FACULTY OF ENGINEERING
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Economic Feasibility Analysis of Demand Responsive Transportation Services

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Master's dissertation submitted in order to obtain the academic degree of
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Preface

First of all, I am grateful for the opportunity to perform this research. It was an interesting journey that allowed me to further develop and apply skills that were teached to me during my time as a student. This master's dissertation is considered my final work in obtaining the degree of Master of Science in Industrial Engineering and Operation Research.

I would like to thank both my promoters, prof. dr. ir. Sofie Verbrugge and prof. dr. ir. Didier Colle, for allowing me to tackle this challenging project. Secondly, A special thanks to Timo Latruwe, it was he who gave me highly appreciated guidance throughout this project. He answered my questions, gave critical remarks and encouraged me to continue my quest.

Finally, a big thank you to all my friends, family and girlfriend. Before the darkening by the covid pandemic, my time as a student was the most fun I ever had. I'm grateful to my parents in allowing me to pursue my dreams and supporting me whatever my decisions were. Lastly, I would also like to thank the city of Ghent and its university. My love for this place will never perish.

Arthur Versieck, January 2021

Permission for usage

Arthur Versieck, January 2021

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Summary

The transportation landscape is currently in a disruptive change. Car ownership among millennials is declining, urbanization is causing increasing congestion and environmental concerns are rising. Additionally the Flemish government is interested in alternative, cheaper, more durable and flexible transportation services to serve all citizens. Fortunately, driven by the enormous progress in computational power, telematics (telecommunications and informatics), GPS-tracking, and the introduction of other intelligent transport systems, the mobility marked is currently undergoing one of the major shifts of a generation. One emerging solution would be Demand Responsive Transportation (DRT) services, aiming to eliminating the need of fixed-time stops, providing door-to-door service in a ride-sharing scheme. Scale is considered one of the main challenges for DRT, since trips can be optimized not only across the total of destinations, but also the total amount of vehicles and daily demand. However, achieving large scale is a challenge considering initial investments and start up costs. The aim of this project is to assess the economic feasibility of a DRT-service in Ghent. This will be done by combining an adapted simulation model, originally built by M. Čertický, M. Jakob, R. Píbil and Z. Moler and a dynamic cost model built for this project. This way some crucial parameters of different DRT-services under various conditions will be evaluated. Also the economic feasibility of an DRT-provider to operate in Ghent will be discussed.

Keywords: DRT, FTS, cost-modelling, techno-economics, agent-based-simulation

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Abstract— **The transportation landscape is currently in a disruptive change. Car ownership among millennials is declining, urbanization is causing increasing congestion and environmental concerns are rising. Additionally the Flemish government is interested in alternative, cheaper, more durable and flexible transportation services to serve all citizens. Fortunately, driven by the enormous progress in computational power, telematics (telecommunications and informatics), GPS-tracking, and the introduction of other intelligent transport systems, the mobility marked is currently undergoing one of the major shifts of a generation. One emerging solution would be Demand Responsive Transportation (DRT) services, aiming to eliminating the need of fixed-time stops, providing door-to-door service in a ride-sharing scheme. Scale is considered one of the main challenges for DRT, since trips can be optimized not only across the total of destinations, but also the total amount of vehicles and daily demand. However, achieving large scale is a challenge considering initial investments and start up costs. The aim of this project is to assess the economic feasibility of a DRT-service in Ghent. This will be done by combining an adapted simulation model, originally built by M. Čertický, M. Jakob, R. Píbil and Z. Moler [1] and a dynamic cost model built for this project. This way some crucial parameters of different DRT-services under various conditions will be evaluated. Also the economic feasibility of an DRT-provider to operate in Ghent will be discussed.**

Keywords—**DRT-FTS-cost modelling-techno economics-agent based simulation**

I. INTRODUCTION

Transportation has always played a crucial role in our economic and social activities and it has given shape to the world in which we live. Prime examples are agglomeration and urbanization. While offering lots of advantages, urbanization is also posing problems which are increasingly difficult to solve. One major problem is transportation. As populations inside cities explode, road-infrastructure reaches its limitations and the demand for transportation outreaches the supply of road-networks cities can provide. Congestion levels are rising, increasing travel time, costs, air pollution, accidents and noise [2]. Efforts to reduce congestion levels are hindered by the fact that people still maintain firmly by the idea that owning a car remains a necessity in our current society [3].Given the current limited transportation services active in some of our communities it is also hard to refute that idea. Owning a car does not only increase congestion levels, it is also forcing cities to free up precious space to park these vehicles.

Luckily, driven by environmental and economical concerns, the enormous progress in computational power, telematics (telecommunications and informatics) and GPS-tracking, and the introduction of other intelligent transport systems, the automotive, transportation and mobility marked is currently undergoing one of the major shifts of a generations. KPMG states that mobility transformation is fueled by three key technology-driven disruptive trends: Electric Vehicles (EV) and alternative powertrains, connected and Autonomous Vehicles (AV) and Mobility-as-a-Service (MaaS) [4]. The rise of Mobility-as-a-Service and on-demand mobility can be explained by a clear shift in the way costumers view mobility. The desire for car ownership among younger generations, and city residents is declining [5]. Even if this cannot be fully allocated to environmental concerns [6], an increasing number of (young) people strive for a more sustainable way of living, in which mobility is considered as a service

One such solution, Flexible Transportation Services (FTS) is gaining popularity. FTS is an emerging term covering the vast amount of possibilities for innovative mobility providers. DRT is considered as one of the solutions inside FTS, in which the service is fully demand responsive. Demand responsive transportation (DRT), aims to decrease the need for car ownership by providing a new form of public transportation. DRT is a form of public transportation that excludes the need for fixed routes and schedules by dynamically routing its fleet of vehicles based on passenger requests. The main advantage is the possibility to provide trips without transfers and the fact that it frees passengers from time tables and planning. If implemented correctly, DRT could provide taxi-like levels of comfort at reduced costs. DRT can use a similar pricing model to traditional public transportation, as costs can be shared over multiple customers.

