Public Transport assignment executed in PTV Visum. Furthermore, based on the description of the operation of the ridesharing systems developed in 6.1, it is assumed that the operator cost evaluated in this scenario only considers the distance-based cost (fuel consumption of the operator) and the cost of the workforce (drivers) required for the operation, such that the cost of the operator under this scenario is given simply by the consumption of fuel of the ridesharing fleet of vehicles and the cost per hour of labor force of the drivers of these. The km-based cost of the operator is done in terms of the number of total vehicles composing the fleet (m equals the fleet size).

$$C_O = \left[\sum_{l}^{m} K_l \cdot C_{\ R\$/km} + m \cdot C_{m\ R\$/h}\right]_{Ridesharing} \tag{8}$$

5.5.3 Scenario II (Fixed route feeder + DAR)

In scenario II, the operation of the system is done by the existing bus lines inside the area of study and complemented by the introduction of dial-a-ride (DAR) services with vehicles of small capacity (15 pax/veh) as the ones operated by microtransit start-ups such as Swvl, Via, or Shotl, among others. This scenario explores the possibility of complementing the Public Transport supply by offering shuttle services (few-to-few) between the zones inside the area of study. The motivation for this scenario arises from the large proportion of interzonal trips inside the area of study. (9) develops the distance base cost associated to fuel consumption and the workforce cost for the operation of the system. The subscript DAR in (9) denotes the new introduced mode and the terms m_{Bus} and m_{DAR} refer to the fleet size of buses and DAR services correspondently. Note that the fleet size of feeder buses m_{Bus} is held constant, while the fleet size of DAR services varies according to the values described in 5.5.1 and 6.2. Since the cost of the workforce for both DAR and feeder bus services is assumed to be the same (see section 5.8), it is possible to multiply both fleet sizes of feeder buses and minibuses by C_m.

$$C_O = K_C \cdot C_{d_C} + K_M \cdot C_{d_M} + K_{DAR} \cdot C_{d_{DAR}} + (m_{Bus} + m_{DAR}) \cdot C_{m\ R\$/h} \tag{9}$$

5.5.4 Scenario III (Reduction of feeder lines by dial-a-ride service and Intermodal assignment)

This scenario is a consideration about the operation of dial-a-ride services inside the area of study. In this case, the initial set of 16 feeder lines operating inside the area of study is reduced by selecting 8 lines with low ridership inside the study area and eliminating them (see description in section 6.2) to be replaced by dial-a-ride services. In this case, the hypothesis is that feeder lines are replaced by demand responsive transport under the form of dial-a-ride services and the performance of the system improves (system total costs decrease, user costs decrease, or operator costs decrease). The goal of this scenario is to evaluate if multimodality and DAR inside the study area could be a better option, and whether eliminating some of the existing feeder lines inside the zone would make sense. Nevertheless, due to the long running times of the simulation for multimodal assignment, this scenario will only explore 1 system configuration with 1 simulation run and a fleet size of $m_{DAR} = 30$ vehicles and a maximum wait target time of 20 minutes.

$$C_O = K_C \cdot C_{d_C} + K_M \cdot C_{d_M} + K_{DAR} \cdot C_{d_{DAR}} + \left(\sum_{i=1}^{m_{Bus}=8} \sum_{i=1}^{m_{DAR}=30} i \right) \cdot C_{m\ R\$/h} \tag{10}$$

5.6 Public Transport User Cost

The public transport user cost in its most simplified form is composed by the access, waiting, in-vehicle travel time, transfer time, and fare that a user incurs when using Public Transport. This generalized form is given by (11) were the β_k constant relates to the value of time β [R$/h] that a passenger of demand segment k attributes to one hour of time.

R$/trip

$$C_U = \beta_k (A + W + TT + \tau) + \theta \tag{11}$$

PTV Visum allows to obtain the previous cost components and more complex combinations of user costs to obtain the assignment of the network. Furthermore, in practice the user costs are assessed by calculation of skim matrices in PTV Visum and can be developed in a much more profound way. Skim matrices allow to calculate thus the costs or impedances of users to use public transport given the system characteristics. These types of matrices can be used to evaluate large sets and combination of factors that may affect user costs and choice of modes and routes (see Figure 33). Figure 33 show the calculation of the impedance of public transport assignment for the PTV Visum Curitiba model after shifting form a headway-baes to a timetable-based Public Transport assignment, this impedance is composed by the perceived journey time and the fare. Observe that the components of the perceived journey time (PJT) have different weights and portrait thus more or less cost related to what is perceived to be desirable from the user perspective.

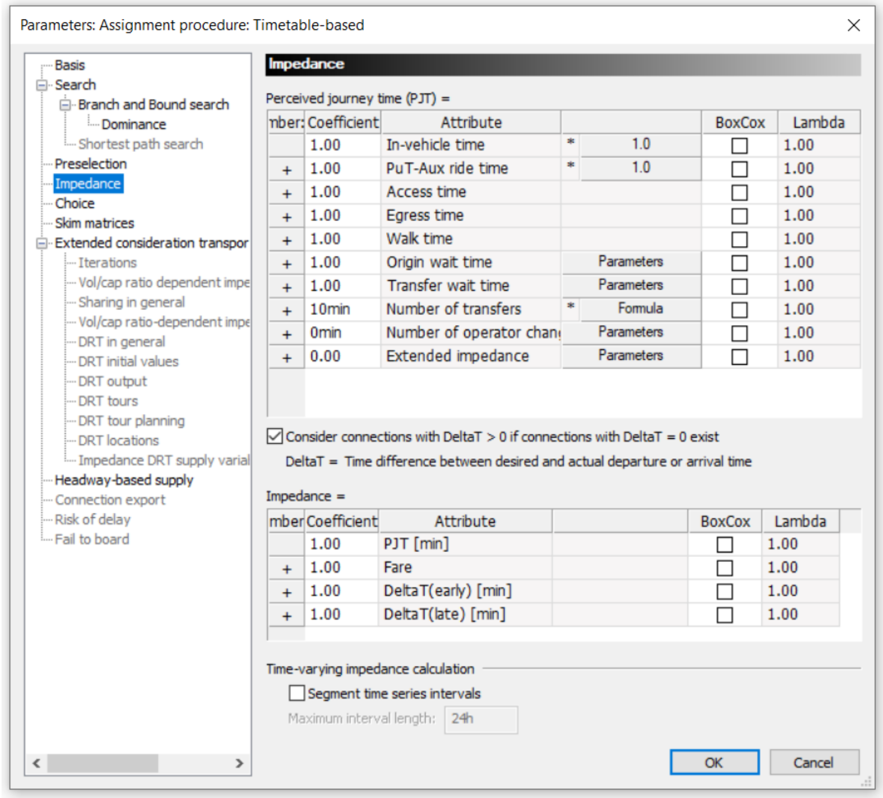


Figure 33. Parameters for impedance calculation of public transport timetable-based assignment in PTV Visum 2022.

In this degree project, the assessment of the user costs will be simplified and single components of the PTV Visum model will be extracted after running the assignment, in such a way it is possible to compare costs in a common unit [R$/h] by means of a generalized cost function for the system operation.

Expression (11) gives the simplified user cost for one single trip in the system with units [R$/h]. To obtain a generalized cost function and combine the user costs with the operator costs there are several approaches available, these approaches are further developed in section 6.2.

Due to the introduction of different mobility services in each scenario, the expression given in (11) takes a particular form for each one of the proposed scenarios, this is assessed by the following expressions. For this degree project the level of aggregation for user costs related to travel times will be based on links and zones. For scenario I the aggregation is done to the link level, such that the sum for costs of the links inside the zones of study and the costs of the fleets are obtained for the study area. On the other hand, the user costs related to travel times are aggregated at the zone level, while the collected fares are aggregated at the line level.

NOTE:

For scenario II, it should be noted that the level of aggregation for total and average user costs is obtained at the zone level. Furthermore, it is acknowledged that **while in reality the operator costs include the operation of all lines in the network**, and these lines contribute to the user costs inside the zones (travel times), **the focus of this degree project is on feeder lines**. The costs of the users will be aggregated in terms of zones where different type of lines operate, but the cost of the operator will only consider the operation of the feeder lines.

Base scenario

In the base scenario, users have only common fixed route buses to their disposal, such that the simplified costs of the users are given by:

$$C_U = \left[\sum_{i}^{N} \left((A_i + W_i + TT_i + \tau_i) \cdot \beta_k + \sum_{l=1}^{n} \Lambda_l \cdot \theta \right) \right]_{Bus} \tag{12}$$

Where the subscript i relates to the specific zone inside the area of study composed of a total number of N zones inside the area of interest, and n denotes the total number of feeder lines operating inside the zone. Furthermore, the Λ_i quantity is the total demand of carried passengers for zone i in one hour of operation of the system, and is a quantity given by the Public Transport assignment procedure of PTV Visum.

5.6.1.1 Scenario I (Ridesharing)

As mentioned previously, this scenario considers a modal shift from private car trips to ridesharing with no intermodal transport PuT-DRT or DRT-PuT. In this case, the total cost of the users will be given by the cost of the users using conventional Public Transport and the users using shared-taxi services. The cost of the PuT users is given simply by (12). Nevertheless, the cost of the ridesharing users is added now to the user cost, this latter contains some of the terms in (12) but does not consider transfers, and access and egress times since these are equal to zero. Additionally, it considers the km-based fares of the requested trips where the aggregation is not done in terms of links, but in terms of the number of requested DRT services during peak hour. Therefore, R in (13) accounts for the total number of requested services.

$$\begin{aligned} C_U = \quad & \left[\sum_{i}^{N} \Lambda_i \big((A_i + W_i + TT_i + \tau_i) \beta_k + \theta \big) \right]_{Bus} \\ & + \left[\sum_{r}^{R} \big((W_r + TT_r) \beta_c + \theta \big) \right]_{Ridesharing} \end{aligned} \tag{13}$$

5.6.1.2 Scenario II (Fixed route feeder + DAR)

In this scenario the users will be able to use both buses (all the existing n lines) as well as dial-a-ride services inside the defined service area. It should be noted that the dial-a-ride services under this scenario work as shuttle services serving interzonal trips inside the area of study. Furthermore, the aggregation of the user travel time related costs is done at the zone level (N total zones), while the fares are calculated at the line level (n existing lines)

$$C_U = \left[\sum_{i}^{N}\left((A_i + W_i + TT_i + \tau_i)\cdot\beta_k + \sum_{l=1}^{n}\Lambda_l\cdot\theta\right)\right]_{Bus} + \left[\sum_{i}^{N}\left((A_i + W_i + TT_i + \tau_i)\cdot\beta_k\right) + \sum_{c}^{C}((\Lambda_c)\cdot\theta)\right]_{DAR} \tag{14}$$

In the previous expression Λ_c denotes the demand served by DAR services, these trips are loaded into the network at the selected connectors which have been abled for DRT (see section 5.2). The remaining user costs in (14) are aggregated at the zone level as explained previously.

5.6.1.3 Scenario III (Reduction of feeder lines by dial-a-ride service and Intermodal assignment)

This scenario is an extension of scenario II (DAR) and is a consideration about the operation of dial-a-ride services inside the area of study. In this case, the initial set of 16 feeder lines operating inside the area of study is reduced by selecting 8 lines with low ridership inside the zone and eliminating them (see description in section 6.2). The user costs under this scenario have the same form as expression (14), but consider the elimination of the previously named lines.

5.7 Private Car User Cost

The private car user costs are simplified and account only for the travel time, the rolling costs associated to fuel consumption, and the parking costs associated to private car.

The private car user cost is given then by taking the cost produced by a combination of the previously mentioned metrics. The total cost is given by the following expression, where the sum of the costs for traveling in the set of k links inside the area of study is obtained by adding up the costs of the links inside the area of study.

$$C_C = \left[\sum_{i}^{k} TT_i\cdot\beta_C + K_i\cdot C_{R\$/km} + \tau_{parking}\right]_{Car} \tag{15}$$

Table 6. Equivalent metrics between analytic expressions and PTV Visum attributes

Metric	Analytic notation	PTV Visum Link Attribute
Traveled distance [km]	K_i	VehKmTravPrT (AP)
Traveled time [h]	TT_i	VehHourTravPrT (AP)
Speed [km/h]	v_i	VCur_PrTSys (C)

Finally, to obtain the previously mentioned simplified costs which have been developed in (15), it is necessary to have an equivalent between the analytic expression and the PTV Visum output attributes of interest. Therefore, Table 6 shows an equivalent between the interest metrics in (15) and the correspondent PTV Visum output attributes.

Private user costs base scenario

The $C_{R\$/km}$ accounts for the consumption factor of fuel per veh-km travelled and is a constant made on the following reasoning and assumptions:

Accounting for the private car fleet composition of the study zones see section 5.1, it is important to notice that the average vehicle inside the study area is on average 10 years old. Furthermore, regarding the socioeconomic income component attributed to the neighborhoods in the study area (see Figure 28) the typical vehicle of a household in the mid-income area can be assumed to be a passenger vehicle of small engine size with efficient fuel consumption. Therefore, in first instance, it is assumed that the consumption factor for a passenger-car vehicle inside the zone can be approximately derived by taking the average fuel consumption of a Chevrolet Corsa Classic 1.6 model 2008 operating in urban environment is $11km/l$ (Automobile Catalog, 2008) and an average of $7{,}283\ R\$/l$ price for fuel in Brazil in May 2022 (*Global Petrol Prices,2022*).

$$C_{\ R\$/km} = \frac{7{,}238\ R\$/l}{11km/l} = 0{,}662R\$/km \tag{16}$$

The $\tau_{parking}$ is a fixed quantity and will be assumed to be the cost that a car user will incur by parking a one-hour time when arriving to its destination. It should be remarket that although the study are is not inside the regulated-parking zone "EstaR- Estacionamento Regulamentado" it will be assumed that a minimum parking fare of 3 R$ (minimum parking fare of Zone 1) will be charged to each user parking inside the study zone (URBS, 2020).

The β_C quantity is the value of time of the car users $[R\$/h]$ which in this case will be assumed to be 38 $R\$/h$ based on an average user of mid-income group earning 5MMW of 1212 $R\$$/month and working 4 weeks per month with a work journey of 8 hours per day.

$$\beta_C = \frac{5 \cdot (1212\ R\$/month)}{160\ h/month} \approx 38R\$/h \tag{17}$$

5.8 Vehicle Costs and labor force costs

This section reports approximate values for the distance-based cost and fuel consumption of different type of vehicles based on literature review from different sources. Previously, expressions (6) to (10) introduced the distance-based cost $C_{d\,j}$ for type of vehicle type j, now these costs will be reported in monetary units per km traveled ($C_{\ R\$/km}$). Furthermore, the fuel consumption factor of vehicle type j CF_j [km/l] and other relevant emissions related values will be reported. It should be noted that the values reported here are average values for operation of vehicles in urban environments and are obtained from different sources. Therefore, the following values serve as guiding points, but can vary greatly with respect to real average values of the quantities of interest. The fuel costs used for the calculations of $C_{\ R\$/km}$ are $7{,}238\ R\$/l$ for common petrol (*Global Petrol Prices,2022*) and $7R\$/l$ of biodiesel (Quatro Rodas, 2022).

Table 7. Vehicles costs for selected vehicle types operating in feeder lines of the RIT. Made by the author.

Vehicle capacity [pax/veh]	85
Acronym	ConvTwo
MJ fuel/km	17.46
Fuel consumption biodiesel B7 [km/l]	1.86
C R$/km	**3.76**
Manuacturer	Caio Induscar
Chassis	Agrale, Man, Mercedes-Benz
Emission standard	Euro 5
g CO2/km Well-to-Wheel	1539

Vehicle type
Comum

Sources: (URBS, 2020), (Caio Induscar, 2022), (Dreier et al., 2018), (Sportbus.br, 2019)

Vehicle capacity [pax/veh]	85
Acronym	HybTwo
MJ fuel/km	17.46
Fuel consumption biodiesel B7 [km/l]	2.43
C R$/km	**2.88**
Manuacturer	Caio Induscar
Chassis	Agrale, Man, Mercedes-Benz
Emission standard	Euro 5
g CO2/km Well-to-Wheel	1071

Vehicle type
Microespecial

Sources: (URBS, 2020), (Caio Induscar, 2022), (Dreier et al., 2018)

Table 8. Vehicles costs for private vehicles and ridesharing vehicles analyzed under scenario I. Made by the author.

Vehicle capacity [pax/veh]	4
Model	Corsa 5p GLS 1.8
Year	2008
Fuel consumption [km/l]	11
C R$/km	**0.66**
Manuacturer	Chevrolet

Vehicle type
Passenger car

Sources: (Automobile Catalog, 2008)

Vehicle capacity [pax/veh]	4
Model	Corsa 1.2 (70) ecoFLEX (man. 5)
Year	2014
Fuel consumption [km/l]	15.62
C R$/km	**0.46**
Manuacturer	Opel

Vehicle type
Passenger car

Sources: (Automobile Catalog, 2014)

Table 9. Vehicles costs for assumed average minibuses operating dial-a-ride services in scenario II. Made by the author.

Vehicle capacity [pax/veh]	15
Model	Transit 410 L3 Minibus (14/15 seats)
Year	2018
Fuel consumption [km/l]	3.185
C R$/km	**2.27**
Manuacturer	Ford
Emission standard	Engine 2.2 125 PS HDT Euro 6
g CO2/km	196

Vehicle type
Minibus

Sources: (Ford, 2019),(Ford People Carriers GLP, 2021)

Labor force costs

With respect to the labor force costs (drivers’ salaries) it will be assumed that the each driver earns a minimum monthly wage of R$ 3000/month which is equivalent to the adjusted salary in April 2022 for a bus driver in Curitiba (this salary is reported to be the highest bus driver salary in Brazil) (Tribuna do Paraná, 2022) and that there is no cost associated to the auxiliary staff collecting the fares (Cobradores). A bus driver in Curitiba works 39 hours per week and four weeks per month (Tribuna do Paraná, 2022), which represents a total of 156 work hours per month, taking the minimum monthly wage and dividing it by the amount of worked hours per month, it is estimated that the cost of employing 1 driver per hour in Curitiba is approximately $\boldsymbol{C_{m\ R\$/h}} = \mathbf{19,23R\$/h.}$

5.9 Environmental costs

The environmental costs will be calculated based on the GHG emissions and pollutants produced by road base transport inside the study area. CORINAIR developed by the European Environment Agency (EEA) establishes an inventory of emissions of air pollutants form which certain methodologies to calculate estimates of GHG emissions generated by human economic-based activities can be calculated (EEA, 2007). Group 7 of CORINAIR focuses entirely on the emissions generated by road transport.

CORINAIR Road Transport develops several methodologies to calculate the estimate GHG emissions with different levels of accuracy. For this degree project, the simplified version of CORIANIR used to estimate global emissions for one country will be applied, this emission calculation is given by (18). It should be noted that the present analysis only considers the "Hot Emissions" which occur under conditions of thermally stabilized engine operation and are associated to fuel consumption.

$$E_{i,j} = \sum_{j} FC_j \cdot EF_{i,j} \tag{18}$$

Source: (EEA, 2007)

The grams of pollutant of type i from vehicle of category vehicle j $E_{i,j}$ [g pollutant i] in (16) is obtained by multiplying the fuel consumption of vehicle type j FC_j [kg fuel] by the fuel consumption specific emission factor $EF_{i,j}$ [g/kg fuel] (EEA, 2007).

The considered pollutants for this degree project are CO, NO_x, CH_4, PM, and CO_2 and are show in Table 10. Here it is assumed that based on the characteristics of the average 10 years old fleet of private vehicles inside the zone (see Table 5), it is assumed that the emissions associated to this can be approximately like those reported for Portugal in year 2005. Furthermore, the fuel consumption FC_j will be the one attributed to the average vehicle mention in section 5.7.

Table 10- Bulk emissions assumed for assessing environmental costs associated to road base transport. Source (EEA, 2007)

Table 4-18: Bulk emission factors (g/kg fuel) for Portugal, year 2005.

Category	Portugal					
	CO	NO_x	NMVOC	CH_4	PM	CO_2 [kg/kg fuel]
Gasoline PC	61.56	9.18	8.50	0.71	0.03	3.18
Diesel PC	3.20	11.28	0.57	0.04	0.72	3.14
Gasoline LDV						
Diesel LDV	9.39	17.91	1.72	0.11	2.05	3.14
Diesel HDV	7.14	34.09	1.14	0.24	1.04	3.14
Buses	11.88	40.75	4.18	0.31	1.85	3.14
Mopeds	403.89	3.62	360.25	6.55	6.32	3.18
Motorcycles	590.71	5.89	128.94	4.57	2.80	3.18

Shadow prices for pollutants

The cost of the reduction of pollutants will be based on the economics concept of shadow prices. This previous concept is used among other purposes to give a "real" price to goods which otherwise when priced in markets do not include the social costs associated to the externalities produced by their consumption. Shadow prices are used to cover the externalities thus of economic-based activities that can introduce externalities in society. In 2010 CE Delft (sustainability consulting group) published the

Shadow Prices Handbook (*CE Delft*, 2010). In this degree project, the shadow prices related to abatement *"marginal costs of securing standing environmental policy targets"* (*CE Delft*, 2010) will be adopted. These shadow prices are shown in the Annex (see Tabell 19)and are given in units of €/kg for the Netherlands in currency of 2008, these values will only be exchanged to $R\$$ and no inflation rate will be assumed, the converted values into $R\$$ are shown in Table 11.

Table 11. Shadow prices assumed for pollutants included in environmental costs. Based on "Shadow prices of emissions in the Netherlands in 2008 based on abatement costs (€2008/kg)". Source (CE Delft, 2010).