However, the launch and failure of multiple DRT-services, such as Kutsuplus [7] in Finland, shows that it is far from sure these services are economically feasible. Scale is considered one of the main challenges for DRT, since trips can be optimized not only across the total of destinations, but also the total amount of vehicles and daily demand. However, achieving large scale is a challenge considering initial investments and start up costs. It is expected that large-scale deployment and the present of a large customer base will provide the necessary scale.

This research project tries to give answer to the question if DRT is economically viable, and how much it would benefits from a large-scale deployment. This project will focus on the region Flanders, because it's urban sprawl might make it a good candidate for a DRT solution. Additionally the Flemish government is reconsidering its transportation services, until now covered by De Lijn [8], this makes it even more interesting to present an alternative solution.

II. What is DRT?

”DRT is a user-oriented form of transportation characterised by flexible routes, smaller vehicles operating in ride-sharing mode, traveling between pick-up and drop-off locations according to passengers needs.” (Community Transport Association, [9]). DRT differentiates itself from current fixed transportation services by replacing fixed-routes and timetables by a service that is fully driven by its own demand, constantly altering its routes based on new requests.

A. Today’s need for new mobility solutions

Urbanization is presenting lots of advantages to the people and organizations in our cities. Congestion levels and the need for private parking space are increasing through the global rise in personally owned vehicles. [10]. Congestion leads to increasing travel time, costs, air pollution, accidents and noise. Personal parking space consumes large amounts of space in our cities, and provides little to no economic benefit if not monetized. Car ownership provides a fully on demand, door-to-door mobility, a flexibility still unmatched by any other mode of public transport. Nowadays, still 84% of drivers globally consider owning a car in the future as important or more important than today. Yet, nearly half of all current car owners (48%) said they would consider giving up car ownership if comparable mobility solutions were available [3].

It is clear that current transportation problems could be alleviated by decreasing the need for personally owned vehicles through improvement of a more on-demand responsive public transportation service. For years, fixed transportation services, with fixed routes and time tables, are operating in our cities, yet their market share stays rather low [11]. Also, operating a public transportation service has historically always been unprofitable and deficits were solved by subsidies provided by the government because this provides benefits on many other aspect (environmental, less accidents, social (making transportation available to a population with lower income)) ([10], [12] and [13]). Nowadays this business model is more and more criticized and, like many other governments [14], the Flemish government is also searching for a possibility to make public transportation more profitable by investing in new and innovating mobility concepts [8].

B. DRT as a mobility solution

Ride-sharing services, providing on-demand responsive transportation is one such innovation becoming more and more popular. Historically, DRT-services always existed, yet it is the evolution in computational power and fast-telecommunication and telematics that changed the concept from a rather inefficient service, with manual planning, to one which is now capable of handling multiple vehicles and requests. The increased popularity in the service is explained by several factors which are leading to a mentality shift towards mobility. The idea of owning a car is now changing to sharing one. This is fueled by both policy decisions in our cities as well as environmental decisions.

C. difficulties for current DRT-providers

Based on [15]:

C.0.a Local regulations. DRT and other forms of shared mobility are heavily influenced by local regulations. This has prevented services like Uber to scale-up to their full potential. Some local regulations represent such high entrance barriers, that DRT-providers simply choose not to enter. This is one of the reasons why the DRT market remains highly fragmented and why their are so many different operators worldwide.

C.0.b Acquisition of customers. The economics of PHV-operators, taxi ride-hailing and public DRT-services (DRPT) are quite different. Still, all business models rely on what is called a ”network effect”, which means that large scale is needed to be profitable. To gain market share, each type of service provides highly competitive pricing and gives discounts to new passengers. This aggressive pricing is fueled by the fierce competition in the ride-sharing market. Most of the revenues of PHV-services are currently invested in Customer acquisition costs (CAC). It can be expected that CAC will be lower for DRPT platforms and taxi ride-sharing, certainly if they operate in partnership with more traditional public transportation platforms or existing taxi-hailing operators. However this does not mean that DRT-platforms are by definition more profitable, as other costs are also important:

C.0.c Costs of drivers and vehicles. To be operational, PHV, DRPT and taxi ride-sharing services currently depend on drivers. With PHV, drivers are usually less expensive. This is explained due to the fact there is no need to train and support employed drivers nor do PHV-services have to provide, and invest in, vehicles. While CAC are typically lower for taxi ride-sharing and DRPT compared to PHV, driver costs tend to be higher. Both DRPT and taxi ride-hailing services have to invest more in assets (vehicles) and drivers, who are now licensed taxi or bus drivers, which are more expensive then PHV-drivers. Moving forward, if and when the development of self-driving vehicles is successful, DRT-providers will be able to dramatically reduce their costs and become more profitable.

C.0.d Questions rise if DRT-services are reducing congestion. In contrary with the story Uber, Lyft, and their peers like to tell, ride-hailing services are not reducing traffic in American cities [16]. Even if they meet their goals for converting solo passenger trips to shared rides they will not reduce traffic [17]. This is mainly allocated to the fact most users switch from non-auto transportation modes.