Pollutant	€/kg	R$/kg
CO	0,025	0,135
NO_x	8,72	47,088
CH_4	0,625	3,375
PM	2,3	12,42
CO_2	0,009	0,0486

Considering the previously mentioned pollutants, the environmental costs considered in the analysis of this degree project are given by (19) which is based on the obtained quantity of pollutants [kg] from the multiplication of the fuel consumption factor and the emission factor in (18), and the shadow price of the pollutant i given in the above shown table.

[R$/h]
$$C_E = \sum_j [CO + NO_x + CH_4 + PM + CO_2]_{kg/h} \cdot S_{i_{R\$/kg}} \tag{19}$$

Note: In the case of scenario II and scenario III, the calculated environmental costs will be only related to greenhouse gas emissions under the form of kg CO_2/h of operation of the system. The shadow price for kg CO_2 emitted is assumed to be R$ 0,5/kg.

6 Simulation results

In this section the results obtained for the two previously discussed studied scenarios are presented. Scenario I contemplates the introduction of ridesharing inside the area of study. Scenario II analyses the introduction of DRT under the form of dial-a-ride services which complement the public transport supply inside the area f study.

6.1 Scenario I

Scenario I analyses a reduction of 5% private vehicle based trips inside the area of study. A 5% reduction of intrazonal trips is equivalent to slightly more than 500 private car trips or to a demand density near to 15 pax/h-km2 generated during the morning commuting period (07:00-08:00) inside the study area, this previous quantity of trips is slightly larger than 3% of the total generated and attracted trips from (16604 car trips trips). The previous number of trips are assumed to be shifted to ride-sharing systems where users will share a ride which has a distance-based fare starting with 1R$ (fixed start price) and continues with a km-based fare of 1R$/km, the motivation to choose this values has been the recent readjustment of feed in ride-sharing services introduced by companies such as Uber, which in late 2021 readjusted its fares to R$ 1,03/km traveled due to the increase in petrol prices (TDN, 2021). The results of 10 simulation runs for the described operation of the system will be presented here and consequently analyzed afterwards in section 7.

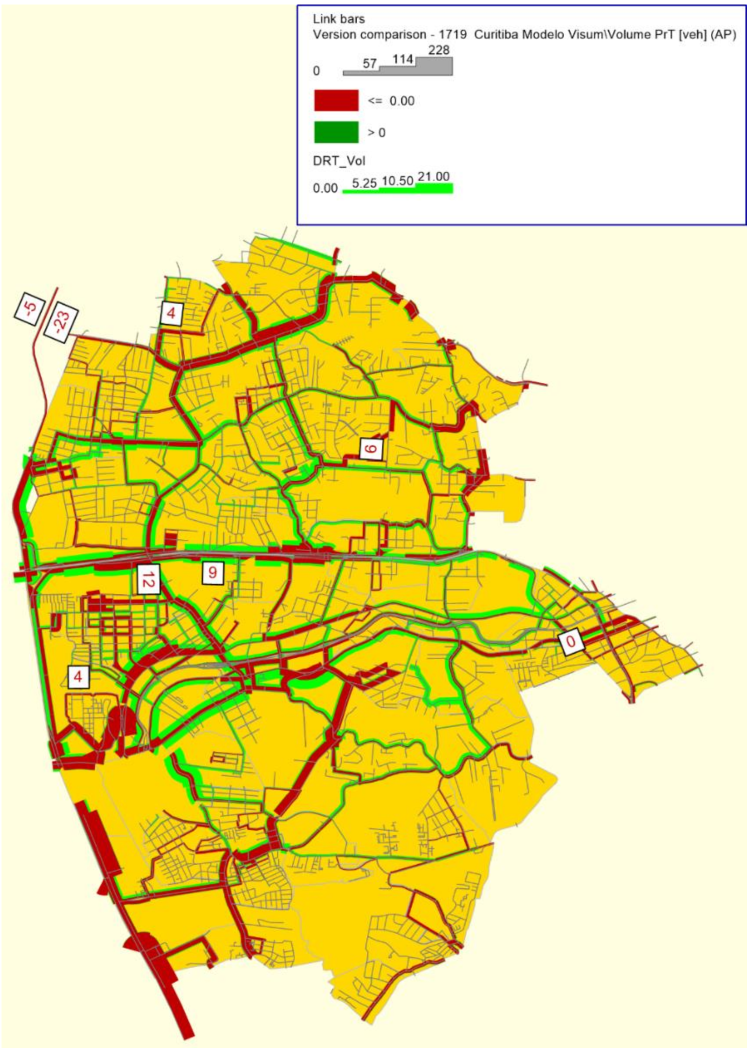


Figure 34. Traffic volumes reduction and DRT volumes (ridesharing) inside the study area for Scenario I simulation run No.2. Made by the author on PTV Visum 2022.

The discussed reduction of 5% of private car-based trips inside the zone produces a reduction in traffic volumes, but also the introduction of new volume of vehicles performing the operation of the ridesharing system. Figure 34 illustrates the reduction in volume of private vehicles per hour during the peak hour. The red bars represent the reduction in traffic volumes in the links of the network, while the green light green bars represent the new flows of DRT vehicles carrying passengers inside the area of study.

With respect to the results obtained in Scenario I, it should be noted firstly that the occupancy of the vehicles has been assumed to be high since the goal of this scenario is to evaluate a reduction in private car ridership. The distribution of the occupancy of the vehicles is assumed to be 3 pax/veh (50%), 2 pax/veh (33%), and 1 pax/veh (17%). The occupancy of the vehicles is an input parameter of the model (See Annex Figure 71) and can be regarded as an initial target to reduce car ridership inside the zone. Furthermore, a second important aspect that should be recalled again is the stochastic disaggregation of demand introduced in section 4.2.Due to the stochastic nature of the generation of trips (discrete and random in time and space) the trips generated inside the zones can have multiple several configurations, such as different PUDOs generation points (origins), different PUDOs attraction points (destinations), different times of request, and number of passengers requesting the service. This stochastic characteristic of the demand for the trip requests in turn modifies the operational costs of the system since the vehicles have different routes to serve different origin-destination demand at different times shown in the next figure.

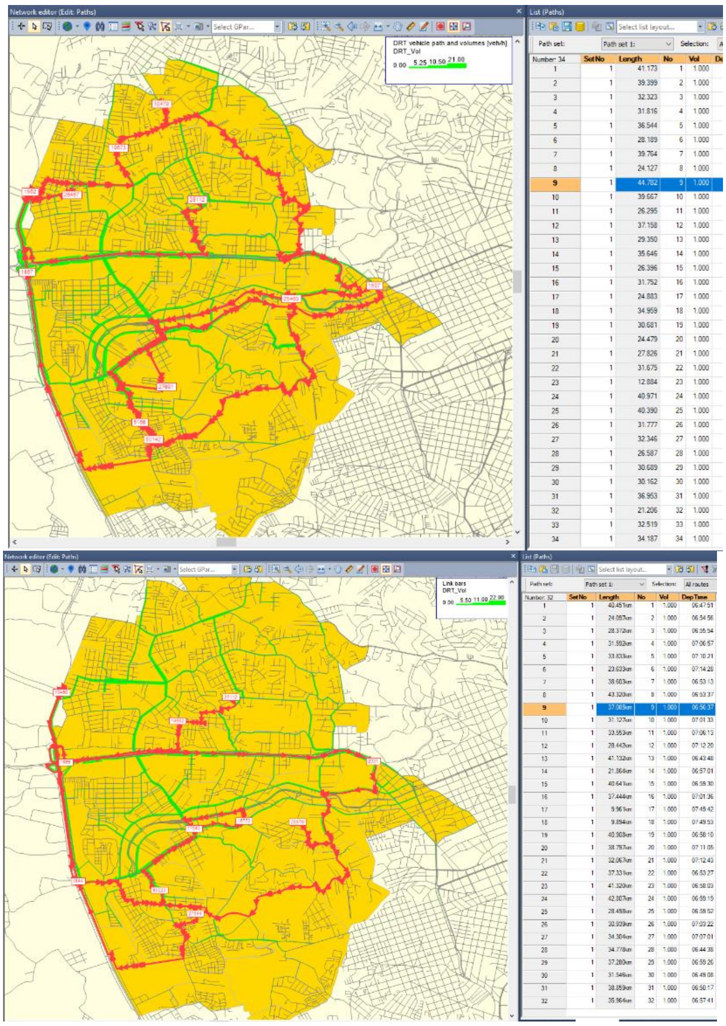


Figure 35. Screen shot showing different vehicle routes for vehicle No. 9 in simulation 2 and simulation 9.

The environmental costs of the system are calculated following straightly the expressions of section 5.9, and the assumption of private vehicle types discussed in sections 5.7 and 5.8.

The costs of the users are calculated following expression (15) and using the corresponding values assumed for the value of time per hour. For both private car and ridesharing vehicles, the prices of petrol are the same as reported in section 5.7.

Finally, the most important assumption to notice about the results obtained for the system in Scenario I is the one made about the cost of workforce (drivers' salaries) for operation of the ride-sharing system. It is assumed that the operation of the system is profitable for the operator or ridesharing /ride-hailing platforms offering the service, such that the drivers receive a wage paid per hour equivalent to the hourly wage of a bus drivers of the RIT in Curitiba. This previous assumption does not hold in many countries. Ridesharing or ride-hailing platforms connect users and drivers by means of a platform adapting different business models, where the most common form of revenue is to take a cut on the drivers' earnings. It should be noted that the established km-based fare of 1 R$/km travelled is similar to those established by ride-sharing platforms such as Uber in Brazil) (TDN, 2021). Nevertheless, it is worth mentioning that although the model includes the distance-based fare and an initial fare of 1 R$ to start the service, it does not include additional fees that ride-sharing/hailing platforms usually have such as booking fares, minimum fares, fare per minute, or cancellations fares (see Figure 73 in the Annex for the additional fees of requesting a ride-sharing service with Uber in Curitiba).

Considering the previously mentioned assumptions and characteristics of the model, the global cost function for the evaluation of system costs is given by(20), which sums up the different components of the operator costs, private car user costs, the ridesharing user costs, and the environmental costs respectively. The units of both (20) and (21) are R$/h.

$$C_{total\ I} = C_O(8) + C_C(15) + C_U(13) + C_E(19)$$

$$\begin{aligned} C_{total\ I} \quad = & \left[\sum_{l}^{m} K_l \cdot C_{\frac{R\$}{km}} + m \cdot C_{m\frac{R\$}{h}}\right]_{Ridesharing} \\ & + \left[\sum_{i}^{k} TT_i \cdot \beta_C + K_i \cdot C_{\frac{R\$}{km}} + \tau_{parking}\right]_{Car} \\ & + \left[\sum_{r}^{R} \left((W_r + TT_r)\beta_c + \theta\right)\right]_{Ridesharing} \\ & + \left[\sum_{j} (CO + NO_x + CH_4 + PM + CO_2)_{\frac{kg}{h}} \cdot S_{i\frac{R\$}{kg}}\right] \end{aligned} \tag{20}$$

And the function cost for the base scenario,

$$C_{total\ BS} = C_C(15) + C_E(19)$$

$$\begin{aligned} C_{total\ BS} = & \left[\sum_{i}^{k} TT_i \cdot \beta_C + K_i \cdot C_{\frac{R\$}{km}} + \tau_{parking}\right]_{Car} \\ & + \left[\sum_{j} (CO + NO_x + CH_4 + PM + CO_2)_{\frac{kg}{h}} \cdot S_{i\frac{R\$}{kg}}\right] \end{aligned} \tag{21}$$

With respect to (20) and (21) it should be noted that the costs of operation of the Public Transport System have not been included since this scenario only evaluates a shift from private car to ridesharing. $C_{total\ I}$ stands for the total cost of the system of scenario I and $C_{total\ BS}$ stands for the total cost of the base scenario.

6.1.1 Travel times

The travel times have been evaluated based on total travel times in hours on links inside the area of study and the costs associated to these travel times considering the value of time private car users discussed in section 5.7. Since the disaggregation of demand is a stochastic process, 10 simulation runs have been executed to evaluate different travel times generated by the same aggregated OD demand. When this demand is disaggregated at different time points (trip requests and desired departure time) and at different origin and destinations (different combinations of PUDOs), different travel times and costs are produced for the system.

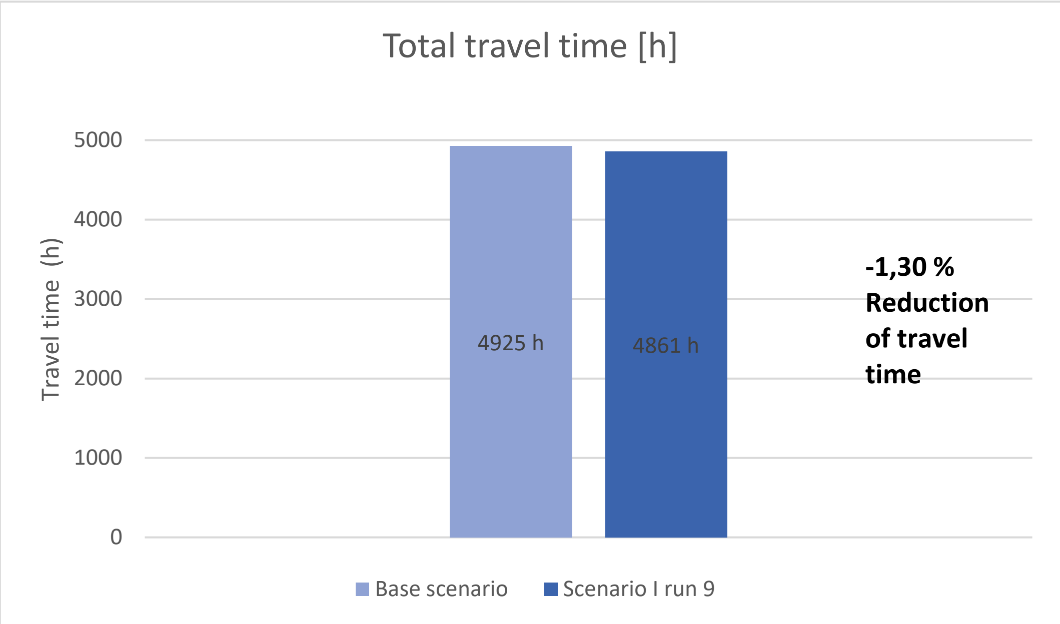


Figure 36. Travel time comparison between base scenario and scenario I simulation run No. 9. Made by the author.

Figure 36 shows the comparison of total travel times inside the study area between the base scenario and the simulation run which generated the best results (simulation run No. 9). In this case a reduction of 1,30% in travel times inside the area of study was achieved. Nevertheless, across multiple simulation runs, the travel times vary and produce different system costs as shown in the boxplot in Figure 37.

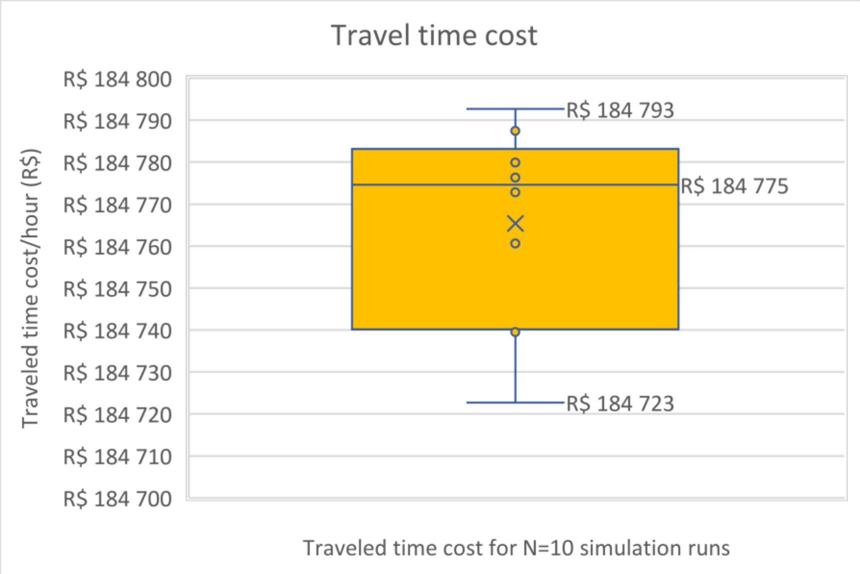


Figure 37. Travel time cost for multiple simulations runs. Made by the author.

6.1.2 Travel distances

The travel distances are evaluated based on the total travel distance in km inside the area of study. Same as with the travel times, the stochastic disaggregation of demand generates different vehicle paths to serve the demand in Figure 35, these vehicle paths modify the costs of the system and vary depending on the geographical allocation of requested trips, the request times, and the allowed detour factors for picking up and dropping off passengers.

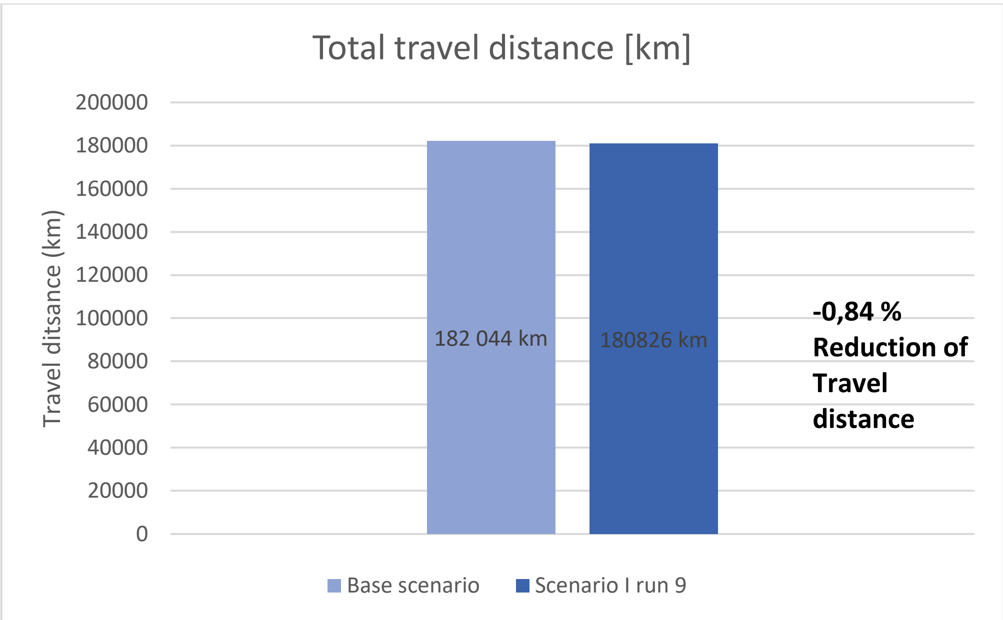


Figure 38. Travel distance comparison between base scenario and scenario I simulation run No. 9. Made by the author.

The above shown travel distances concern the comparison between the base scenario and the simulation run which generated the best results (simulation run No. 9). In this case a reduction of 0,84% in travel distances inside the area of study were achieved. Nevertheless, across multiple simulation runs, the travel distances vary and produce different system costs associated to the fuel consumption generated, these costs are shown in the boxplot in Figure 39.

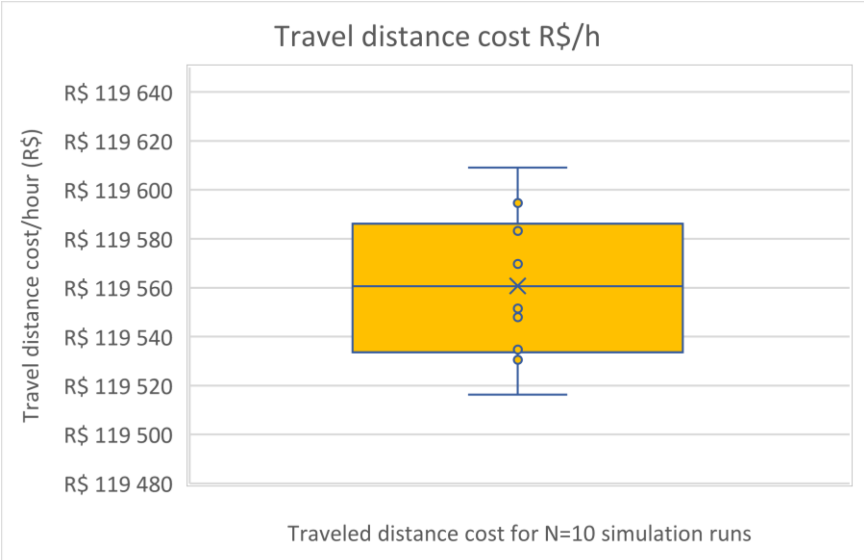


Figure 39. Travel distance cost for multiple simulations runs. Made by the author.

Furthermore, regarding the travel distances, an additional level of aggregation is relevant for assessing the costs of the system. While Figure 39 concerns the total travel distance costs of the area of study, the distance in km traveled by the ridesharing fleet is an important quantity for assessing the financial sustainability of the system. Therefore, Figure 40 shows the costs associated to the travel distances performed by the ridesharing fleet of vehicles across 10 simulation runs, these distances are performed by a fleet of size $m = 35$ vehicles passenger vehicles with distribution of occupancy of passenger inside the vehicles as the ones described in the introductory section of this scenario, it is clear that the ridesharing traveled distance varies largely with respect to the stochastic disaggregation of demand in the zones. The previous variability in stochastic demand also generates a partial use of the total fleet which can be appreciated in Table 22 in the Annex, this table shows how the use of the fleet can vary between 32 vehicles being used to a maximum of 35 vehicles depending on the characteristics of the demand in the study area. Nevertheless, regardless of whether the whole fleet (35 vehicles) has been used or not, the workforce of 35 drivers has been kept constant, which implies that the workforce costs (drivers' salaries) have remained constant for the computation of the system costs across all the simulation runs. Finally, Figure 41 represents simply the translation of travel distances in Figure 40 to monetary costs in R$/h which result from the multiplication of the travel distances of the ridesharing fleet by the rolling-distance cost $C_{R\$/km}$ of the vehicle introduced in section 5.8.