III. Methodology

The goal of this paper is to assess the economic feasibility of demand responsive transportation services. This will be done based on their most important KPIs. By combining both a dynamic cost model and simulation testbed, different providers will be assessed. The simulation model provides values for different KPIs such as vehicle productivity, occupancy and the amount of vehicles needed each hour. The cost model will use these KPI to generate a PV (Present value) and HW (Hourly Worth) of the service costs, this way, a break-even price for the service will be derived.

A. *Cost modeling approach*

Cost modelling was done using a work breakdown structure (WBS) as framework. Each level of the WBS divides the cost elements into increasing detail. The total discounted cost of the system is then obtained by estimating all cost drivers in this WBS, see Figure 1. Next, to construct a dynamic cost-model, all costs are further divided into operational costs (OpEx) and fixed capital expenses (CapEx). With this classification of costs an hourly cost is generated. This will be used to generate both a PV and HW of the service, which can then be used to calculate a break-even price.

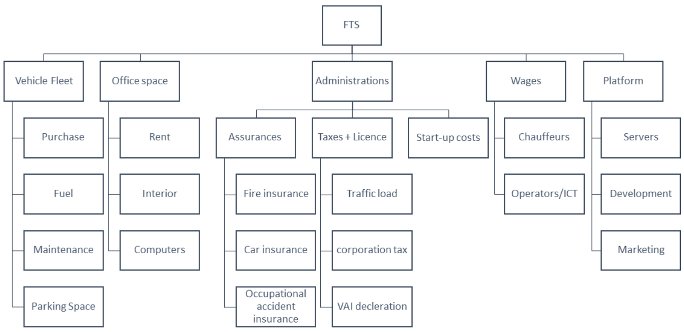

Fig. 1. Work breakdown structure for a DRT-service

B. *Input parameters*

Estimations of all costs is done by performing desk research on existing, or failed, DRT-providers, such as Kutsuplus, combined by an thorough internet search. Notice that this paper focuses on a potential DRT company situated in Flanders. Therefore all values are based on actual prices found for similar enterprises in Flanders. For the time-variant assumptions a time window of 10 years is considered in which the vehicle fleet will be replaced once (the fifth year). Inflation and discount rates are 2% ([18]) and 15% respectively.

C. *Important KPI and output parameters of the simulation*

When assessing the viability of DRT-providers it is not only important to consider break-even pricing. Other KPIs such as their total share of combined trips could also introduce positive externalities that would make the service more viable. The simulation software is altered to calculate following KPI: the success rate of the service (share of all passengers that could be accepted) , the total distance traveled with and without passengers, the total distance shared, the average productivity rate (passengers/hour) of the vehicles, occupancy rate and the amount of taxis required each hour. The success rate, total distance traveled and the amount of taxis required each hour will produce a break-even pricing for the service while the other KPIs are considered when positive externalities.

IV. Simulation Model

A. *Simulation software*

The open-source simulation software build by Michal Certicky, Michal Jakob, and Radek Píbil. [19] is provided by the Czech Technical University. It is an interaction-rich simulation tool for testing and evaluating control mechanisms for traditional demand-responsive transport services (Dynamic Dial-A-Ride Problem) as well as next-generation flexible mobility services. A thorough explanation of the software is given in [1].

B. *Extension of the model*

Currently, the simulation model presented has not yet implemented a ride-sharing DRT-algorithm. For this project, the DRT-algorithm was implemented inside the centralized control mechanism. In short: when a request arrives, the control mechanism first calculates and stores all information it needs for this specific passenger. Next the control mechanism decides on which driver are available for the request, and stores them based on their distance to the new origin at the earliest departure time of the new request. Once all available taxis are listed, the mechanism will iterate over this list until it finds a possible taxi to assign to the new passenger. Two possibilities for each taxi arise. When a taxi has no passengers boarded or queued at the time of the new request, the taxi can be assigned without any problem (as he was already available). In the other case when passengers are already boarded or queued in the taxi, the DRT-algorithm will try to find a possible solution to combine these trips in the most efficient way (minimizing total distance) while still respecting all constraints of the passengers. When a possible solution is found for the requested trip, the passenger receives a notification his request is accepted, and a new trip plan is sent to the taxi driver.

Next to the dispatching logic other functions were also altered to handle ride sharing.

C. *Experiment Process*

To simulate Dial-A-Ride transportation services inside the testbed, three-aspects are considered as explained in article [1].

C.1 Simulation Area

The city of Ghent and its surroundings was set to be the simulation area for this thesis. Together with its surroundings it makes a typical Flemish candidate for DRT solutions.

C.2 Customer demand

Daily demand distribution: To simulate a realistic demand, the daily demand in Ghent is based on an analysis of Berlin's taxi services [20] and an ex-post evaluation of the (failed) DRT-service, Kutsuplus [21]. This paper will focus on weekdays.

Time windows for the requests: The demand distribution is used to generate a latest departure time for all request. Based on this latest departure time and the trips distance the earliest departure and arrival time is calculated. The ride-sharing nature of DRT requires its passengers to accept an increase of their travel time, compared to direct travel. But this increase has to be limited by an allowance factor (a percentage of the direct travel time) that can be altered inside the testbed. A Graphic representation on the requests time-windows can be found in figure 2.

trip - origin and destination: Based on the implemented so-called "center-points" or "hot-spots" (highly visited places in Ghent) the GPS generator generates both a longitude and latitude for the trips origin and destination. These longitude and latitude values are randomly chosen from a normalized distribution around the center-points. Requests also have to have a minimal distance of 1km. To test the viability of this method, 100000 requests were generated giving resulting in an average distance of $9.62 \pm 0.14 km$ *CI 99%*, the max distance is 24.5 km and is only bounded by the area in which we simulate.

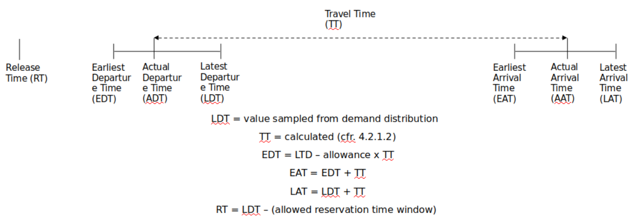

Fig. 2. Graphic representation on requests time-window

C.3 Driver Agents

Driver agents are defined by their ID, an initial position and the properties of their vehicles including capacity, fuel consumption, CO2 emissions or non-standard equipment (e.g.wheelchair accessibility). Their initial positions will also be sampled from the GPS distributions explained in the previous section.

V. Scenario Analysis

A. Introduction: simulating Kutsuplus

Both the simulation model and cost model were initially tested for their correctness by simulating the same settings of Kutsuplus during its last years of operation. By comparing results found by the simulation and the actual values on Kutsuplus, it seems clear both the testbed and cost model are generating results in the correct range. The break-even pricing found in this project is €26.88 while Kutsuplus had a break-even price of €25.8.

B. Impact of different policies

B.1 Impact of centering taxis

the centering of taxis was introduced in order to reduce the large differences in the number of passengers handled between taxis. This was because some taxis ended their last trip far out of the city center and where less likely to be assigned a new passenger. Two policies are considered: Centering to one particular "hot-spot" (Korenmarkt) that is also considerably close to all other hot-spots, or driving back to the closest "hot-spot" after dropping their last passenger. Both options succeeded in their purpose, but it is also concluded that the centering to the Korenmarkt outperforms the other second policy. This because it is also relatively close to all other "hot-spots". It is thus recommended to centralize to one central location that is relatively close to all demand "hot-spots".

B.2 Impact of the extra allowed travel time

Compared with traditional public transport, travelling by car or taxi will typically be less time consuming. To be competitive, DRT should also provide its users an acceptable travel time, which of course will be somewhat higher then a direct travel time because of its ride-sharing nature. An interesting question for DRT-providers arises: "If we allow extra travel time, will the gains in success rate and price be important enough to offset the negative impact on the comfort level of passengers?". To help answer the question different allowances (as explained in IV-C.2) are compared: 30%, 50%, 70% and 100%. This maximum value was chosen because a bus takes about twice as long compared to car travel in Ghent, and if DRT does require the same travel time, the passenger would probably choose the bus because of its lower price. These are the conclusions drawn from the experiment:

- The relative (percentage) average increase in travel time is generally low: This points to the fact that there is not much ride-sharing taking place yet. And if this occurs the extra travel time remains quite low. For a max allowance of 100% the average relative increase is 15% and most of the trips (>60%) only see a maximum increase of 5%. The distribution of the relative increase is also uniformly distributed between 5-100% for all other trips.
- The average drop in price by increasing the maximum allowance is always greater then the monetary equivalent of the additional on-board time. It should thus be highly advisable increase the allowed travel time to te maximum.

B.3 Impact of an increase in allowed reservation time-window

Kutsuplus used a maximum allowed reservation time of 45 minutes before the actual earliest departure, this way the service tried to be as efficient as possible whilst still providing accurate travel times to its customer. This is described both by [22] and [7]. This way of working seems quite bizarre, as one could argue the service would benefit from an increase in the allowed reservation time-window. Also, when using data analysis, it should become increasingly easy to predict travel times, even if reservations are made days in advance. To simulate an increase in allowed reservation time, the initial setting in which requests have to submitted between 60 and 30 minutes before the requested departure time is increased to 120 and 180 minutes (still min. 30 minutes in advance). Following results are found: The performance of the service clearly decreased with an increase in the allowed reservation time-window. This is visible in the average vehicle productivity (passengers/hour) and the amount of distance shared (both reduced). As a result both the success-rate and price of the service are found to be negatively impacted by an increased reservation time window. The explanation for this contra-intuitive result is the fact that it's harder for the algorithm to predict which vehicles will be closer to the request at the time of its earliest departure. This makes it increasingly difficult to efficiently combine passengers, even resulting in a higher total distance driven with less daily passengers travelled.

Thinking about possibilities to overcome this phenomena, an extension to the algorithm could probably be implemented that re-releases previous accepted requests. Rejecting the request would now be impossible, but it would now become easier to predict which taxi will be closer to the request. If a more appropriate taxi is found it could be assigned to the old request and the originally assigned taxi is then released from its duty to pick up this passenger.

B.4 Impact of a flattened demand-curve

Flattening the daily demand distribution of a DRT-service could possibly increase the efficiency of the service by reducing the bottleneck of the service during peak-hours and spreading those passengers over other, less busy, times. This prediction seemed interesting enough to try and simulate. Flattening the daily demand could be done by implementing a variable pricing which would stimulate passengers to travel during a less busy time of the day. This paper will not focus on how big the impacts of variable pricing would be on the customers demand-curve, but will use different demand curves to compare the KPIs. Two different situations are found:

- For less-loaded services (relative low-demand for the amount of vehicles available) it is noted that prices rise when demand is flattened. By flattening the demand the opportunity to share rides during peak-hours is reduced. This reduction is greater then the increased ride-sharing now taking place during other, less busy, times. Resulting in a net reduction in the amount of ride-sharing. This increases the total distance and driver hours needed to serve the same amount of passengers. Therefore it is not advised for services operating with high success-rates to implement a variable pricing scheme.
- For high-loaded services (low success-rates) spreading demand can greatly benefit the service. The net gain in the amount of ride-sharing during non-peak hours now outreaches the net losses of ride-sharing during peak hours. This reduces the total distance driven while in the same time increasing the success-rate. Resulting in a lower pricing for the service.