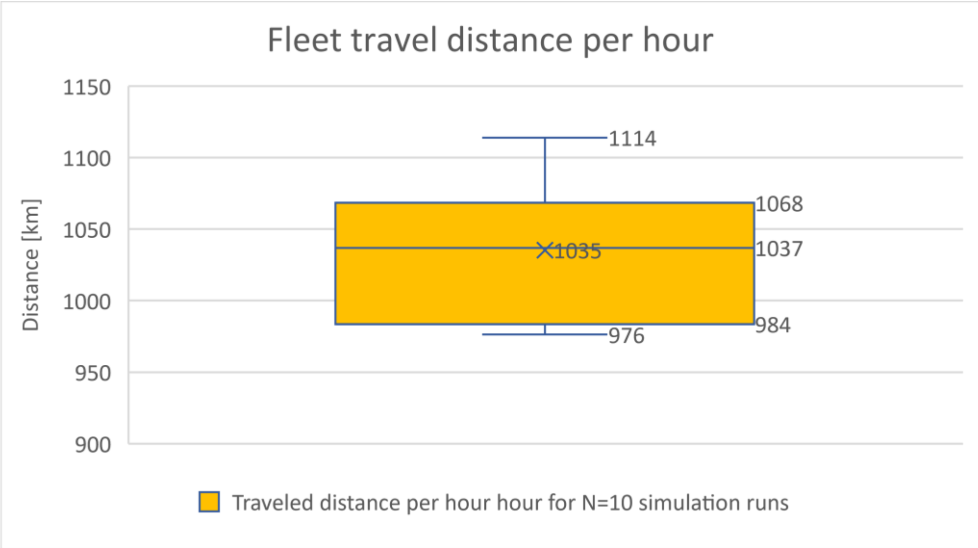


Figure 40. Fleet travel distance per hour for multiple simulation runs. Made by the author.

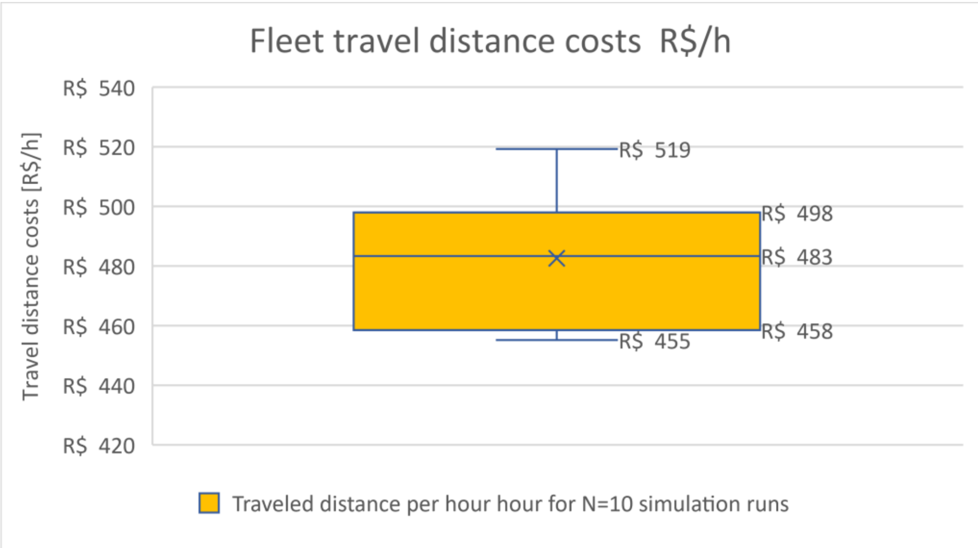


Figure 41. Fleet travel distance costs for multiple simulation runs. Made by the author.

6.1.3 Collected ridesharing fares and financial sustainability of the system

The collected ridesharing fares serve as a proxy for financial sustainability and profitability of the system. Although, as mentioned previously, scenario I only analyses the travel distance costs (fuel consumption) for the operator, it is considered that paying special attention to the variability of the collected fares is important from both the operator's and the user's perspective. Same as with the travel times and travel distances, the stochastic disaggregation of demand generates different vehicle paths to serve the demand (see these vehicle paths generate different travel distances which affect the km-based fares paid by users.

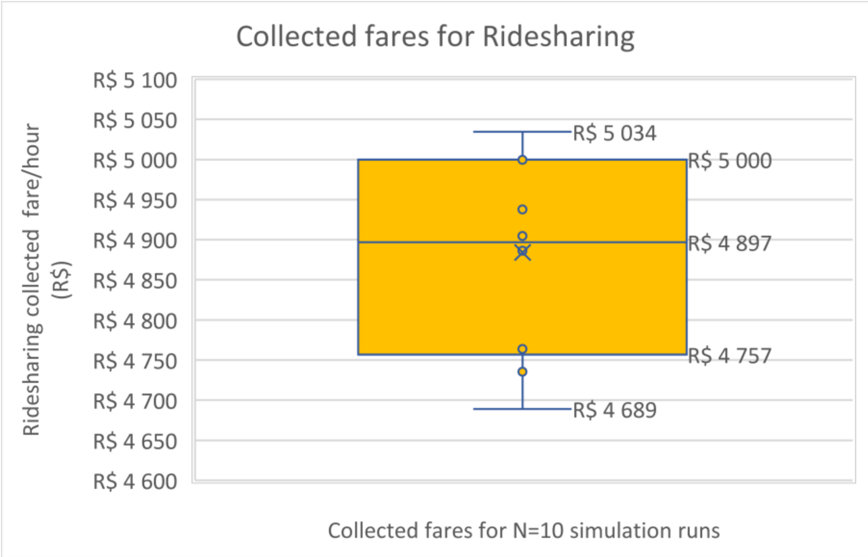


Figure 42. Collected fares by ridesharing system for multiple simulation runs.

The boxplot in Figure 42 shows the different collected fares by hour of operation of the ridesharing system across 10 simulation runs. These collected fares can be directly linked to the travel distances in Figure 40 and the correspondent travel cost in Figure 41. Furthermore, recalling that the workforce costs are assumed to be constant and equal to R$ 673/hour (cost of 35 drivers per one hour of operation of the system, see description in section 5.8), if the average costs associated to fuel consumption in Figure 41 (which in average represent a cost of R$ 483/hour) are added to the average costs of labor force for the system, then an average cost of R$ 1256/hour for the operator of the system (only including labor force and rolling-distance costs) is obtained, this cost is fully covered by the average R$ 4 884/hour fares collected. The system leaves therefore on average a margin of approximately R$ 3 728/hour, this previous margin could be in principle used to cover costs that have been obviated in the simplified analysis of Scenario I such as acquisition costs, insurances, depreciation of the vehicles, lubrication oil, or maintenance of the vehicles among other costs.

6.1.4 Environmental costs

The environmental costs of the system have been obtained following the methodology introduced in section 5.9, this section introduced the methodologies developed by CORINAIR with respect to road transport based emissions (EEA, 2007). **It should be noted that the environmental costs for private vehicles estimated here are based on fuel consumption averages and bulk emission factors based on several assumptions (see section 5.9). The big reduction in environmental costs is explained mainly by one single cause: the vehicle type assumed for the operation of the ridesharing services**. More in depth, the socioeconomic characteristics of the area of study collected for the survey origin-destination of Curitiba revealed that on average the vehicle owned inside the area of study were at least 10 years old back in 2017 (see Table 5). Therefore, the vehicle introduced in section 5.7 (Chevrolet Corsa Classic 1.6 model 2008) was assumed to be the average vehicle for the private vehicle calculation of emissions. Nevertheless, modern ridesharing/ride-hailing platforms only allow drivers who own vehicles which match certain requirements to be riders and offer the service. As a departing point, it has been found that the oldest year a vehicle can be when operating for Uber in Curitiba is 2013 (Uber Brazil, 2022). Therefore, without losing generality, the same vehicle model from year 2014 was assumed for ridesharing (Opel Corsa 2014) which is included in the list of allowed vehicles (Uber Brazil, 2022).

6.1.5 Total system costs

The assessment of the total costs of the system is made on the average of 10 simulation runs for the ridesharing system with the characteristics described in the previous sections of this scenario is shown in Figure 43. The ridesharing system succeeds to minimize the total system costs by a relative difference of 1.28%. Furthermore, it should be noted that the strong reduction in environmental costs of for scenario I is due to the assumption of the composition of the fleet of ridesharing vehicles. Another important aspect that should be considered and partially included in the model is the reduction in use of public space taken by private cars.

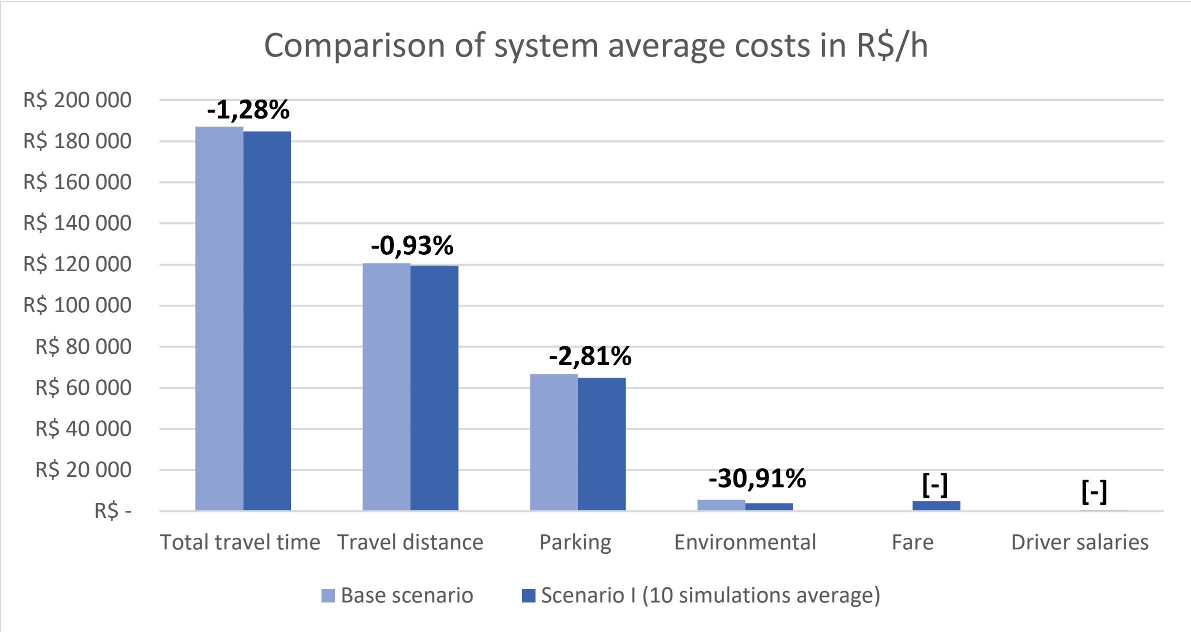


Figure 43. Comparison of system costs and relative differences in costs for scenario I (ridesharing). Made by the author.

6.2 Scenario II

This scenario evaluates the introduction of dial-a-ride services in the public transport supply inside the area of study. As explained previously, in section 5.5.3, the operation of the system is done by the existing bus lines inside the area of study and complemented by the introduction of dial-a-ride (DAR) services with vehicles of small capacity (15 pax/veh) as the ones shown in

Table 9. Considering the research done by Currie and Fournier (2020) about the failure of DRT systems, the preferred structure coded for this new service is to operate under a few-to-few (shuttle) configuration where users are transported from origin zones to destination zones without considering intermodal transport, users book their trips before-hand up to a maximum time before the desired departure of the service (5 minutes hold constant for all services). From the modelling point of view a few-to few configurations is achieved through loading the demand for DRT services at the level of the private mode connectors in PTV Visum see Figure 44, these connectors which connect the demand of zones to the links/physical infrastructure of the network or vice versa, can exist therefore from zone to node or from node to zone, and there are different ways to code them in the model. The current PTV Visum model features connectors which start/end at the geographical centroid of the in-question zone, it is from these or to connectors that the DRT demand will be loaded in the model. Therefore, the nodes starting or ending at these connectors will be passenger pick-up or drop off point (PUDOs) and are part of the set of nodes with the user defined attribute "PUDO2" = 1, "PUDO 2"is used in order to differentiate these PUDOs from the ones created in scenario I. Considering this previous information, under scenario II, the model simulates the travel behavior of users having at their disposal the existing bus lines inside the area of study and DRT dial-a-ride services under a commute period of analysis of 4 hours in the commute peak period (07:00-11:00). Users can book trips from/to one PUDO inside the area of study to all other PUDOs in the same area (see Figure 45. Pick up and drop off points for dial-a-ride service and main bus lines inside the area of study. Screenshot of PTV Visum model. Made by the author.).

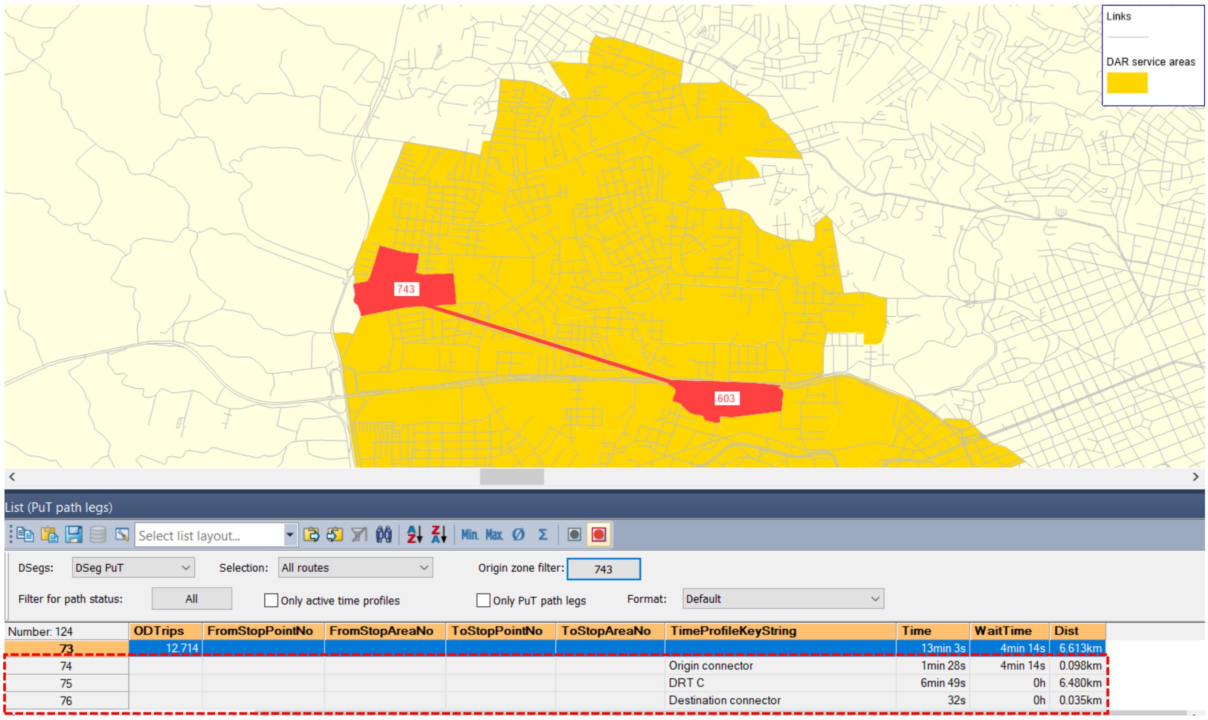


Figure 44. DRT demand loaded into the network for origin zone 743 and destination zone 603. Screenshot of PTV Visum model.

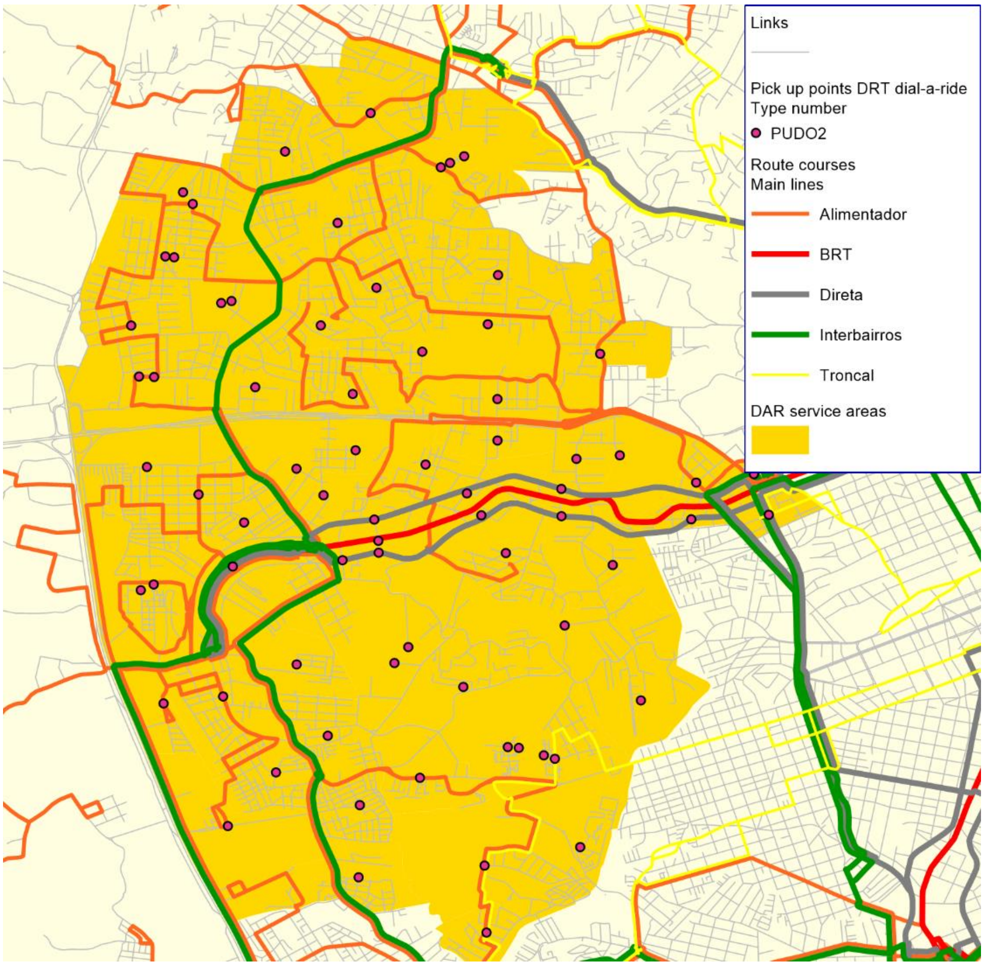


Figure 45. Pick up and drop off points for dial-a-ride service and main bus lines inside the area of study. Screenshot of PTV Visum model. Made by the author.

To evaluate the results of the model, a form of generalized or total cost function is required to be developed such that a comparison between the system costs of the modification to the system can be assessed with respect to the base model. Expression (11) in section 5.5.1 introduced the simplified user cost for one single trip in the system with units [R$/h]. To obtain a generalized cost or a total cost function and combine the user costs with the operator costs there are several approaches available. Three approaches are identified and described here.

1. ***Average cost per passenger carried in the system*** **[R$/pax-h]**
   This approach divides the total cost of the operator in (6) by the total demand of the system given in units of pax/h, such that an average cost per passenger carried in the system is obtained [R$/pax-h]. Then subsequently, by taking the mean user costs in terms of average travel times in hours [h] and multiplying them by the β_k value of time of a user [R$/h], a combined cost function in units of [R$/pax-h] is obtained.
2. ***Total system costs in*** **[R$/h]**
   This approach sums up over all the costs in (11) obtaining thus the total travel time (access/egress, waiting, in-vehicle, and transfers time) of the system in [h], then this time which in [h] units is multiplied by the β_k value of time of a user [R$/h] such that the total costs of the users (whole demand) in [R$/h] is obtained, then the fare is added by multiplying the total demand of the system by the cost of the fare. Finally, the costs of the operator are obtained

in [R$/h] and added to the previously described user costs, by which a generalized cost function in units of [R$/h] is obtained, the denominator "h" relates to one hour of operation of the system.

3. ***Total system costs in* [h]**
   This approach converts the total costs of the system to equivalent units of hours. The travel times remain unchanged in hours, and the costs of the operator and fares are converted into [h].

This degree project will give priority to the comparison in terms of total system costs. Considering the operator, user, and environmental costs associated to the operation of the system under scenario II (see sections 5.4 to 5.6) the following generalized cost function is obtained.

$$C_{total\,II} = C_O(9) + C_U(14) + C_E(18)$$

$$\begin{aligned} C_{total\,II} = & \left[K_C \cdot C_{C\frac{R\$}{km}} + K_M \cdot C_{M\frac{R\$}{km}} + m_{Bus} \cdot C_{m\frac{R\$}{h}}\right]_{Bus} \\ & + \left[K_{DAR} \cdot C_{d_{DAR}} + m_{DAR} \cdot C_{m\frac{R\$}{h}}\right]_{DAR} \\ & + \left[\sum_{i}^{N}\left((A_i + W_i + TT_i + \tau_i) \cdot \beta_k + \sum_{l=1}^{n} \Lambda_l \cdot \theta\right)\right]_{Bus} \\ & + \left[\sum_{i}^{N}\left((A_i + W_i + TT_i + \tau_i) \cdot \beta_k\right) + \sum_{c}^{C}\left((\Lambda_c) \cdot \theta\right)\right]_{DAR} \\ & + \left[CO_{2\frac{kg}{h}} \cdot S_{i\frac{R\$}{kg}}\right]_{Bus} + \left[CO_{2kg/h} \cdot S_{i_{R\$/kg}}\right]_{DAR} \end{aligned} \tag{22}$$

And the correspondent cost function for the base scenario:

$$C_{total\,BS} = C_O(9) + C_U(12) + C_E(40)$$

$$\begin{aligned} C_{total\,BS} = & \left[K_C \cdot C_{C\frac{R\$}{km}} + K_M \cdot C_{M\frac{R\$}{km}} + m_{Bus} \cdot C_{m\frac{R\$}{h}}\right]_{Bus} \\ & + \left[\sum_{i}^{N}\left((A_i + W_i + TT_i + \tau_i) \cdot \beta_k + \sum_{l=1}^{n} \Lambda_l \cdot \theta\right)\right]_{Bus} \\ & + \left[CO_{2\frac{kg}{h}} \cdot S_{i\frac{R\$}{kg}}\right]_{Bus} \end{aligned} \tag{23}$$

Both (22) and (23) have units of [R$/h] and only environmental costs related to GHG emissions in the form of produced kg of CO_2 by bus and dial-a-ride fleets are calculated, these calculations are made based on the simplified emission methodology of CORINAIR (EEA, 2007). In the case of dial-a-ride minibuses the correspondent emission factor is the one reported by the manufacturer (see Table 16 in the Annex). On the other hand, the emission factors of CO_2 for feeder bus lines are the ones reported by Dreier et al. (2018) and are based on a Well-to-Wheel analysis of different bus types and their energy efficiency in some corridors of the RIT in Curitiba. Furthermore, **the value of time of public transport users is assumed to be the same as the value of time of the bus drivers (19,23 R$/h)**, and the **dial-a-ride service is assumed to have the same fare as the public transport fare of the RIT (5,50 R$)** (URBS, 2020).