B.5 Is it worth it to offer a night service?

In previous settings the DRT-provider operated 24hours a day. This provides its users with a great experience but it seems economically less beneficial for the service. The pricing used in previous experiments was the price all customers would have to pay if, by the end of the day, the service would run break-evenly. It is also possible to further investigate on break-even prices by keeping track of the amount of drivers and passengers present each hour. This way a break-even price per hour can be calculated. This showed that the service was much more expensive during the night (even without higher wages). This made it appealing to consider a service only operational between 5-24h. After comparing both services it can be concluded that it is (almost) always cheaper for the service to only provide a daytime service. But, overall the difference in pricing is small and averaging over all simulations this came down to a 2.46% reduction in price, this would by no mean change the viability.

B.6 Impact of an increased vehicle capacity

All previous simulations were done with taxi-services operating with sedan-type vehicles, offering a capacity limited to four passengers. Increasing the capacity could hopefully reduce the amount of vehicles needed to gain the same successes. Results found for this experiment showed that the amount of ride-sharing for the simulated scale (100-150 vehicles, 3000-9000 daily trips) is rather limited (30% of total distance) and that for most of the time ride-sharing is limited to only two different passengers traveling together. Averaging over all instances simulated showed that 85% of shared-rides consists of two passengers, 14% consists of three passengers and only 2% of shared-trips consists of 4 or more boarded passengers. These results are consistent with results found in real-life implementations [23] in which it is concluded that over 90% of shared-rides consist of only two shared rides. When considering which vehicle to use, DRT-providers should focus more on the vehicles purchase price, life expectancy, fuel-efficiency and fuel-type rather then the vehicles capacity.

B.7 Scalability effect on pricing for DRT-services

To finish the scenario analysis, the scalability effect of DRT was considered. This was done by estimating pricing for different sized providers under the same general assumptions (service area, vehicle type, policies in place,...). Two concussions on scalability can be drawn. First, by increasing the amount of passengers per driver, prices drop. This was expected as the vehicle is now serving more passengers per day and the operational expenses are spread over more passengers. Next, with increasing number of drivers (and passengers) the costs also initially seem to drop substantially, but this drop is stabilized and it seems that the prices converge to a minimum. This is indicates that the scalability of DRT-services should not be overestimated. This result is unfortunately not what was had hoped for and it is hard to validate the scalability effect on DRT-services based solemnly on this experiment. However, it can be said that the scale which was considered in this experiment is not considered extreme. This is due to a relatively time-inefficient algorithm combined with extremely high demand. There are still lot of opportunities here that could help reduce calculation time. However, these will not be elaborated here because the scale of this experiment would lead us too far from the economic feasibility analysis for which this paper was intended.

VI. Economic Feasibility Analysis

The economic feasibility analysis is done by estimating pricing for different type of providers based on acceptable demand levels. If this pricing could compete with other modes of transportation, it can be concluded that DRT-services are feasible.

A. Acceptable trip-demand levels in Ghent

To validate the economic feasibility of DRT-services in Ghent three different scenarios are taken into consideration. An optimistic, a pessimistic and a most probable scenario in which trip-demand levels differ. Estimations are done based on results found by Kutsuplus [7] and an overview on mobility, made by the city of Ghent in 2019" [24].

	Pessimistic	Realistic	Optimistic
privately-owned DRT	2000	7500	15000
DRPT-service	2000	8000	12500

Fig. 3. Estimated amount of daily trips

B. Break-even price found for different providers

Following table represents break-even prices found for the different type of considered providers. These differ based on costs. For each level of demand the amount of drivers is minimized but the success-rate must be at least 95%. "DRT" is a newly introduced-service, "coalition" is a coalition between an existing taxi-service and DRT provider, "PHV" is private hire vehicle, and "DRPT" is a publicly provided and owned service.

daily demand -drivers	DRT	coalition	PHV	DRPT
2000-55	€ 10.63	€ 9.96	€ 6.07	€ 10.63
7500-185	€ 8.99	€ 8.78	€ 5.14	€ 9.12
8000-195	€ 9.12	€ 8.76	€ 5.11	€ 8.99
12500-300	€ 8.87	€ 8.63	€ 4.96	€ 8.87
15000-375	€ 8.98	€ 8.8	€ 5.02	€ 8.98

Based on a sensitivity analysis the driving cost factors are considered (in order of influence): driver wages, purchase price of vehicles, fuel price and or fuel efficiency, maintenance costs and the insurance of the vehicles. Notice that other influences are also considered, yet their impact on pricing is minimal (if occurring separately).

C. Comparing DRT to its competitors

C.1 Private car ownership

Ownership of a car has a fixed cost of around € 13.5 per day and a variable cost of around € 0.09 per km [2]. In this experiment the average distance of each trip was 9.62km. Considering the average of 2.3 daily trips per person [24] the price for car-ownership would be € 15.5/day or € 6.7 per trip. Here the car owner uses his car daily. It is easy to see that when car-owners are not daily users, trips would be more expensive. Because of the relative low difference for trip prices, DRT is considered a valuable alternative at the estimated levels of demand.

C.2 Public Transportation

The cheapest possible option to use public transportation in Ghent would be to purchase a yearly subscription to the service. In Flanders this will cost € 334 [25]. Considering the average amount of daily trips (2.3), each trip would cost € 0.4. This price seems hard to beat for DRT-services, yet public transit is much more time consuming and public transport is heavily subsidized, so the mentioned price will not reflect the real cost. If the difference in travel time and the equivalence money value of time are taken into consideration, it is estimated that public transportation trips cost somewhere between € 4 and € 7.6. This shows that public transportation would not necessarily be a much better alternative than DRT.

C.3 Car-sharing

By using pricing levels found for the most famous car-sharing provider in Ghent, Cambio [26], and an average car-sharing user (50-300km/month), each trip is validated at around € 3.2. This is only including the time in which the vehicle is driven. For each hour spend with the vehicle not being parked at a Cambio spot, the trip cost is increased with € 1.75 (excluding parking fees). The low availability of cambio cars in rural areas is also a disadvantage. DRT is thus considered a viable alternative to car-sharing.

C.4 taxi-services

It is clear that DRT-services would be a worthy alternative if customers accept the possible ride-sharing and its increased travel time. Taxi-services are basically DRT-services in which rides are not shared. The price difference is also considerably in favor of DRT with ride-sharing. In Ghent, the average price for a taxi is between € 1.6-2.3/km plus a base fee of around € 9 (including the first 3km). For the a trip of 9.62km the customer would pay $\pm$€ 22.4.

D. Conclusion on viability

The presupposed amount of daily trips were estimated without considering any pricing. After calculating break-even prices for the different type of providers and proving that these are considered competitive to most likely competitors, it is shown that the estimated amounts are achievable. Therefore it can be concluded that DRT is economically feasible in Ghent.

E. Operating with an existing taxi-services

To reduce risks for new operators it would be an option to work together with existing taxi services in the area. For this experiment V-tax (the biggest taxi-provider in Ghent-130taxis) was considered. With the existing levels of demand for the service (1000 trips/day) prices were reduced with 10% by implementing ride-sharing. This section also concluded that their are way to many operators operating in the area. Even if no ride-sharing was allowed, the vehicle fleet of v-tax was able to reach much higher levels of demand while maintaining a stable success-rate (%). The current taxi market in Ghent is considered unhealthy as the total fleet of available taxis are spread over way to many providers (73 taxi services operating with an average of 1.25 vehicles each). Uber has currently entered the marked in Ghent, and it seems that, if taxi-operators are not willing to collaborate and increase the efficiency of the available total amount of vehicles, they will have a hard time surviving.

VII. Conclusions

This thesis subject was initialized to validate the economic feasibility of DRT-services. After constructing both a dynamic cost model and agent-based simulation model, it can be concluded that DRT-services are economically feasible in the considered area (Ghent). This conclusion was drawn by estimating realistic demand levels for DRT in Ghent and comparing prices with existing alternatives such as car-ownership. Here, DRT was found to always be a possible cost efficient alternative. While a positive indication for economic viability is now established, it seems that the current implemented DRT-algorithm is still not perfect and struggles to simulate high levels of demand. For this reason this thesis was unable to consider large scale services. This could be the focus for a new thesis subject.

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Contents

List of Figures

List of Tables

List of Abbreviations

DRT	Demand Responsive transport.
FTS	Flexible Transportation Service
P2P	Peer To Peer
STS	Special Transport Services
PHV	Private-Hire Vehicles
DRPT	Demand Responsive Public Transport
AVL	Automated Vehicle Locationing
MaaS	Mobility as a Service
FPT	Fixed Public Transport
CAC	Customer Acquisition Costs
PV	Net Present Value
AW	Annual Worth
DW	Daily Worth
HW	Hourly Worth
CapEx	Capital Expenditures
OpEx	Operating Expenditures
KPI	Key Performance Indicators
DARP	Dial-A-Ride Problem
AV	Autonomous Vehicle
EV	Electric Vehicle

Chapter 1

Introduction & Motivation

Transportation has always played a crucial role in our economic and social activities and it has given shape to the world in which we live. Prime examples are agglomeration and urbanization. The existence and growth of cities can be explained by considering the fact that transportation costs for goods and people are easily reduced by centralizing activities. But, next to a reduction of transportation costs, lots of other advantages are presented by urbanization and agglomeration, such as the large demand and supply for labor, knowledge transfer between organisations and a great internal market. Nevertheless, urbanization also comes with increasingly difficult disadvantages and problems. As populations inside cities explode, road-infrastructure reaches its limitations and the demand for transportation outreaches the supply of road-networks cities can provide. Congestion levels are rising, increasing travel time, costs, fuel costs, air pollution, accidents and noise [6]. Efforts to reduce congestion levels are hindered by the fact that people still maintain firmly by the idea that owning a car remains a necessity in our current society [7]. Given the current limited transportation services active in some of our communities it is also hard to refute that idea. Extensive private use of cars is not only increasing congestion levels, it is also forcing cities to free up precious space to park these vehicles. Imagine the opportunities created by freeing up this parking space in our cities. Parking lots could become recreation areas or city parks, less on-street parking could create space for more trees and green areas next to the street etc...