Another important aspect when introducing the new dial-a-ride service is the choice of users for available public transport supply. In this context, it should be noted that the introduction of the new DRT dial-a-ride services affects the Public Transport assignment of the network, since there are new connections possible, these need to be assessed to determine the change in users' impedances. A change in impedances implies a change in the utility of public transport users when choosing a particular connection. This previous fact in turn modifies the ridership of lines inside the zone since new connections from/to the zones inside the area of study are created by the introduction of the new service. The (by default) impedance calculation parameters for timetable-based assignment of PTV Visum 2022 (see Figure 74 in the Annex) have been used for the calculation of the impedance, as well as the parameters for the choice model (Kirchhoff).

Finally, the most relevant aspect about the characteristics of the system under modification in scenario II is the one related to the size of fleet size and the target level of service attended by the service. Previously, the literature review discussed the interests of the operator when offering dial-a-ride services and emphasized that according to Daganzo & Ouyang (2019a, 2019b), "***the aim of the operating agency is to maintain a desired level of service*** **(target maximum waiting time)** ***and reduce the cost associated to the fleet size m"*** (the bigger the fleet, the bigger the operational cost due to rolling costs, and wages of the drivers among others). Therefore, in scenario II the design of the system with respect to these two decision variables have been assessed. By performing a search inside some points of possible system configuration shown in Figure 46,some of the possible configurations and correspondent costs of the system are evaluated and shown in the next sections. It should be noted that not all the points inside the grid in Figure 46 provide a feasible solution for design of the system, and that the approach developed here is not concerned with finding the optimal solution of the design of the system with respect to the two key decision variables (this could be done by an exhaustive grid search for example, or by more sophisticated methods), due to the long to the long run times needed to execute and run the procedure sequence to calculate the PuT assignment, the scope of search for configurations of the system has been limited, and falls under the scope of future work. Configurations with longer maximum target waiting times ($Tmax = 15\ min$ to $Tmax = 25\ min$) have been run for larger fleet sizes under first instance, but the larger fleet sizes shown in Figure 46($m = 30$ to $m = 40$) are sufficient to provide an outstanding level of service with maximum target waiting time $Tmax = 10\ min$, however the operator costs and the costs of the system increment largely with such high fleet sizes. It should be acknowledged that the trajectory of search show by the red arrows in Figure 46 is not aiming to obtain a minimum cost, but rather to evaluate the performance and costs of the system with different combination of decision variables, and showing how after some point it is not desirable from a societal perspective to increment the fleet sizes, since the system costs start to increase instead of decreasing.

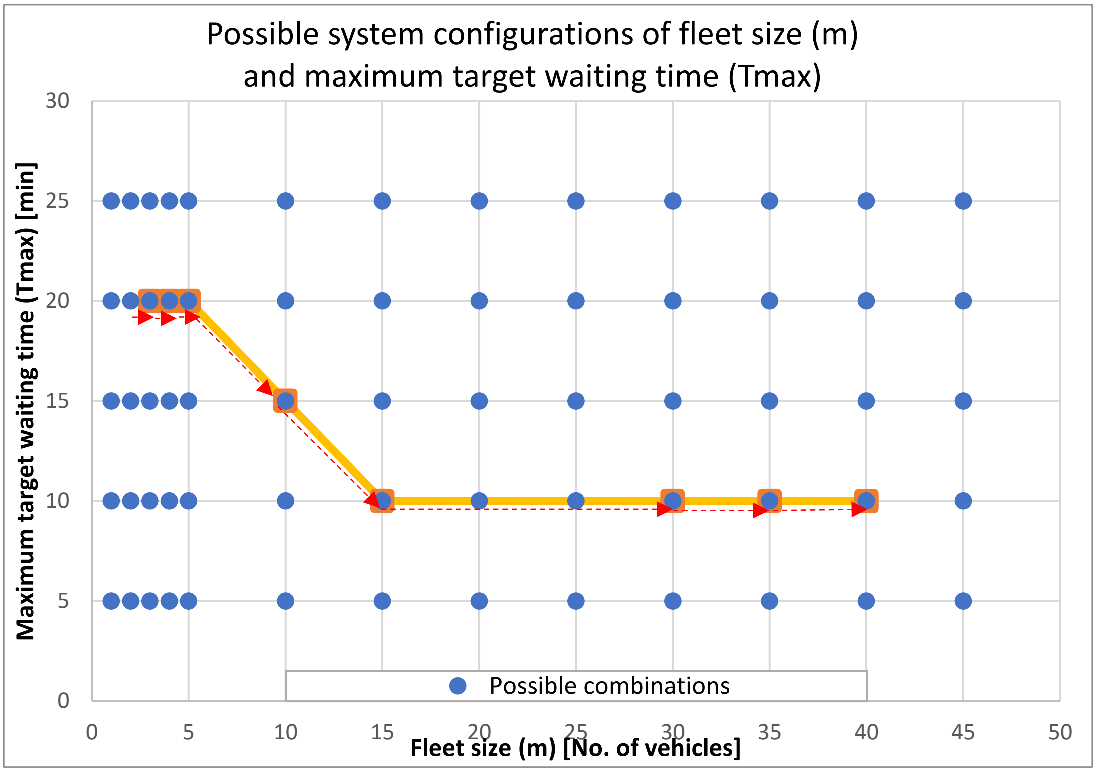


Figure 46. simulated configurations of the key decision variables of the system (fleet size and maximum waiting time). Made by the author.

Both user costs and operator costs will be assessed as groups with respect to maximum target wait times (level of service) aimed to be provided by the operator and will thus follow the same order as the trajectory shown by the red arrows in the figure above.

6.2.1 User costs

In this section the user costs associated to the total in-vehicle travel time, the total wait transfer time, and the total access time will be shown according to the selected configurations of the system given in Figure 46. The aggrupation of the figures is done by maximum target waiting time, this latter is a proxy for the desired level of service (LOS) that the operator aims to provide to the average user. Generally, a total reduction of the system total costs is achieved since the users' riding, waiting, and access times are reduced by the introduction of the new dial-a-ride service. Nevertheless, the operators cost increase dramatically, as the fleet size increases.

Users in-vehicle travel time

Figure 47 and Figure 48 show how by increasing fleet size, the in-vehicle travel times of user are reduced in general. This last result comes as no surprise since by offering more transport supply, the user is provided a better level-of-service, which is reflected in the reduction of the in-vehicle travel times. Nevertheless, by inspection of Figure 47 and Figure 48 it can be seen that the users in-vehicle travel times are not significantly reduced by increasing the fleet size, this previous fact suggests that the demand for the service can better and more optimally served by a small fleet of 3 to 5 vehicles. Furthermore, this las statement is also supported by the results of the maximum target waiting time of $Tmax = 10\ min$ and the larger fleet sizes coded in the model and shown in Figure 48, the increasing fleet size does not seem to produce a significant reduction in users in-vehicle travel times.

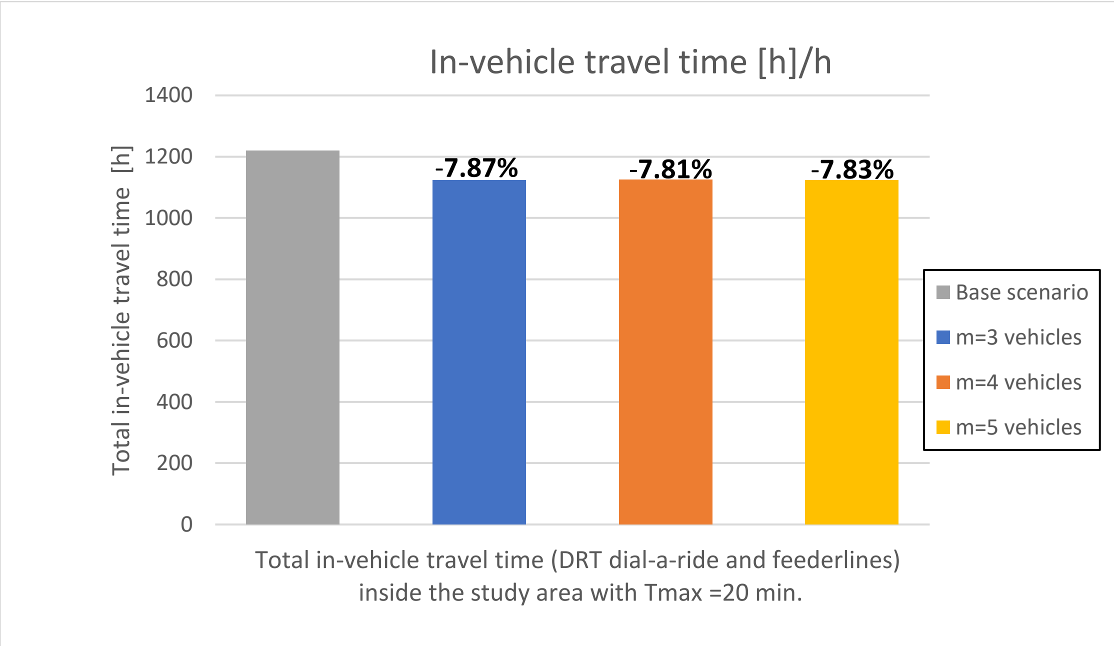


Figure 47. User in-vehicle travel times with maximum target waiting time Tmax = 20 min. Made by the author.

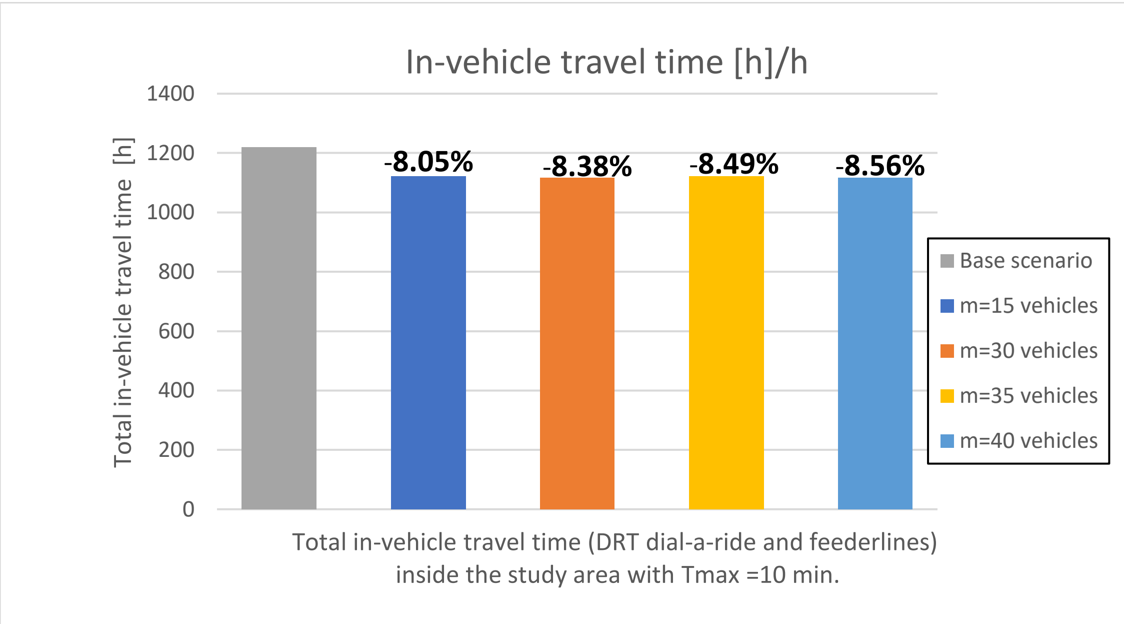


Figure 48. User in-vehicle travel times with maximum target waiting time Tmax = 10 min. Made by the author.

Users transfer wait time

Same as in the case of in-vehicle travel time, Figure 49 and Figure 50 show how by increasing fleet size, the users transfer wait time is reduced in general. Again, by offering more transport supply, the user is provided a better level-of-service, which is reflected in the reduction of transfer wait times. Moreover, the transfer wait times are strongly reduced due to the configuration of the system which offers dial-a-ride services with intrazonal origins and destinations and no transfers (see Figure 45). The system reduces the total number of transfers and therefore the total transfer wait time. It should be noted again that increasing the fleet size does not significantly reduce the total transfer wait time.

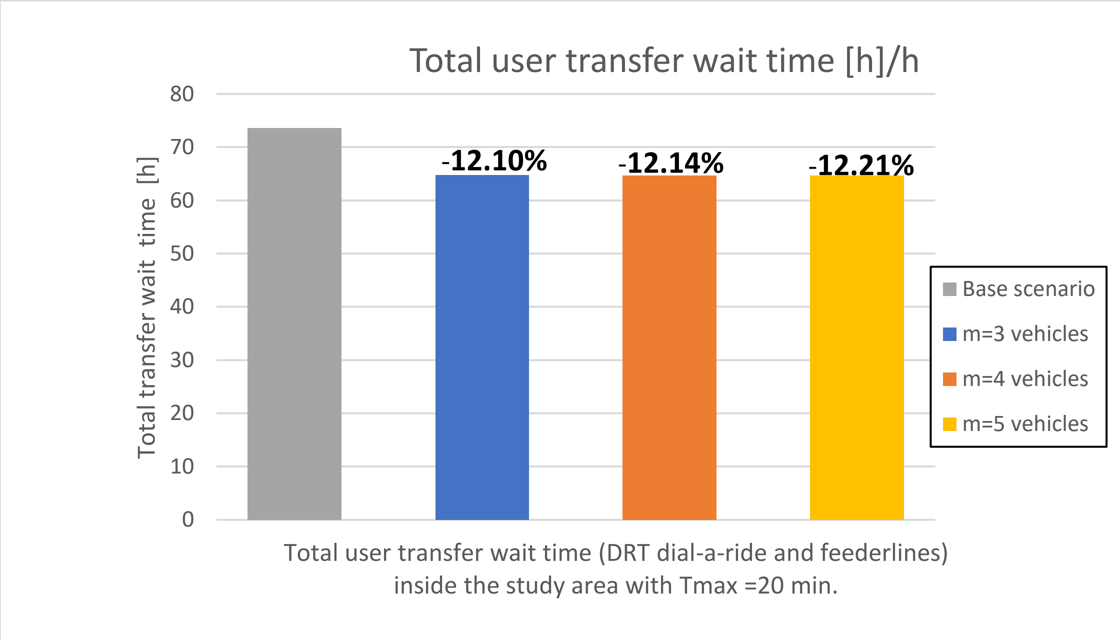


Figure 49. User transfer wait times with maximum target waiting time Tmax = 20 min. Made by the author.

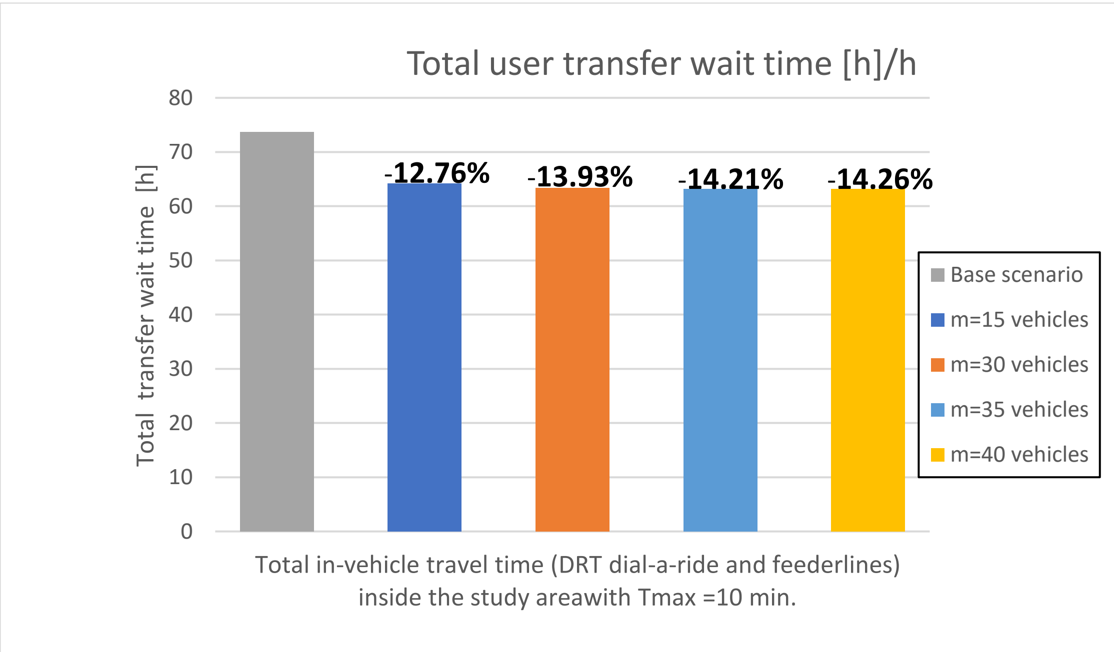


Figure 50. User transfer wait times with maximum target waiting time Tmax = 10 min. Made by the author.

Users access time

Figure 52 show how by increasing fleet size, the total user access time is reduced in general. The user access time is reduced due to the configuration of the system which offers dial-a-ride services with intrazonal origins and destinations that can be booked at the PUDOs in Figure 45. The system works as a dial-a-ride service with no transfers and can be accessed in several locations, this may be the cause of reduction in accesss time. Finally, Figure 51 shows that increasing by a small amount the fleet size does not reduce at all the total access time, this may be attributed to the fact that the demand for the service (derived from the impedance of users) can be served with a fleet size $m = 3$, adding additional vehicle to the fleet does not generate any positive effect for the system.

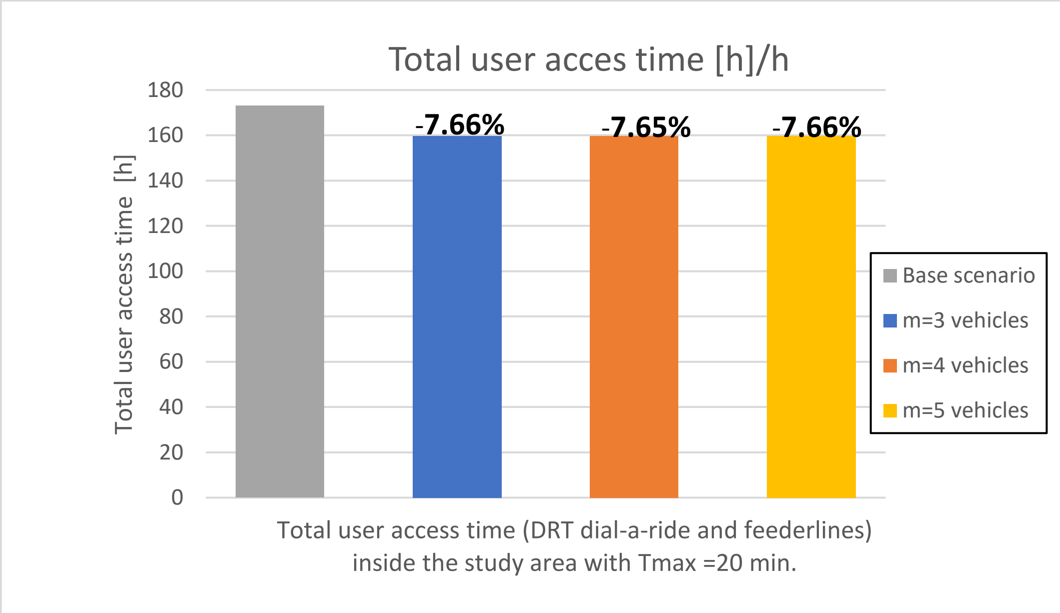


Figure 51. User access time with maximum target waiting time Tmax = 20 min. Made by the author.

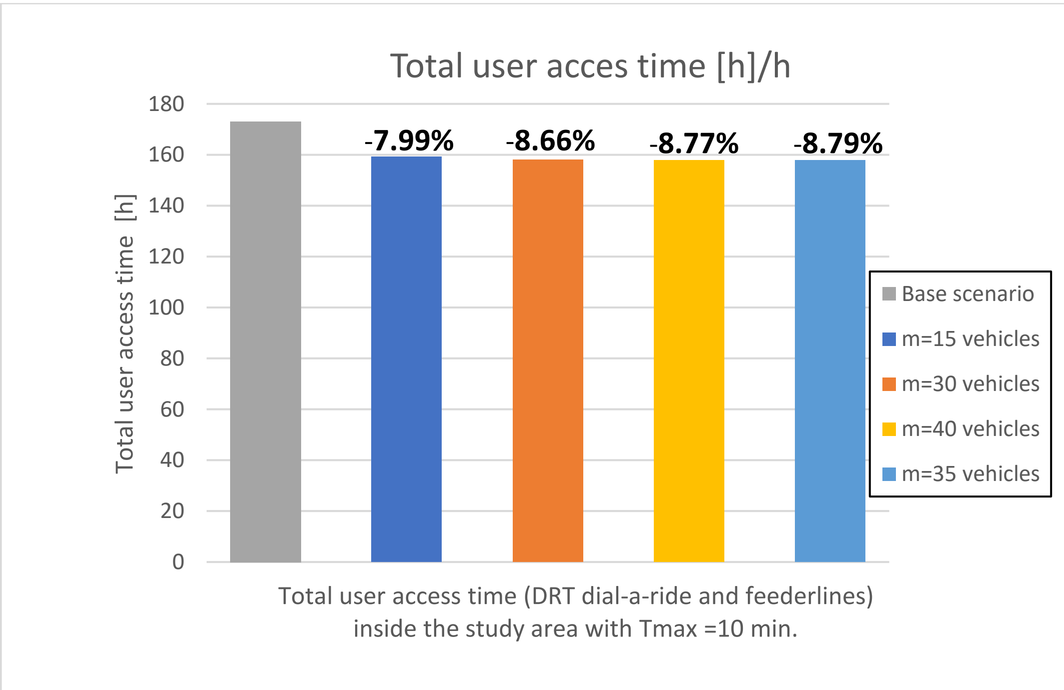


Figure 52. User access time with maximum target waiting time Tmax = 10 min. Made by the author

6.2.2 Operator costs

The costs of the operator under scenario II will comprehend the operation of the 16 existing feeder lines inside the area of study and the dial-a-ride fleet introduced in the system. The drivers of the dial-a-ride fleet have the same wages as the drivers of conventional collective transport. Note that the buses of the feeder lines operate consuming biodiesel B7 while the minibus fleet is operated with vehicles that use normal fuel (see sections 5.8 and 5.9). As mentioned previously, the costs will be grouped by target maximum waiting time.

Distance based cost (km-traveled by the fleet)

The rolling distance-based costs show in Figure 53 and Figure 54 show how by operating a larger fleet, the rolling distance costs of the operator obviously increase. Nevertheless, observe that the reduction of user costs in Figure 47 to Figure 52 reduce in small percentages with respect to one another, in contrast to the abrupt increase in rolling-distance costs for the operator shown in Figure 53 and Figure 54.

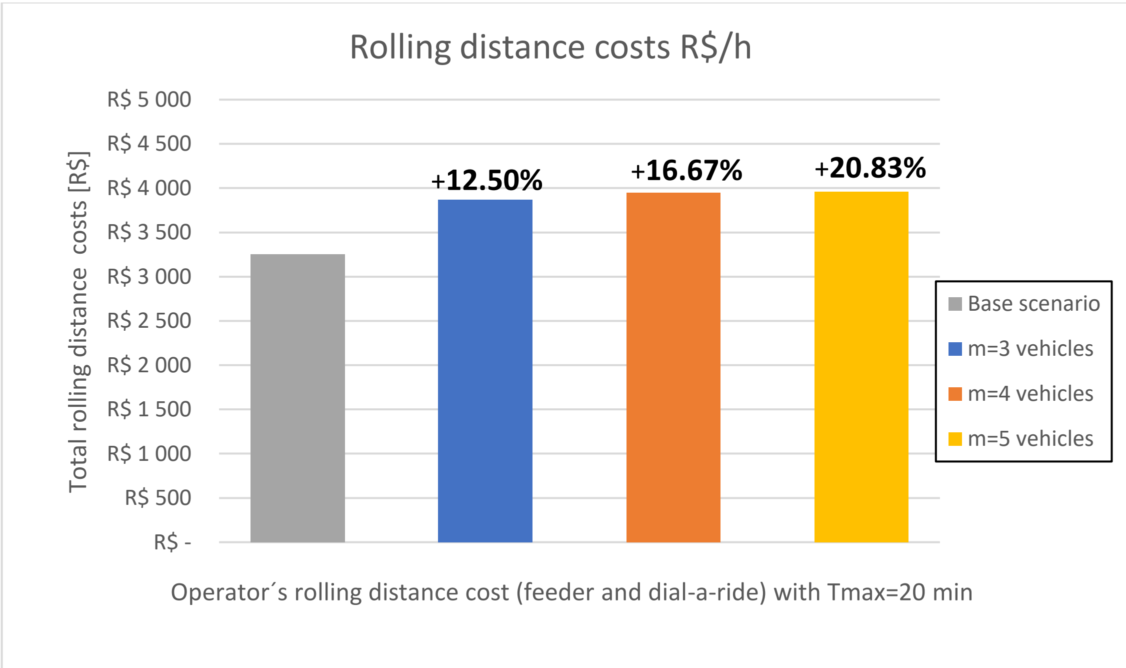


Figure 53. Operator distance-based cost for maximum waiting time Tmax= 20 min. Made by the author.

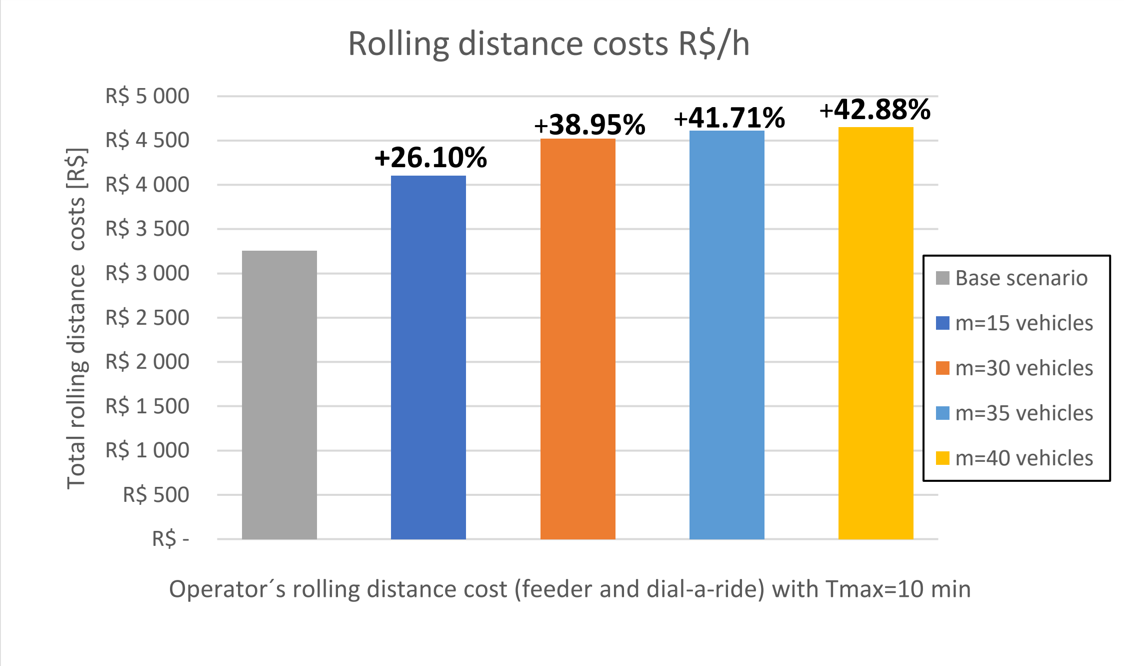


Figure 54. Operator distance-based cost for maximum waiting time Tmax= 10 min. Made by the author.

Labor force costs (drivers' salaries)

Same as in the case of rolling-distance costs, the labor force costs required for deploying a larger fleet increment largely. The increase of costs in Figure 55 and Figure 56 is linear and accounts for the additional cost of 1 hour of work paid for adding a new dial-a-ride driver to the system, this cost is assumed to be the same as the workforce cost of feeder bus drivers $C_{m\ R\$/h} = 19{,}23 \mathrm{R\$/h}$. Observe again that the reduction of user costs in Figure 47 to Figure 52 occurs in small percentages with respect to one another, in contrast to the abrupt increase in labor force costs for the operator when more and more drivers are added to operate the fleet as shown in Figure 55 and Figure 56.

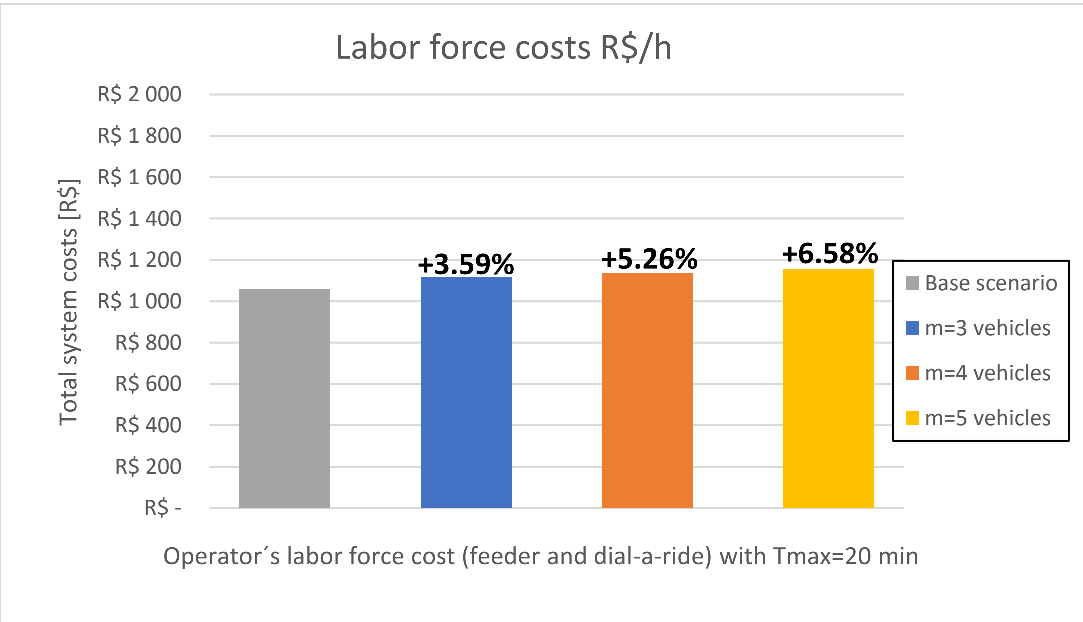


Figure 55. Operator's labor costs (drivers' salaries) for a maximum waiting time Tmax=20min. Made by the author.

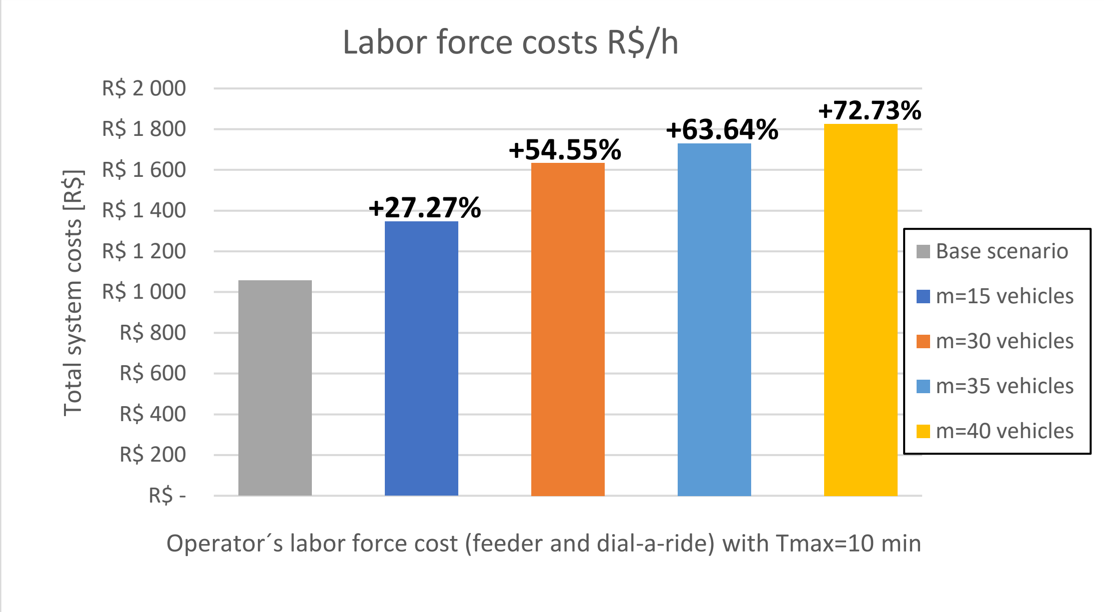


Figure 56. Operator's labor costs (drivers' salaries) for a maximum waiting time Tmax=10min. Made by the author.

6.2.3 Environmental costs

The total environmental costs measured as the total kg CO_2 emitted per hour of operation of the system tend to increase by the introduction of the dial-a-ride system, and evidently they do also increase with larger fleet sizes as shown in Figure 57and Figure 58. Nevertheless, observe that in Figure 57 the percentual change between the total kg CO_2 emitted per hour of operation kg fleet size $m = 4\ vehicles$ and $m = 5\ vehicles$ is very small, which could suggest that adding vehicle No. 5 to the fleet may be unnecessary, since the demand could be met with a smaller fleet size.

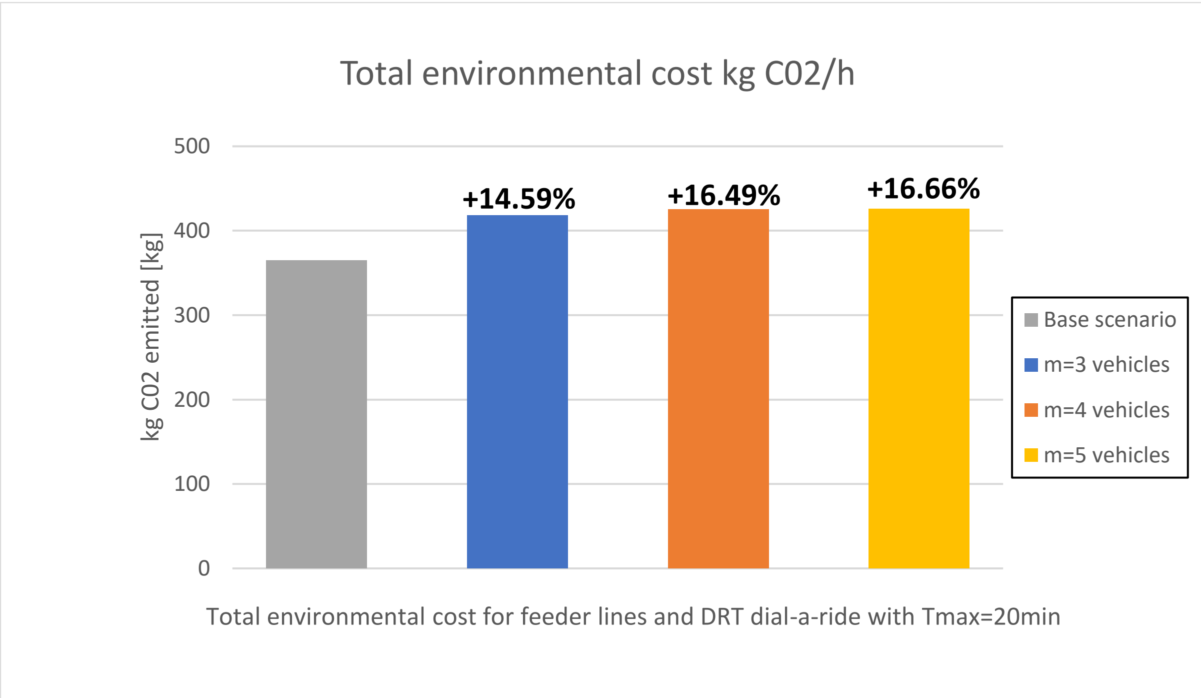


Figure 57. Environmental costs linked to CO2 emissions with Tmax =20 min. Made by the author.

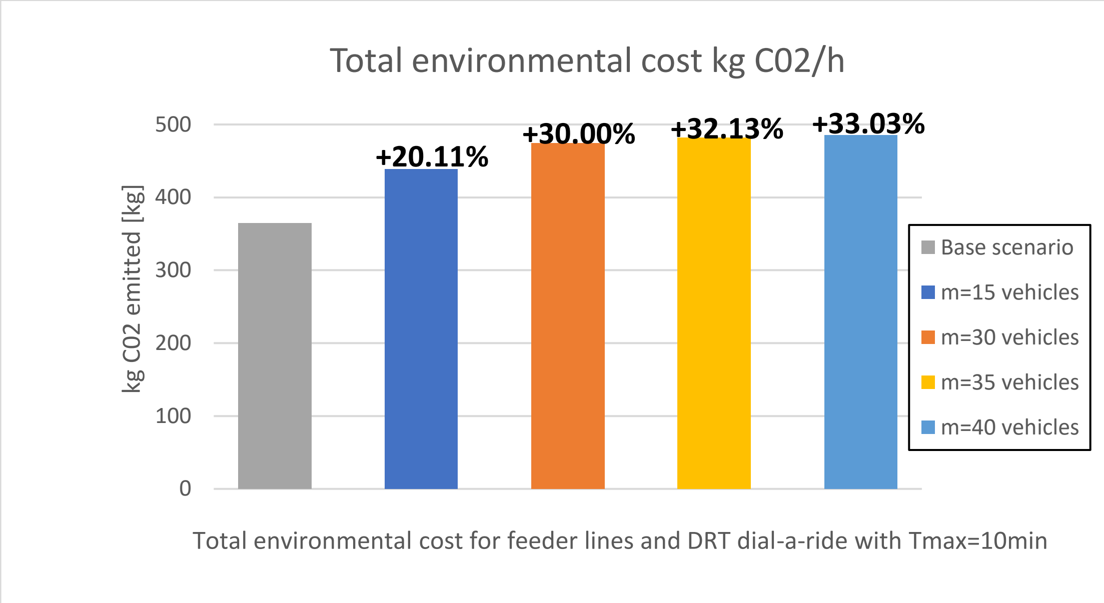


Figure 58. Environmental costs linked to CO2 emissions with Tmax =10 min. Made by the author.

6.2.4 Total system costs

The total system costs for increasing fleet sizes and more demanding target waiting times are shown in Figure 59 and Figure 60. The maximum reduction of system total costs is – 6.04% and is achieved by a fleet size $m = 3\ vehicles$ with $C = 15\ pax/veh$, this configuration of dial-a-ride system reduces the users' costs associated to in-vehicle travel time, waiting times and, access times. Nevertheless, the reduction of users' costs is accompanied by an increase in operator's costs by +12,50% in rolling distance costs, and a + 3.59% in workforce costs. It should be noted that by adding more vehicles to the fleet size after a certain point, although the user costs are reduced, the system total costs start increasing, this can be seen in the increasing values of system total costs in Figure 59 and Figure 60.

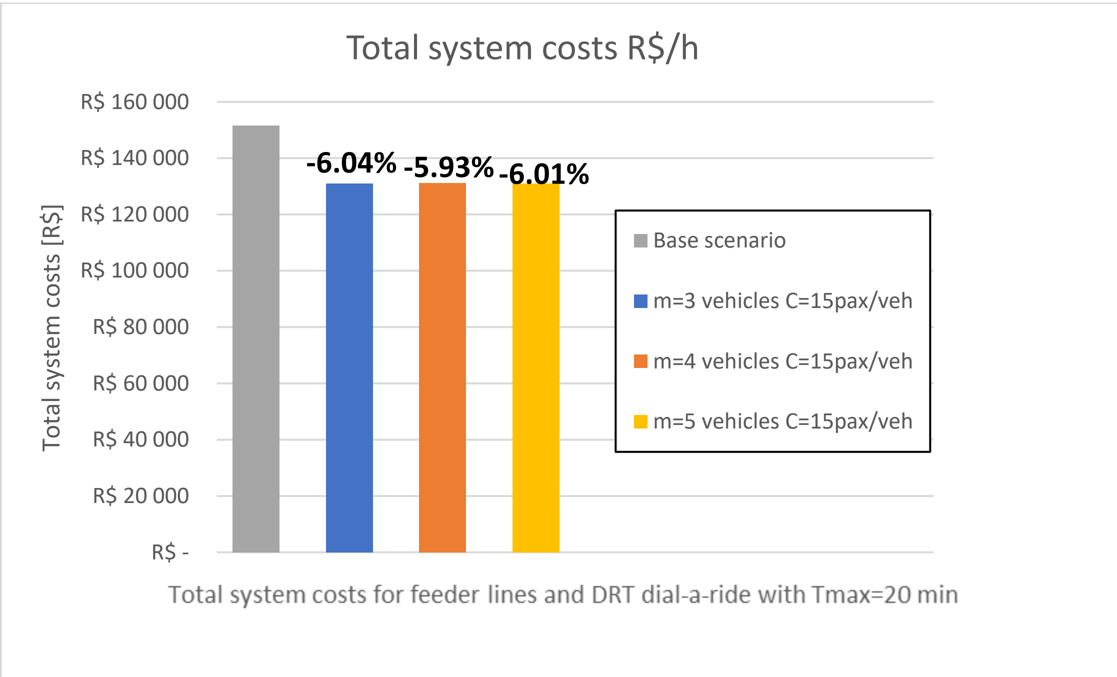


Figure 59. Total system costs for scenario II and Tmax=20 min. Made by the author.