Luckily, driven by environmental and economical concerns, the enormous progress in computational power, telematics (telecommunications and informatics), GPS-tracking, and the introduction of other intelligent transport systems- the automotive, transportation and mobility marked is currently undergoing one of the major shifts of a generation. KPMG states that mobility transformation is fueled by three key technology-driven disruptive trends: electric vehicles and alternative powertrains, connected and autonomous vehicles and Mobility-as-a-Service (MaaS) [8]. The rise of Mobility-as-a-Service and on-demand mobility can be explained by a clear shift in the way people view mobility. The desire for car ownership among millennials, those born in the 1980s and 1990s, and city residents is declining [9]. Even when this cannot be fully allocate to environmental concerns (Nicholas J.Klein, Michael J.Smartb [10]), an increasing number of (young) people strive for a more sustainable way of living, in which mobility is considered as a service. For the current and future industry players, this disruption creates opportunities for alternative and economically interesting solutions.

One of these solution, Flexible Transportation Services (FTS) is gaining popularity. FTS aims to decrease the need for private car usage by providing a new form of public transportation. Demand Responsive Transportation (DRT) is one category of FTS. DRT is a form of public transportation that excludes the need for fixed routes and schedules by dynamically routing its fleet of vehicles based on passengers trip requests. The main advantage of DRT-services is the possibility to provide trips without transfers and it frees its passengers from time tables and planning. If implemented correctly, DRT could provide taxi-like levels of comfort at reduced costs. DRT can use a similar pricing model to traditional public transportation, as costs can be shared over multiple customers. The idea of DRT is not new, but the difference is that in the past routing and planning had to be done manually, which implied customers had to arrange trips long in advance. Nowadays, because of the technological evolutions its possible to calculate and offer shared trips in the blink of an eye. In combination with self-driving vehicles, DRT shows lots of potential.

However, the launch and failure of multiple DRT-services, such as Kutsuplus in Finland, show that it is far from sure these services are economically feasible. Achieving scale is one of the main issues for DRT. Since trips can be optimized not only across the total of destinations, but also the total amount of vehicles, it is expected that large-scale deployment and liquidity of customers have huge benefits of scale.

This research project tries to give answer to the question if DRT is economically viable, and how much it benefits from this large-scale deployment. This project will focus on the region Flanders, because it's urban sprawl might make it a good candidate for a DRT solution. Additionally the Flemish government is fading out the third layer of transportation services, until now covered by De Lijn, through the "basic reachability" policy [11], this makes it even more interesting to present an alternative solution.

In Chapter 2, the literature study, a further introduction on the concept of demand responsive transportation (DRT) is given. It gives an introduction on the idea behind DRT, its history and the current need for an updated version of DRT. Next, some examples of DRT services are given to illustrate the large flexibility DRT services can offer. Of course, DRT-services also face important difficulties in reaching scale. These difficulties will be presented and discussed in a further sub-chapter. To conclude the literature study, a short case study on Kutsuplus, the world's first fully automated, real-time demand public transportation service is given. This translates the theoretic implementation of DRT in a real-life example, making DRT more tangible for the reader.

Chapter 3 discusses the methodology on how this paper will assess DRT-providers. This will be done by combining a dynamic cost model (introduced in Chapter 3) with simulation software (introduced in Chapter 4) to compare important performance indicators for different DRT solutions. These performance indicators include break-even pricing, vehicle efficiency, daily distribution of vehicles needed, occupancy rates and total distance driven without and with one or more passengers.

Chapter 5 will first introduce a simulation done on a Kutsuplus-like service. This way, the reader will get an overview on how important KPI are considered. Next, the impact of different policies will be discussed, such as the impact of an increased maximum travel time to allow for more ride-sharing or the impact of allowing reservations to be made earlier on. These results will provide insights on the question how beneficial large-scale deployment of DRT is, both economical as environmental.

Chapter 6 will focus on the economic feasibility of DRT. An overview is given of the most important cost factors for the different types of providers, both privately as publicly owned. To conclude, the economical feasibility of DRT-services is discussed.

Chapter 2

Literature Study on-demand-Responsive Transportation

"In an ideal world public transport would be as convenient as private transport, suggesting that all public transport should be demand responsive." (Corinne Mulley, John D.Nelson [12])

2.1 What is demand responsive transport?

"DRT is a user-oriented form of transportation characterised by flexible routes, smaller vehicles operating in shared-ride mode between pick-up and drop-off locations according to passengers needs." (Community Transport Association, [13]). DRT differentiates itself from current transportation services by replacing fixed-routes and timetables by a service that is fully demand driven, constantly altering its routes based on new transportation service requests. Fueled by ubiquitous connectivity, ever more powerful smartphones, and cloudhosted applications, DRT-services, both privately and publicly owned, are changing the urban mobility landscape for good [1].

Demand responsive transportation is a scheme in which three entities are constantly interacting:

- **Passengers**: Passengers who want to make use of the transportation service make a reservation some time in advance (usually around one hour before the actual trip) by using a specific application or by visiting the website of the service provider. To make such a reservation, passengers have to define an origin and destination, the number of seats needed and a desired arrival time. If their request is accepted, they receive multiple possible solutions with different price depending on parameters such as speed, walking distance or their travel time during the day. From these options, the passengers can choose the solution that best fits their wishes.