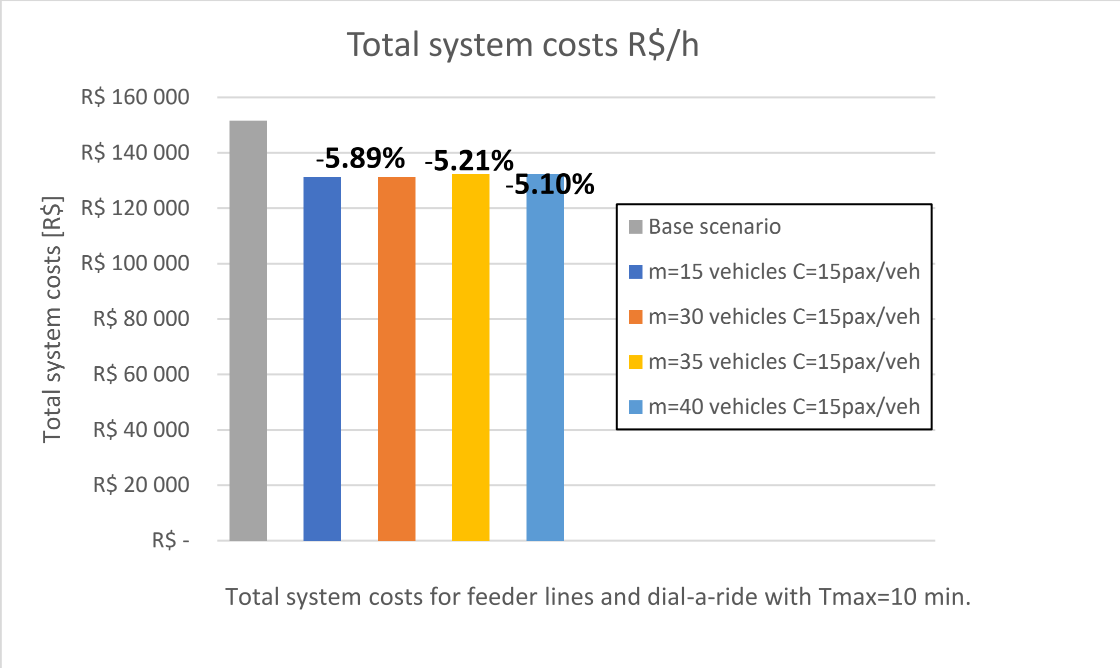


Figure 60. Total system costs for scenario II and Tmax=10 min. Made by the author.

Figure 59 and Figure 60 show again the importance of determining the right scale of the system and dimensioning the fleet size according to the demand attracted by the service. By inspecting Figure 59 and Figure 60, it can be seen that after meeting the demand of the system, bigger fleet sizes do not benefit the performance of the system, and only contribute to higher operational costs for the operator, this latter statement is in accordance with the findings of failures of DRT systems as reported by Papanikolaou et al. (2017) and Currie & Fournier (2020) in section 3.4.

6.3 Scenario III

Scenario III considers the case in which some feeder lines inside the area of study are to be eliminated due to their low ridership (Figure 61 on the righthand side). The hypothesis under scenario III is whether providing a DRT dial-a-ride service and eliminating some feeder lines could prove to be a better alternative with respect to the system performance, and the system total costs. This scenario considers intermodality between DRT and conventional collective transportation, and therefore adds additional PUDOs (pick up and drop off points) at some stops/stations of the main lines of the network (see PUDOS along the BRT corridors and the Interbairros lines on the right-hand side map in Figure 61).

The elimination of lines (U811, U821, U822, U823, U825, U827, U829) is expected to decrease the operational cost of the operator. Nevertheless, the introduction of the dial-a-ride service with fleet size $m = 30\ vehicles$ and maximum target waiting time $Tmax = 20\ min$ is expected to increase the operator's cost. It is not clear a priori which will be the outcome of this modification, this provides the motivation for the development of scenario III. Note: Due to larger running times of the multimodal assignment, scenario III has only been simulated for the (1) system configuration mentioned above. More configurations of the system modifying the key decision variables fleet size and maximum waiting time, as well as to which set of feeder lines could be candidate to be eliminated are topic that fall under future work.

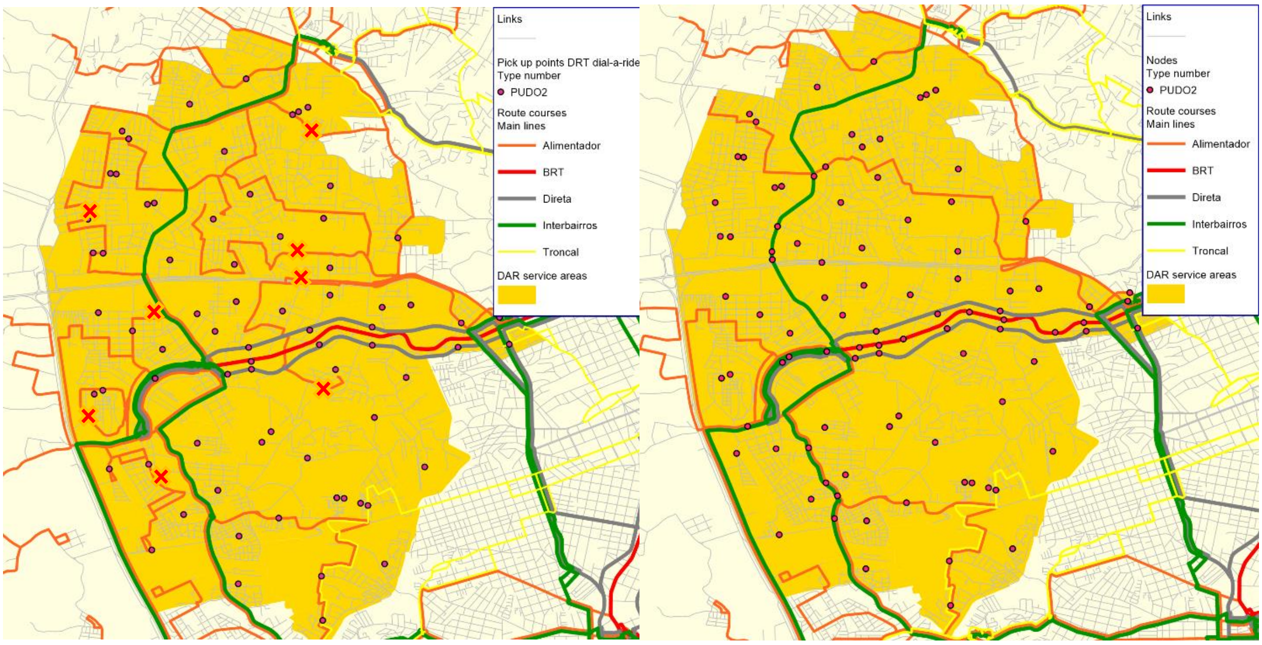


Figure 61.Eliminated feeder lines (left) and new pick up and drop off points connecting dial-a-ride services to the main bus lines inside the study area(right). Made by the author.

The form of the cost function used to assess the system costs under scenario III is given by (24) and is like the one of scenario II, but now the set of feeder lines has been reduced form an original set of n= 16 to a set of n=8 lines in the first term of the expression.

$$C_{total\ III} = C_O(10) + C_U(14) + C_E(18) \quad (24)$$

$$C_{total\,III} = K_C \cdot C_{d_C} + K_M \cdot C_{d_M} + K_{DAR} \cdot C_{d_{DAR}} + \left(\sum_{i=1}^{m_{Bus}=8} \sum_{i=1}^{m_{DAR}=30} i \right) \cdot C_{m\ R\$/h}$$
$$+ \left[\sum_{i}^{N} \left((A_i + W_i + TT_i + \tau_i) \cdot \beta_k + \sum_{l=1}^{n} \Lambda_l \cdot \theta \right) \right]_{Bus}$$
$$+ \left[\sum_{i}^{N} ((A_i + W_i + TT_i + \tau_i) \cdot \beta_k) + \sum_{c}^{C} ((\Lambda_c) \cdot \theta) \right]_{DAR} + \left[CO_{2\frac{kg}{h}} \cdot S_{i\frac{R\$}{kg}} \right]_{Bus}$$
$$+ \left[CO_{2\,kg/h} \cdot S_{i_{R\$/kg}} \right]_{DAR}$$

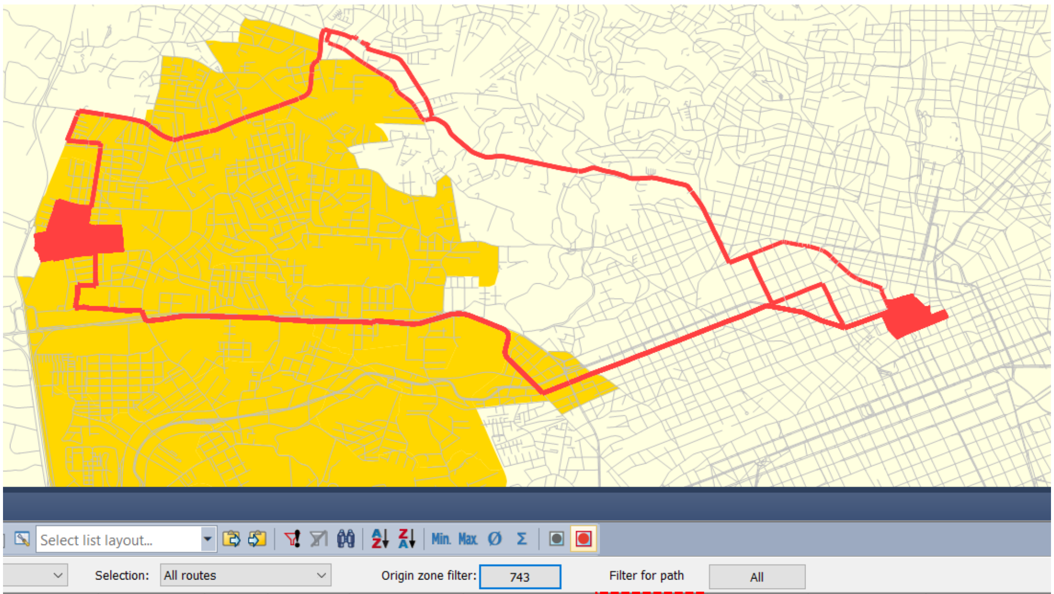
The expression for the assessment of the system costs of the base scenario is given by (23) (same equation as base scenario in scenario II). The multimodal assignment in PTV Visum is illustrated in Figure 62 and Figure 63. The public transport trip starts inside zone No. 743 has as destination <one 482. The Trip is loaded to the model at the connector level, as previously explained, to access the dial-a-ride service, the user walks 1 minute and 28 seconds to one of the PUDO2 points illustrated in Figure 61 on the right side, then waits 2 minutes and 20 seconds for the DRT (dial-a-ride) service that drops him/her off at the X point after 3 minutes and 54 second of ride, then the user makes a transfer and waits 1 minute and 23 seconds for line U 876. Finally, the user continues the last path of the journey using feeder line U 876 (one of the feeder lines with high ridership that was not deleted from the model) and after 25 minutes and 9 seconds of riding line U 876, the user finally reaches his/her destination at the city center in zone.

Figure 62. Illustration of multimodal assignment in PTV Visum. The different trip legs are shown below. Made by the author.

Number: 124	ODTrips	FromStopPointNo	FromStopAreaNo	ToStopPointNo	ToStopAreaNo	TimeProfileKeyString	Time	WaitTime	Dist
1	15.386			110320	110320		36min 20s	3min 43s	11.805km
2						Origin connector	1min 28s	2min 20s	0.098km
3						DRT C	3min 54s	0h	3.175km
4				133740	133740	Transfer	0h	1min 23s	0.000km
5		133740	133740	110320	110320	U_876 SAVÓIA < 3174066	25min 9s	0h	8.460km

Figure 63. Public transport path legs for a multimodal trip from the study area to the center.

The same OD destination demand trip as the one generated in Figure 62 and Figure 63 has been evaluated for the same demand period 07:00 and 08:00 and is shown in Figure 64. Observe how the connections of the base model in Figure 64 range form a minimum journey time of 38 minutes and 27 seconds to a maximum of 52 minutes and 44 s; these values are high compared to the example journey of 36 minutes and 20 seconds with multimodal transport.



OrigZoneNo	DestZoneNo	Index	ODTrips	NumTransfers	TransferWaitTime	JourneyTime	JourneyDist	JourneySpeed	DirectDistSpeed
743	182	7	0.621	1	8min 1s	46min 27s	11.983km	15km/h	12km/h
743	182	8	0.441	1	4min 1s	42min 27s	11.983km	17km/h	13km/h
743	182	9	0.283	1	1s	38min 27s	11.983km	19km/h	14km/h
743	182	10	0.123	1	7min 1s	45min 27s	11.983km	16km/h	12km/h
743	182	11	0.073	1	3min 1s	41min 27s	11.983km	17km/h	13km/h
743	182	12	0.030	1	10min 1s	48min 27s	11.983km	15km/h	11km/h
743	182	13	0.020	1	2min 45s	52min 44s	14.800km	17km/h	10km/h
743	182	14	0.027	1	6min 1s	44min 27s	11.983km	16km/h	12km/h

Figure 64. Comparison of base scenario connections by common collective transportation. Screenshot of PTV Visum base model.

6.3.1 User costs

The user costs evaluated under scenario III include the total and average times for riding, transfer wait, access, and egress. The costs are giving in units of hours and are shown in Figure 64 and Figure 65. It should be noted that the introduction of the new dial-a-ride service affects the impedance of the route choice of the public transport demand (as discussed in section 5.6), so that the total travel times handled here are based on the supply of all the bus routes inside the study area and the newly introduced dial-a-ride service. The largest relative differences achieved with respect to the base scenario are those related to the total ride time with public transport and the average transfer wait time and (-15,23%). The mean journey time is reduced by -6,69% with respect to the base scenario. It should be noted, however, that these reductions in user costs are obviously balanced by the increase in operational costs shown in Figure 67 and Figure 68 assessed in the next section.

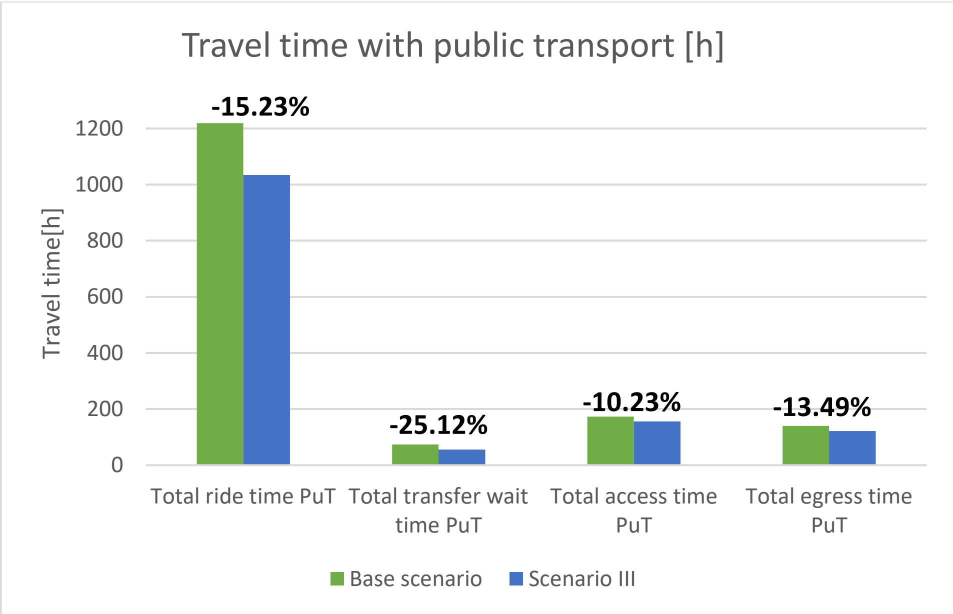


Figure 65. Comparison of travel times with public transport obtained by the multimodal assignment in scenario III.

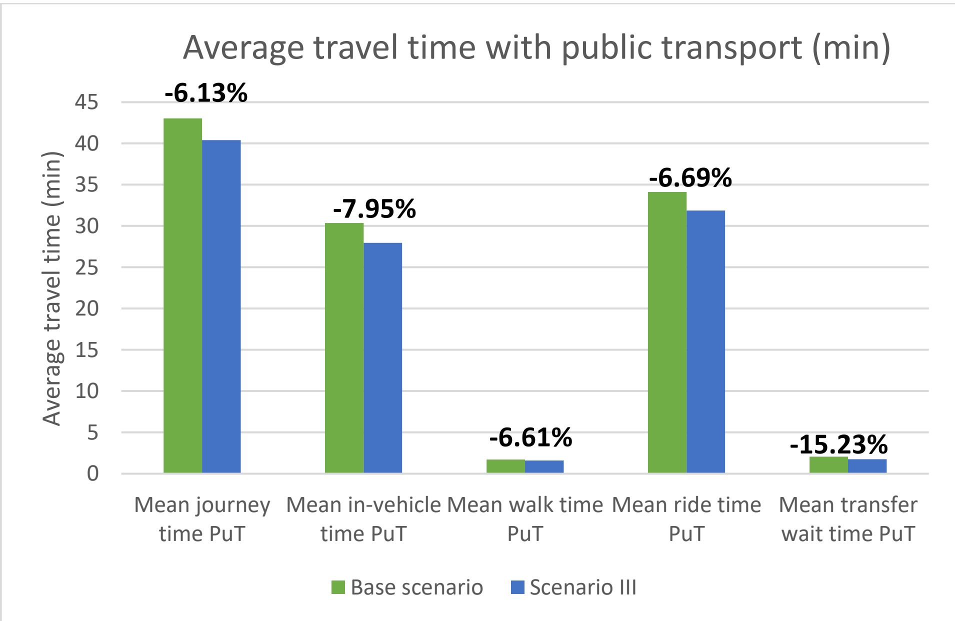


Figure 66. Comparison of average travel times with public transport obtained by the multimodal assignment in scenario III.

6.3.2 Operator costs

Distance-based and work force cost (rolling cost from fuel consumption and drivers' salaries)

The operator costs have been assessed considering the cost associated to the fuel consumption and drivers required for the system composed by dial-a-ride and the now reduced number of feeder lines operating inside the study area. Figure 67 shows an increase of +26,49% in operational costs due to fuel consumption by introduction of the new dial-a-ride fleet. However, as mentioned in scenario II, the feeder lines operate consuming biodiesel B7 which has a lower price $(7R\$/l)$ while the minibus fleet is assumed to be operated with vehicles that use normal fuel with a higher price $(7{,}238\ R\$/l)$, this previous could be a factor that could reduce the increase in operational costs in Figure 67, if the dial-a-ride fleet would for example be operated by a fleet using biodiesel, then the fuel consumption costs could be reduced. However, the environmental costs could increase by operating vehicles with biodiesel. Finally, it should be noted that the reference vehicle selected for performing the evaluation of the costs corresponds to a Ford Transit minibus of year 2018 (see section 5.8) such that the fuel consumption of newer and more efficient models could be lower and consequently the increase in operational costs due to rolling distance in Figure 67 could be less. Finally, it should be noted that the costs of the feeder bus fleet are calculated without considering the distances performed to/from depot, whereas the dial-a-ride fleet is coded to return to the holding areas, such that the increase in costs of +26,49% could be less if the previously mentioned distances were to be accounted for the feeder bus fleet.

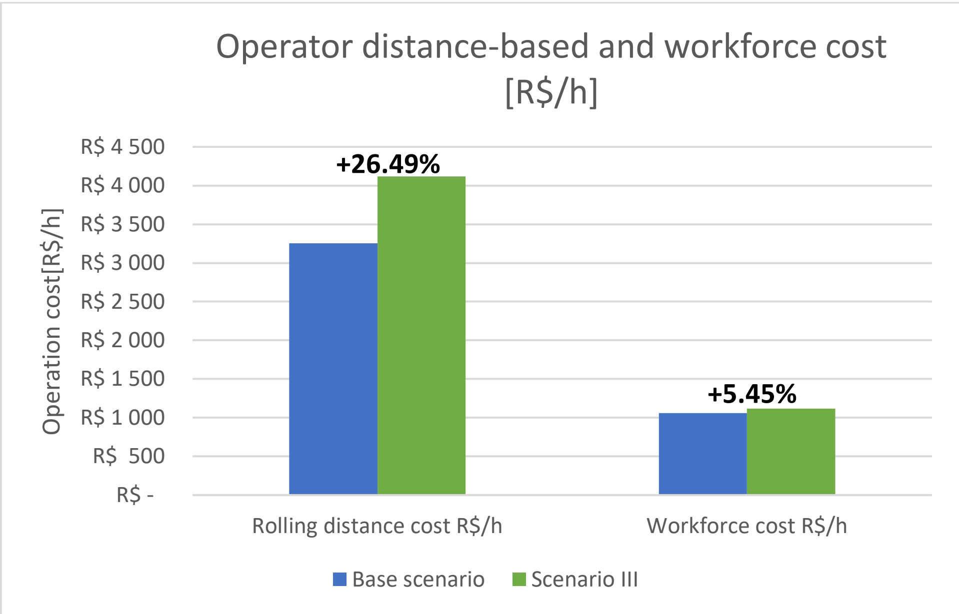


Figure 67. Comparison of operator costs obtained by the multimodal assignment in scenario III

Regarding the workforce costs, since some of the operating feeder lines are shut down, it is assumed that the bus drivers of these lines will serve as dial-a-ride drivers. In the base scenario, the workforce required to operate the existing 16 feeder lines operating in two directions inside the study area is equal to 55 drivers. By eliminating the selected 8 feeder lines, the number of required feeder bus drivers is reduced to 28. Since the dial-a-ride fleet consists of 30 minibuses, and 27drivers of the initial 55 drivers are available to operate the dial-a-ride fleet, the required extra amount of workforce to introduce the new service is only 3 drivers, this is reflected in Figure 67 by a smaller increase of 5,45% in workforce costs in contrast to a much higher increase in rolling distance costs.

6.3.3 Environmental costs

Kg CO_2 produced by operation of the system

The environmental costs have been assessed based on the total kg CO_2 emitted per hour of operation of the system with the new dial-a-ride service and the reduced number of bus feeder lines. Figure 68 shows an increase of 6,85% in emissions of kg of CO_2 due to the introduction of the new dial-a-ride fleet. However, it should be noted that the environmental costs produced by the system are dependent on the number of kilometers traveled by the operating fleet, such that the remarks made in the previous section with respect to the extra distances associated to the from/to depot operations which are not included for the feeder buses could make the environmental costs in Figure 68 decrease.

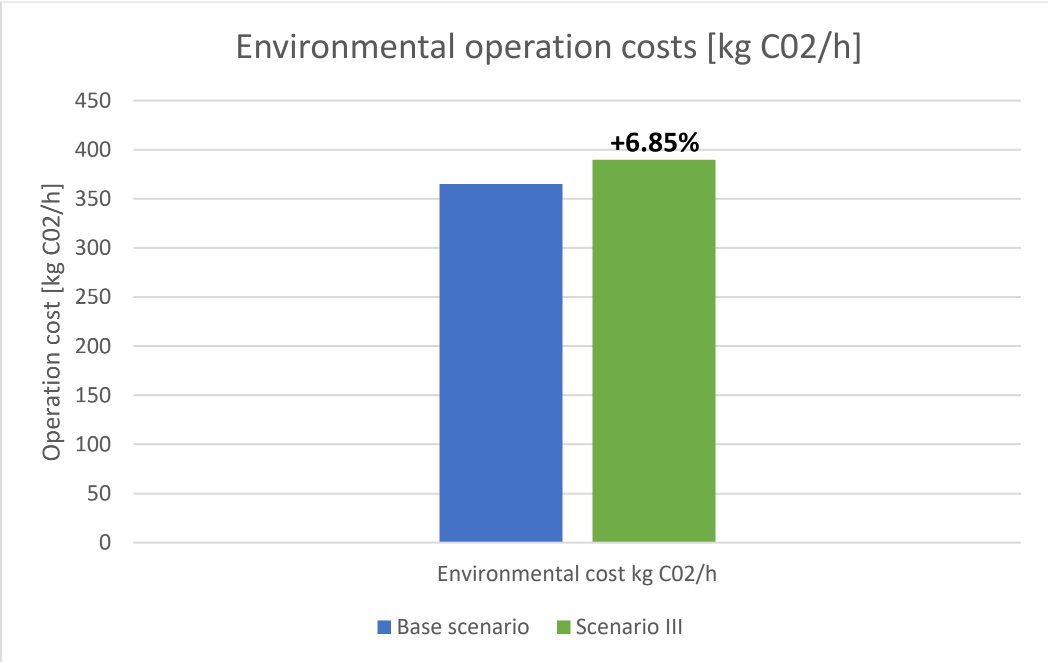


Figure 68. Comparison of environmental costs obtained by the multimodal assignment in scenario III.

With respect to the obtained environmental costs, it should be noted that the emission factors of newer and more efficient minibus models could be lower and consequently the increase in environmental costs Figure 68 could be less or even become a reduction in environmental costs. Recall that the type of vehicle assumed for the operation of the dial-a-ride fleet is a Ford Transit minibus of year 2018 (see section 5.8). Newer models of the same type of minibus could have smaller emission factors because of more strict environmental regulations or improvements in the efficiency of the engines, for example, and contribute to less environmental costs.

6.3.4 Total system costs

The total system costs are obtained by summing up the previously discussed user, operator, and environmental costs as given by (24) in the introduction of this chapter.

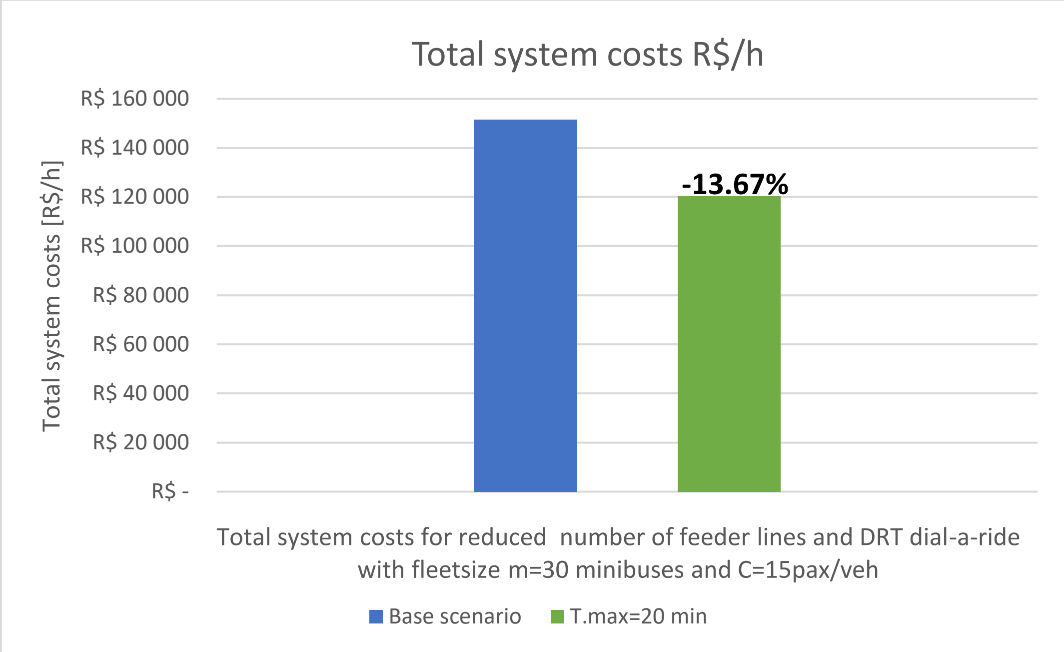


Figure 69. Comparison of total system costs obtained by the multimodal assignment in scenario III.

Figure 69 shows a reduction of -13,67% in total system costs relative to the base scenario, this reduction in total system costs is due mainly to the strong reduction in user costs shown in Figure 65. However, the reduction of user costs is contrasted by the increase in operator costs shown in Figure 67. By providing a higher level of service to the customers, the operator costs increase in terms of rolling distance and required number of drivers. The environmental emission costs associated to the operation of the new dial-a-ride fleet also increase as show in Figure 68. Nevertheless, by providing the new dial-a-ride service, the ridership of public transport may increase, such that the increase in operational costs could be overweighted by the collection of more fares due to the increase in ridership of public transport. This previous hypothesis falls out of the scope of this degree project but could be a motivation for the operator to introduce the new service.

7 Conclusions, discussion, and future work

The first general conclusion to draw form the operation and modelling of the distinct demand responsive transport services modeled inside the area of study under scenarios II, and III, is what already was known form the literature review and Figure 5 in particular, i.e. that the users' costs decrease when the operator's costs increase, this previous fact can also be linked to the trade-off between LOS provided by the operator and increasing operation costs. By the introduction of dial-a-ride services, the user costs are reduced while the operator costs are increased. Nevertheless, scenario III achieves enough good results to be considered a candidate for proof of concept of multimodal DRT inside the area of study.

Scenario III reduces the total system costs by -13,67% while not increasing the operator's cost extremely when compared to the dial-a-ride service configuration of scenario II. Moreover, scenario III reduces by more than 15% the total riding times and mean transfer wait times with public transport inside the area of study, improving substantially the level of service provided to the user. These results can serve operators inside the area of study to test the introduction of DRT services, they also motivate preliminary a possible replacement of selected feeder lines with low ridership by dial-a-ride service with vehicles of small capacity ($C = 12 - 18\, pax/veh$), the same could be implemented for time periods where demand density reduces significantly across the day or during the weekends.

7.1 Conclusions and discussion Scenario I

Scenario I was discussed directly in the results section. It is remarkable that scenario I demonstrated that the operation of ridesharing services inside the area of study could be financially sustainable considering the included variables of the system, the margin between the collected fares enough such that the system could operate providing a fixed wage to the drivers (this is usually not done by ride-hailing companies).

7.2 Conclusions and discussion Scenario II

With respect to the gird search performed following the trajectory in Figure 46, the search revealed that the maximum system cost reduction is achieved by the smallest fleet size analyzed i.e., $m = 3\, vehicles$.

The rolling distance costs shown in Figure 53 and Figure 54 show how by operating a larger fleet than, the rolling distance costs of the operator increase and the users costs decrease in Figure 47 to Figure 52. Nevertheless, the most important conclusion to draw from this observation is that the reduction of user costs in Figure 47 to Figure 52 reduce in small percentages with respect to one another, in contrast to the abrupt increase in rolling-distance costs for the operator shown in Figure 53 and Figure 54, by which it is possible to affirm that operating larger fleets inside the study area once the demand has been met by the fleet of $m = 3\, vehicles$, only increases the operational costs of the system and the overall total costs. This result is not surprising and holds with the considerations of why DRT services fail discussed by (Currie & Fournier, 2020; Daganzo & Ouyang, 2019a; Papanikolaou et al., 2017) since many start-up fail to identify the demand and optimal scale of their operation.

The system costs under scenario II were reduced by a maximum relative difference of -6,04% with respect to the system cost of the base scenario for the peak demand between 07:00 and 08:00.

Finally, it should be noted that as rule of thumb, a successful DRT system should be concerned with identifying the minimum possible operable fleet size to serve a given demand with a maximum target waiting time, and not add unnecessary new vehicles to the fleet unless the demand requires it. In the case of scenario II the demand for the study area varied from a total of 150pax/h to a maximum of 169 pax/h in a total area of 33 km2, this represents a very low demand density of near 5 pax/h-km2, this demand can be served by a small fleet and by adding more vehicles to the fleet, although the user costs decrease, the operator costs increase largely which worsens the overall system performance.

7.3 Conclusions and discussion Scenario III

The first general conclusion to make about scenario III is that it is the most viable scenario under the analyzed scenarios. Scenario III provides the best performance by increasing moderately the operator's costs and reducing largely the user's costs. By offering dial-a-ride service in the area and eliminating the proposed feeder lines, the operation costs are reduced by nearly 13,67%. It is notorious that this scenario is one of the ones that affects less operator costs (which only increase in +5,45% with respect to labor force and +26,49% in rolling distance costs).

By shifting to dial-a-ride services and eliminating 8 feeder lines, the operator sets to work 27 drivers of the initial 55 drivers of the feeder lines to drive the minibuses and only requires additional workforce of 3 extra drivers. As mentioned previously in 6.3.2 and 6.3.3, it should be noted that the cost reduction of this scenario could eventually be higher, since the assumption made about the fleet of minibuses is that these were operated by conventional fuel vehicles (which is higher than the biodiesel B7) used by the feeder bus lines. Furthermore, the operation of the feeder buses did not consider the rebalancing operation to the depot, these rolling distance in contrast are calculated with the dial-a-ride fleet that returns to the holding areas.

Scenario III provides the DRT service with the most environmentally friendly results since it is the one that produces less extra amount of CO2 kg by introducing a new DRT service (+6,85% extra emissions as shown in Figure 68).

Finally, scenario III shows that the preferred configuration of the system would be a few-to-few dial-a-ride service that serves as feeder to conventional public transportation, allowing thus transfers at major transit lines' stop areas and providing trips as the ones shown in Figure 62.

7.4 Future work

Probably the first future work direction is towards reviewing the set of deleted feeder lines under scenario III and testing including different sets of lines, and different values for maximum waiting time and fleet size. Furthermore, there should be work done to continue the dialog with IPPUC and exploring the potential of intermodality between dial-a-ride services and conventional collective transport inside the study area though a proof of concept. Furthermore, from a modelling point of view, there could be much use in determining the optimal size of the areas at which the stochastic disaggregation of demand for DRT services is done. Finally, it is necessary to explore more system configurations with multiple combinations of the decision variable maximum waiting time, as well as the fleet size, such analyzes can be done following different paths of the grid set of possible candidate points Figure 46 and could be automated with use of the COM API of PTV Visum. Future work should focus more on the analysis and interaction between dial-a-ride services to feed public transportation main lines, it should be evaluated if there could be more optimal solutions for scenario III by changing the model parameters. Furthermore, the combination of heuristic methods with PTV Visum as studied and applied by Heyken Soares et al. (2021) to generate optimal networks could be analyzed.

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9 Annex

Table 12. Deleted feeder lines under scenario III. Screenshot of PTV Visum model. Made by the author.

List (Lines)

Select list layout...

Number: 8	Name	TSysCode	FareSystemSet	NumDep(AP)	PassKmTrav(AP)	PTripsUnlinked(AP)	Categoria	InserviceArea	Verificado	Delete
1	U_811	B	1				Alimentador	☒	☒	☒
2	U_821	B	1				Alimentador	☒	☒	☒
3	U_822	B	1				Alimentador	☒	☒	☒
4	U_823	B	1				Alimentador	☒	☒	☒
5	U_825	B	1				Alimentador	☒	☒	☒
6	U_827	B	1				Alimentador	☒	☒	☒
7	U_829	B	1				Alimentador	☒	☒	☒
8	U_918	B	1				Alimentador	☒	☒	☒

Table 13. Feeder lines coded in PTV Visum Curitiba model.

List (Lines)

Select list layout...

Number: 126	Name	TSysCode	VehComb\No	Operator\No	Operator\ Name	TARIFA	Categoria
1	U_211	B	4	1	URBS	4.25	Alimentador
2	U_212	B	8	1	URBS	4.25	Alimentador
3	U_213	B	8	1	URBS	4.25	Alimentador
4	U_214	B	8	1	URBS	4.25	Alimentador

Table 14. Powertrain and chassis types of the city buses analyzed. (Dreier et al., 2018)

Powertrain[a]	Chassis		Operation status in Curitiba		Passenger carrying capacity	Fuel/s	Acronym
	Type	Length (m)	In public bus transport system	In the BRT system			
Conventional	Two-axle	(11.8 m)	In operation	No	85[b]	B7	ConvTwO
Conventional	Bi-articulated	(25.0 m)	In operation	In operation	250[b]	B7	ConvBiO
Hybrid-electric	Two-axle	(11.5 m)	In operation	No	79[b]	B7	HybTwO
Hybrid-electric	Two-axle	(12.0 m)	No	No	95[a]	B7	HybTwA
Hybrid-electric	Articulated	(18.1 m)	Test phase	No	154[a]	B7	HybArA
Plug-in hybrid-electric	Two-axle	(12.0 m)	Test phase	No	95[a]	B7, electricity	PlugTwA

[a] References: ConvTwO: Volvo Bus Corporation (2015a); ConvBiO: Volvo Bus Corporation (2015b); HybTwO: Volvo Bus Corporation (2015c, 2015d); HybTwA: Volvo Bus Corporation (2015e); HybArA: Volvo Bus Corporation (2015f); PlugTwA: Volvo Bus Corporation (2015 g, 2015 h). References for engines: Volvo Bus Corporation (2015i, 2015j, 2015k, 2015l).
[b] Seat configuration according to the local public transport and urban development company in Curitiba (URBS, 2016).

Table 15. Summary of Tank-to-Wheel (TTW) energy use, Well-to-Wheel (WTW) fossil energy use, and WTW greenhouse gas (GHG) emissions estimations. (Dreier et al., 2018)

Scope	Unit	City bus[a]					
		ConvTwO	ConvBiO	HybTwO	HybTwA	HybArA	PlugTwA
TTW energy use							
Overall mean value	MJ_{fuel}/km	17.46	29.92	12.15	12.23	14.72	7.36
Max. value	MJ_{fuel}/km	23.22	40.50	16.87	17.12	20.43	10.87
Min. value	MJ_{fuel}/km	11.50	18.55	8.21	8.21	10.13	5.17
Relative difference[a]	%	0	71	−30	−30	−16	−58
Overall mean value	MJ_{fuel}/pkm	0.38	0.22	0.29	0.24	0.18	0.14
Max. value	MJ_{fuel}/pkm	0.55	0.32	0.41	0.35	0.26	0.23
Min. value	MJ_{fuel}/pkm	0.25	0.14	0.20	0.16	0.12	0.10
Relative difference[a]	%	0	−42	−25	−37	−53	−62
WTW fossil energy use							
Overall mean value	$MJ_{fossil,WTT}/km$	19.46	33.35	13.54	13.64	16.41	4.93
Max. value	$MJ_{fossil,WTT}/km$	25.88	45.15	18.81	19.08	22.77	8.36
Min. value	$MJ_{fossil,WTT}/km$	12.82	20.68	9.15	9.15	11.29	2.77
Relative difference[a]	%	0	71	−30	−30	−16	−75
Overall mean value	$MJ_{fossil,WTT}/pkm$	0.42	0.25	0.32	0.27	0.20	0.10
Max. value	$MJ_{fossil,WTT}/pkm$	0.62	0.36	0.46	0.39	0.29	0.17
Min. value	$MJ_{fossil,WTT}/pkm$	0.28	0.16	0.22	0.18	0.14	0.06
Relative difference[a]	%	0	−42	−25	−37	−53	−77
WTW GHG emissions							
Overall mean value	$gCO_2e_{,WTW}/km$	1539	2638	1071	1079	1298	424
Max. value	$gCO_2e_{,WTW}/km$	2047	3571	1487	1510	1801	679
Min. value	$gCO_2e_{,WTW}/km$	1014	1636	724	724	893	263
Relative difference[a]	%	0	71	−30	−30	−16	−72
Overall mean value	$gCO_2e_{,WTW}/pkm$	34	20	25	21	16	8
Max. value	$gCO_2e_{,WTW}/pkm$	49	28	37	31	23	14
Min. value	$gCO_2e_{,WTW}/pkm$	22	12	17	14	11	5
Relative difference[a]	%	0	−42	−25	−37	−53	−75

[a] Relative difference (%) results from comparison to ConvTwO.

Table 16. Fuel consumption and emission characteristics of assumed minibus vehicle for dial-a-ride services. Source: Passenger carriers Ford Transit (Ford UK, 2017)

	Gross payload	Gross vehicle mass (kg)	Kerb mass (kg)*	Front axle plated mass (kg)	Front axle kerb mass (kg)	Rear axle plated mass (kg)	Rear axle kerb mass (kg)	Axle ratio	Max. GTM (kg)	Max trailer weight braked (unbraked)	CO_2 emissions (g/km)	Fuel consumption in mpg (L/100 km): Urban	Extra Urban	Combined
350 L2 Minibus (11/12 seats)														
2.2 Duratorq TDCi 125PS/155PS Stage VI HDT	854	3500	2646	1750	1349	2100	1297	3.31	3500	n/a	196	31.4 (9.0)	43.5 (6.5)	38.2 (7.4)
410 L3 Minibus (14/15 seats)														
2.2 Duratorq TDCi 125PS/155PS Stage VI HDT	1302	4100	2798	1850	1419	2500	1379	3.31	5500	2450 (750)	196	31.4 (9.0)	43.5 (6.5)	38.2 (7.4)
460 L4 Minibus (17/18 seats)														
2.2 Duratorq TDCi 125PS/155PS Stage VI HDT	1328	4600	3272	1850	1330	3120	1942	3.31	5350	1800(750)	196	31.4 (9.0)	43.5 (6.5)	38.2 (7.4)

L2 = Medium wheelbase, **L3** = Long wheelbase, **L4** = Long wheelbase extended length, **H2** = Medium roof, **H3** = High roof, **SRW** = Single rear wheels, **DRW** = Dual rear wheels. ***Kerb mass** is affected by many factors such as bodystyles, engines and options. It is the weight of a standard-specification base vehicle (different series will have different kerb masses), including fluids and fuel tank 90% full, but without the driver (75kg), crew or cargo. Payload within this guide is the difference between gross vehicle mass (GVM) and kerb mass with a further 75kg deduction for the weight of the driver. It must be noted that actual weight will always be subject to manufacturing tolerances which may result in payload variations between this guide and actual weight. For customers intending to load vehicle close to maximum payload, we suggest you also add a margin for error of 5% of Kerb Mass to the Kerb Mass figure before calculation, to reduce risk of overloading. NB: It is the responsibility of the vehicle operator to ensure their vehicles are legally compliant for road use. . A guide on fuel economy and CO_2 emissions which contains data for all new passenger vehicle models is available at any point of sale free of charge or can be downloaded under http://carfueldata.dft.gov.uk/.

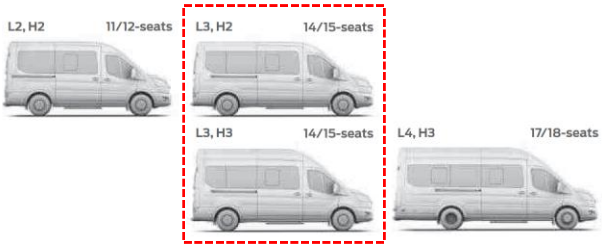

Table 17. Random seeds for disaggregation of demand.

Simulation No.	Random Seed
1	42
2	225
3	87
4	125
5	111
6	146
7	114
8	63
9	5
10	205

Table 18. Comparison of total system costs for scenario I (10 simulation runs) and base scenario.

Scenario	Total system cost	Travel time cost	Travel distance cost	Parking	Pollutant costs	Fare	Workforce
Base Scenario	R$ 380 077	R$ 187 159	R$ 120 529	R$ 66 753	R$ 5 633	(-)	(-)
Scenario I average	R$ 378 655	R$ 184 765	R$ 119 554	R$ 64 878	R$ 3 899	R$ 4 884	R$ 673
Rel. Difference	-0,37%	-1,28%	-0,81%	-2,81%	-30,78%	(-)	(-)

Tabell 19. Shadow prices of emissions in the Netherlands in 2008 based on abatement costs (€2008/kg). Source (CE Delft, 2010).

Pollutant	Total	Climate change	Ozone depletion	Acidification	Photo-ox. formation	Eutrophication	PM formation	Human tox., air	Human tox., water
CO_2	0.0250	0.0250							
CH_4	0.6250	0.6250							
N_2O	7.45	7.45							
CFC-11	149	119	30.0						
CFC-12	303	273	30.0						
CFC-113	183	153	30.0						
CFC-114	278	250	28.2						
CFC-115	197	184	13.2						
HCFC-22	46.8	45.3	1.50						
NO_x	8.72			2.32	5.00	0.896	0.506		
PM_{10} *	2.30 (50)						2.3 (50)		
$PM_{2.5}$*	2.30 (50)						2.3 (50)		
CO	0.009							0.009	

Table 20. Feeder lines inside area of study. Screenshot of PTV Visum Curitiba model. Made by the author.

List (Lines)

Number: 16	Name	VehCombNo	InService/	LinNetLenDir	PassHourTrav(A	TSysCode	PassKmTrav(AP)	Categoria	PTripsUnlinked(AP)	PTripsUnlinked	PTripsUnlinked	PTripsUnlinked2(AP)
1	U_913	8	☒	11.561km	2h 39min 22s	B	35.625km	Alimentador	20	0	10	8
2	U_825	7	☒	17.259km	4h 17min 1s	B	73.541km	Alimentador	23	0	13	8
3	U_823	7	☒	10.198km	8h 41min 9s	B	189.745km	Alimentador	62	5	18	31
4	U_829	4	☒	6.006km	5h 48min 52s	B	156.239km	Alimentador	74	0	19	34
5	U_811	4	☒	14.576km	28h 37min 17s	B	609.107km	Alimentador	148	6	40	80
6	U_822	4	☒	6.934km	43h 9min 53s	B	667.086km	Alimentador	285	3	103	129
7	U_918	8	☒	11.607km	31h 5min 54s	B	501.008km	Alimentador	302	12	126	113
8	U_814	4	☒	13.157km	79h 17min 31s	B	1572.102km	Alimentador	339	8	90	182
9	U_711	4	☒	8.894km	56h 29min 13s	B	810.783km	Alimentador	397	2	157	204
10	U_827	4	☒	17.037km	187h 30min 7s	B	3585.053km	Alimentador	488	4	105	233
11	U_821	4	☒	21.543km	101h 16min 53s	B	1974.837km	Alimentador	508	42	227	175
12	U_720	4	☒	13.476km	117h 39min 27s	B	2325.743km	Alimentador	597	38	298	197
13	U_812	4	☒	17.436km	112h 15min 55s	B	2481.090km	Alimentador	614	65	181	304
14	U_828	4	☒	26.461km	285h 33min 23s	B	4193.407km	Alimentador	1085	68	585	363
15	U_816	4	☒	12.537km	161h 8min 3s	B	5179.901km	Alimentador	1151	16	226	627
16	U_826	4	☒	23.379km	605h 2min 13s	B	11299.949km	Alimentador	1876	87	738	758

Table 21. Vehicle units of the PTV Visum Curitiba model. Screenshot of PTV Visum Curitiba model. Made by the author.

List (Vehicle units)

Number: 11	No	Code	Name	TSysSet	Powered	SeatCap	TotalCap
1	1		Articulado 1	A,B	☐	0	136
2	2		Articulado 2	A,B	☐	0	154
3	3		Biarticulado	A,B,M,R	☐	0	242
4	4		Comum	A,B	☐	0	86
5	5		Hibrido	A,B	☐	0	79
6	6		Micro	A,B	☐	0	39
7	7		Micro Especial 1	A,B	☐	0	61
8	8		Micro Especial 2	A,B	☐	0	67
9	9		PADRON 1	A,B,M,R	☐	0	91
10	10		Padron 2	A,B,M,R	☐	102	102
11	11		Semi Padron	A,B	☐	0	91

Table 22. Distance traveled by ridesharing vehicle fleet. Made by the author.

Veh. No	Traveled distance per hour of fleet operation [km] for N=10 simulation runs									
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
1	41.173338	24.757063	32.933048	47.82733	31.861351	26.766387	47.82733	40.451072	30.582321	24.50148
2	39.399212	30.845473	35.841037	37.076155	30.898338	37.293331	37.076155	24.097329	34.796929	24.237442
3	32.322644	31.69096	33.480921	31.259729	33.996701	32.697602	31.259729	28.372165	32.551462	37.94397
4	31.816172	27.584671	23.817338	44.28914	30.925855	33.807448	44.28914	31.592281	33.676133	22.972607
5	36.543612	20.575129	24.789076	22.804709	30.493583	26.193072	22.804709	33.833311	30.416282	34.559683
6	28.188685	30.337854	7.931081	25.183469	32.382798	30.060098	25.183469	23.63258	26.573169	29.528792
7	39.763949	29.643978	39.433064	34.656289	33.533872	41.324855	34.656289	38.603365	23.787131	36.876031
8	24.127043	35.783324	34.249882	30.782633	32.106469	37.146671	30.782633	43.320144	27.875743	49.18925
9	44.781736	37.563917	5.539048	33.656716	29.413431	37.517455	33.656716	37.085067	34.884957	39.024864
10	39.667198	33.471802	32.580636	23.998767	39.520764	18.853987	23.998767	31.126915	32.806281	14.716825
11	26.294801	41.707267	9.271125	38.099382	34.784815	18.303252	38.099382	33.553448	29.915122	23.308549
12	37.157867	29.414142	32.851806	35.104601	23.844311	22.283365	35.104601	28.441764	24.749021	22.474937
13	29.349933	46.408596	35.981626	31.819304	29.826717	37.37844	31.819304	41.13248	30.441628	18.8247
14	35.64575	34.52261	33.284941	34.269118	26.348852	31.781296	34.269118	21.864017	41.49249	33.481797
15	26.396404	32.026958	43.16077	36.930611	29.897572	32.097791	36.930611	40.641431	39.45062	31.741844
16	31.752002	9.454068	32.420941	32.234377	19.442681	.44403	32.234377	37.444113	30.849533	26.938729
17	24.882762	10.338448	27.206972	27.304363	21.384852	28.866735	27.304363	9.961297	22.139515	28.168946
18	34.959414	9.530594	25.409223	32.16932	16.266895	30.945636	32.16932	9.894007	24.045154	26.190305
19	30.681463	28.20932	37.081523	26.418742	26.890189	25.178213	26.418742	40.908487	30.406887	35.070014
20	24.479283	28.721535	35.948837	30.560899	35.473618	23.278746	30.560899	38.797225	11.707323	27.446925
21	27.825719	23.809994	24.726959	20.50843	24.321387	22.336607	20.50843	32.067285	8.541707	28.895255
22	31.675451	9.205336	19.712041	36.078208	29.297974	17.453596	36.078208	37.330686	15.734569	18.8732
23	12.884123	14.335392	16.16808	32.220653	27.880186	12.323931	32.220653	41.320284	30.872212	28.554692
24	40.971277	35.889336	29.762716	30.376166	30.470433	40.815258	30.376166	42.807448	40.064459	36.919901
25	40.389962	43.971163	21.351644	38.335845	33.291386	36.670348	38.335845	28.498103	45.098997	34.526321
26	31.776741	39.694131	34.974239	34.328869	34.595841	27.202069	34.328869	30.939468	19.422129	36.877056
27	32.345726	38.577967	16.485689	37.250451	26.6066	25.337817	37.250451	34.304068	29.491896	33.937923
28	26.587407	29.264619	22.316893	37.097043	39.24364	34.35962	37.097043	34.777668	19.116862	29.640796
29	30.688638	29.346303	31.939714	34.331998	27.042759	19.62374	34.331998	37.279509	43.742892	20.193622
30	30.162466	35.510518	31.040981	31.331809	36.0737	41.072469	31.331809	31.546215	37.45186	38.449017
31	36.953424	34.982716	28.14445	32.204311	36.148123	34.92444	32.204311	38.859114	32.205091	33.542781
32	21.205941	40.517913	36.10034	31.961273	34.498925	35.085239	31.961273	35.963569	30.85198	26.469297
33	32.519151	45.314017	44.466075	X	27.658972	30.907652	32.884683	X	32.884683	31.169978
34	34.186554	28.327893	35.9794	X	29.815773	28.552128	28.552128	X	X	X
35	X	X	X	X	35.006402	X	X	X	X	X
Total	1090	1021	976	1052	1061	1014	1114	1060	979	985

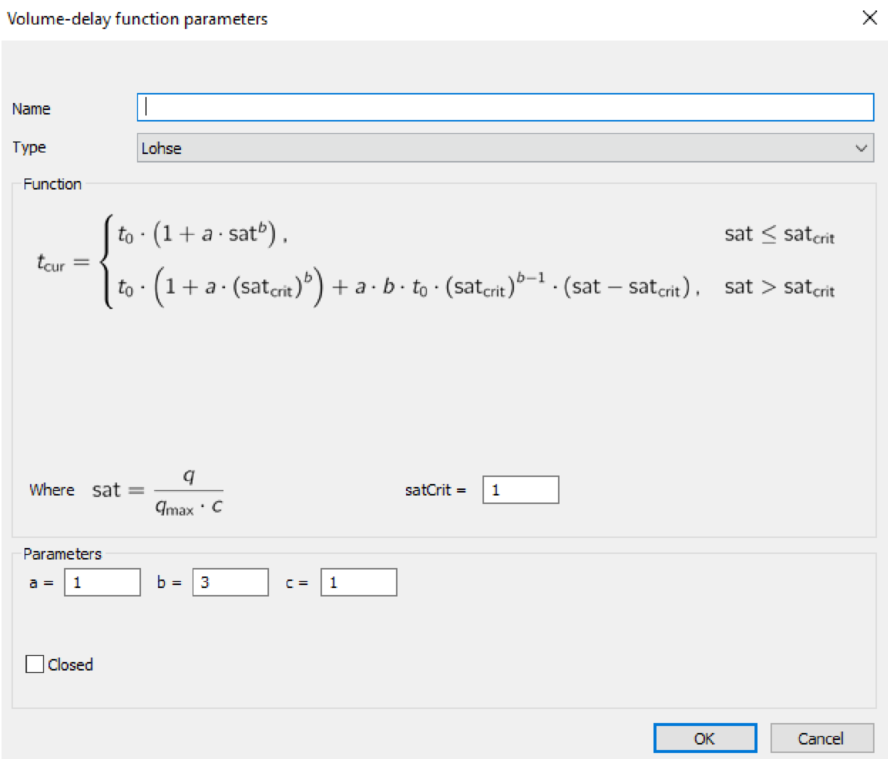

Figure 70. Volume delay functions for links. Screenshot of PTV Visum model. Made by the author.

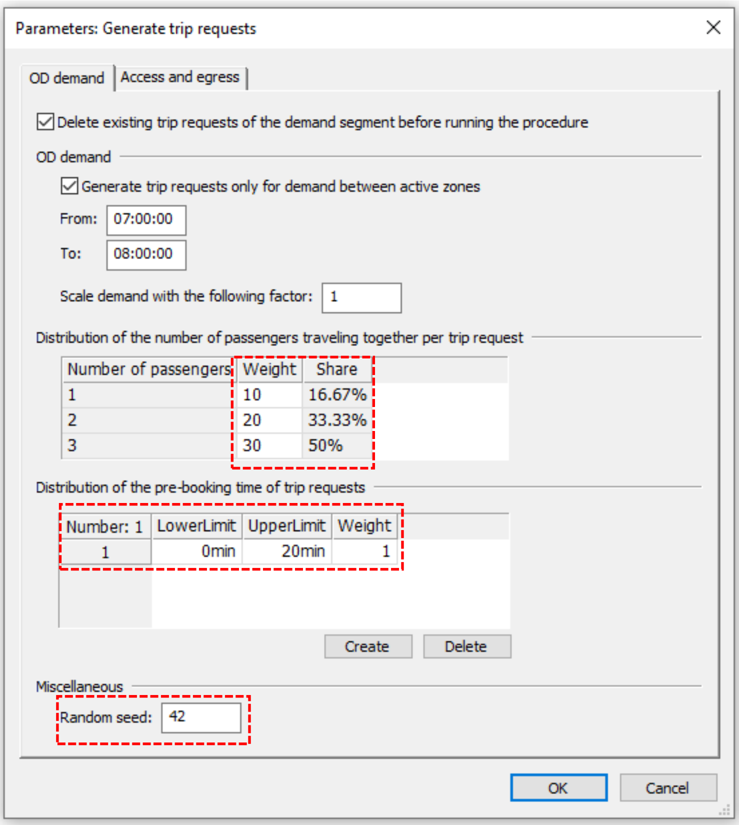

Figure 71. Parameters of the tip generation procedure for simulation run No.2. Screen shot of model using PTV Visum 2022.

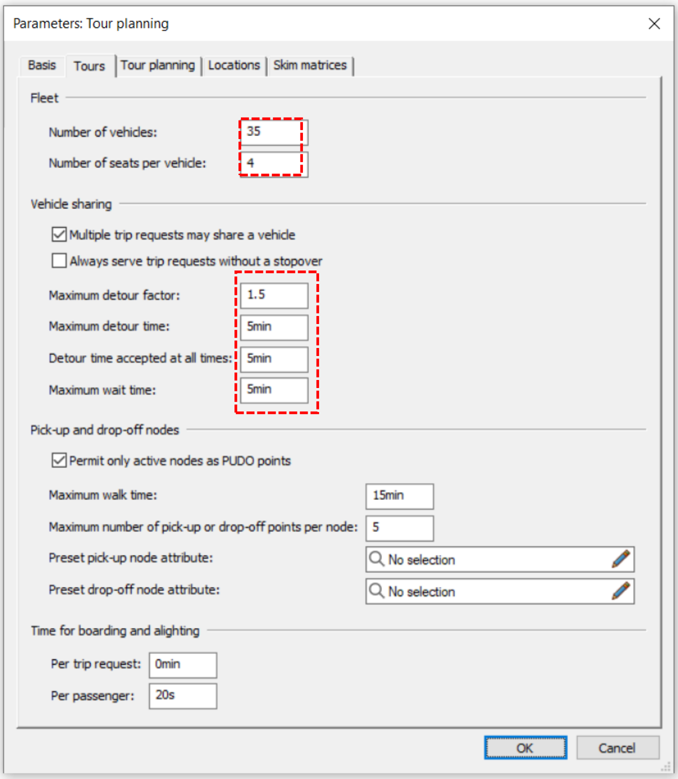

Figure 72. Parameters of the tour planning procedure for ridesharing service. Screen shot of model using PTV Visum 2022.

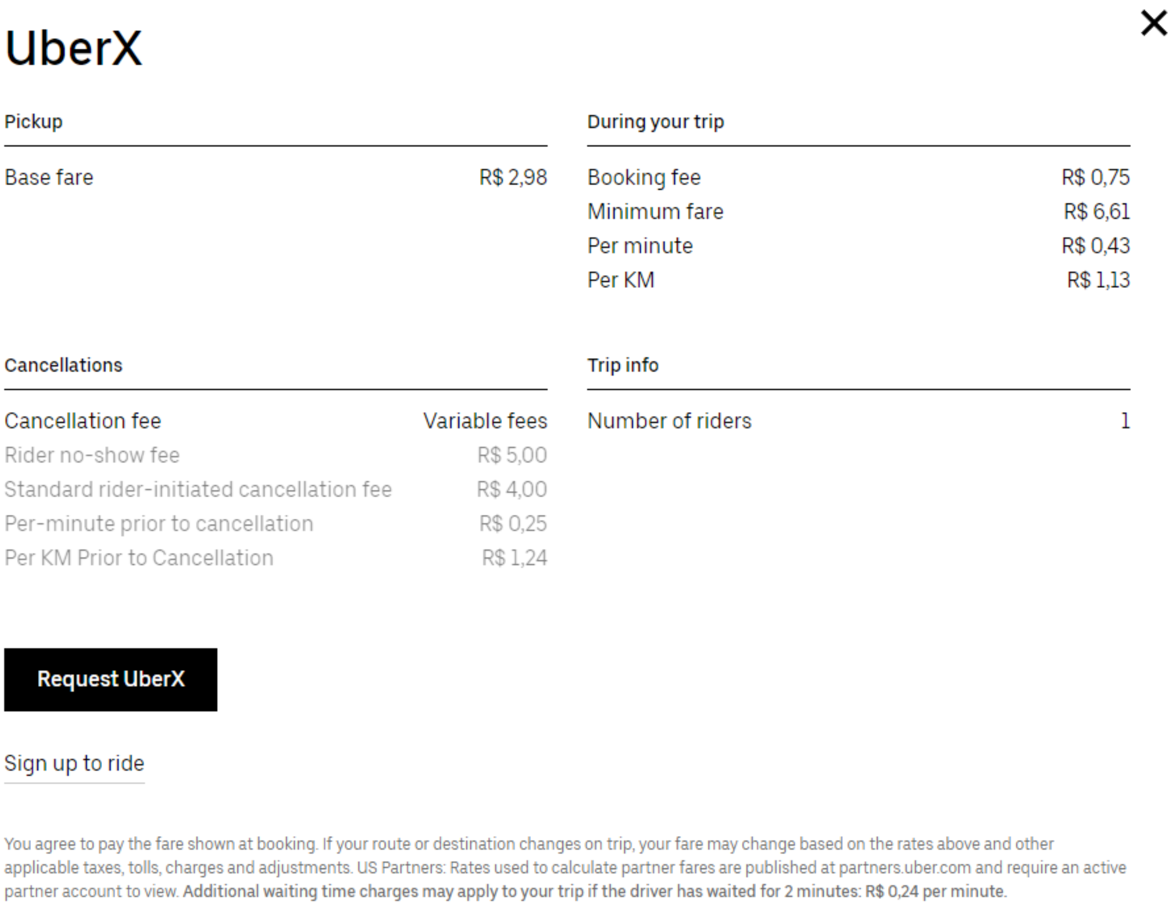

Figure 73. UberX fees details for ridesharing service in Curitiba. Source: Uber Price Estimator (Uber, 2022)

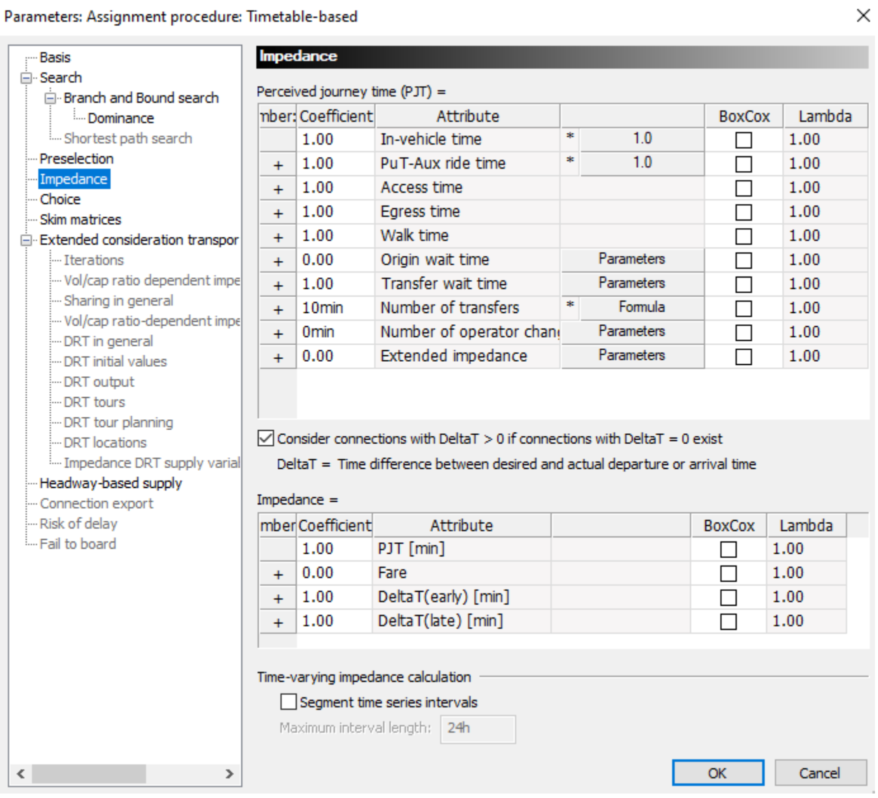

Figure 74. Impedance calculation parameters. Screenshot of PTV Visum 2022.

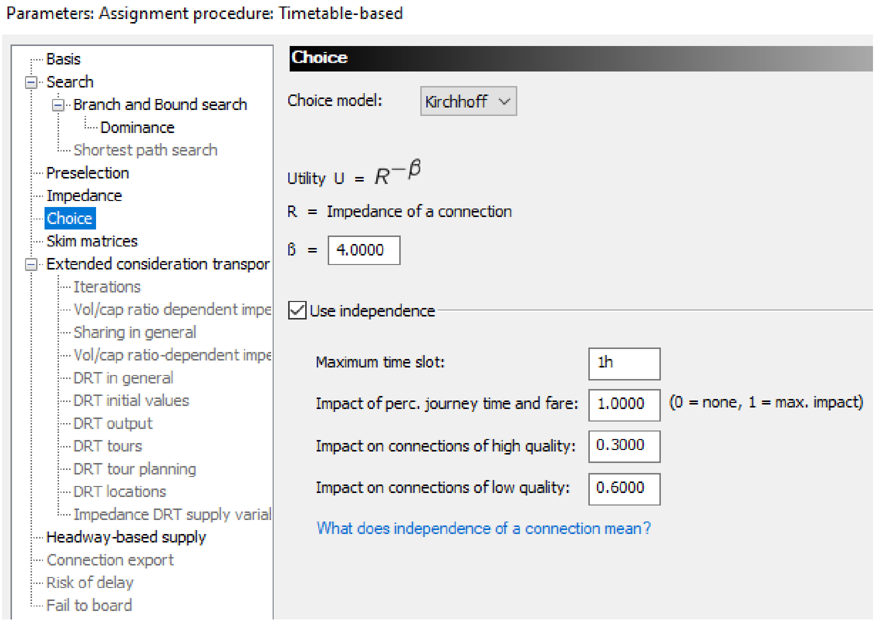

Figure 75. Choice model parameter based on the impedance calculation.