- **Central dispatching agent**: The central dispatching agent, will allocate a vehicle that best suits the needs of the customer, by using an algorithm and real-time information of the network, made centrally available. This information includes actual and planned position of the vehicles, the passengers on board or queued, and their associated pick-up and drop-off times. Using a DRT-algorithm, the agent will try to allocate the new passenger's request to one of its vehicles replanning the route where needed while still maintaining an acceptable solution for the already boarded or queued passengers . Using smart combinations, the agent tries to minimize the total costs for both the provider and its customer.
- **Drivers**: Drivers follow the route communicated to them by the dispatching agent and displayed on their driver application. Drivers can be full time employees or work as free-lancers, using company cars or private cars. Services like Uber and Lyft offer peer-to-peer (P2P) ride-sharing, in which car owners use their vehicles to offer transportation services [14].

The main goal of DRT-services is to provide its passengers with taxi-like levels of comfort: (almost) door-to-door service, direct trips (no transfers), not bound by fixed time tables or fixed departure and arrival location, while still providing a fare structure close to those of current public transportation services by dividing the total cost over multiple ride-sharing passengers.

In the first sub-chapter, some history on the origins of DRT is given, next the challenges of urbanization and transportation are presented. These challenges provide new opportunities for DRT-services, yet, as there are multiple examples of failed DRT-services (such as Kutsuplus), one could question the economic viability of DRT-providers. Therefore, a quick overview on the current challenges and some examples of existing or failed providers are presented in a next sub chapter.

2.1.1 Some history

In the mobility sector, demand responsive transportation (DRT) seems a rather new and innovative concept, yet the idea to provide DRT stems from the early days of public transportation. Two important historical examples show how the idea of DRT combined with ride-sharing grew to what is now becoming one of the most important innovations in the mobility and transportation sector.

For most of its history, public transportation was implemented based on fixed routes with fixed stops and corresponding time-windows. This models works well in urban areas, where population density and the demand for transportation is high. The model however experiences difficulties to operate cost-efficiently in more rural, low-density areas. Without enough demand these public transportation services are not efficient, driving around with low occupancy rate for much of the time. A solution to this problem was to develop a more demand driven transportation service, without the use of fixed routes and schedules. Passengers traveling in rural areas had to make reservations for a trip some time in advance, often at least one day before the actual trip. The operator would then, often manually, generate a route plan for its vehicles, and accept requests if possible. Vehicles thus had no fixed trip plans and the routes were planned on a daily base, depending on the demand. An example for such a service in rural Flemish areas is the so-called "BelBus" [15], a DRT-service provided by the company "De Lijn", which is mostly owned by the Flemish government [16]. This DRT-service came into existence in 1991 . To use the service, passengers have to arrange a trip 30 days to at least one hour in advance and fill in at which stops (not a door-to-door service) they want to enter and leave the vehicle. The operator will then check the feasibility of the requested trip given its current accepted demand. The earlier the customer requested its trip, the higher the probability of its acceptance. An optimal route is made and an acceptation is send via email.

Another important historical example is the service for people with special needs [17] . The so called door-to-door dial-a-ride service (sometimes referred to as Special Transport Services – STSs) provided a solution for the elderly and disabled, who have difficulties using normal public transportation. The operation of this door-to-door service is similar to the DRT service discussed previously: customers would typically call some days in advance to arrange a trip, and the service operator would plan the service manually. One such example is the introduction of a new DRT-service in Ljubljanski in 2008 [18]. The public company LPP introduced a new transportation service for the elderly, which later also became available for the disabled.

These examples show how the concept of on-demand responsive transportation came into existence. It seemed a great solution to multiple transportation problems, still because of the lack of digitalization (partly explained by the time when these solutions were developed) and the limited scope these services remained insignificant for the large public. These services were often criticized because of their relatively high cost, incapability to manage high demand and their lack of flexibility.

2.1.2 Today's need for new mobility solutions

As stated in the introduction, urbanization, is presenting lots of advantages to the people and organizations present in our cities. But, it also comes with its own disadvantages: congestion levels and the need for private parking space are increasing through the global rise in personally owned vehicles (figure 2.1.1, [19]) Congestion leads to increasing travel time, fuel costs, air pollution, accidents and noise. Personal parking space consumes large amounts of space in our cities, and provides little to no economic benefit if not monetized. The increase in car ownership worldwide is a phenomenon partially explained by a global economic growth and the ease of using personal transportation over public transit services. Car ownership provides a full on-demand, door-to-door mobility, a flexibility still unmatched by any other mode of transport. Once individuals get access to a private vehicle the average number of bus journeys they take decreases quickly. Nowadays, still 84% of drivers globally consider owning a car in the future as important or more important than today. Yet, nearly half of all current car owners (48%) said they would consider giving up car ownership if autonomous mobility solutions were available. These were findings by the report "Mobility Services: The Customer Perspective" performed by Accenture [7] based on a survey of 7,000 consumers in the U.S., Europe and China of whom 85 % were car owners. The same report states that revenues from mobility services are projected to reach nearly €1.2 trillion by 2030, with the exponential growth in the market for mobility as a service driven by constant improvements in autonomous vehicle technologies.

It is clear that current transportation problems could be alleviated by decreasing the need for personally owned vehicles through improvement of a more on-demand responsive public transportation service. For years, fixed transportation services, with fixed routes and time tables, are operating in our cities, yet their market share stays rather low, see figure 2.1.2 [20]. It can be stated that, even with the multiple improvements they achieved, they do not seem to convince enough customers, which often require higher standards. A big difficulty for public transportation (Dr. Jean-Paul Rodrigue [19]) is the fact that demand for public transit is subject to periods of peaks and troughs. During peak hours, crowdedness creates discomfort for its users as the system copes with a temporary surge in demand. This creates the challenge of the provision of an adequate level of transit infrastructures and service levels. Planning for peak capacity leaves the system highly under-used during off-peak hours while planning for an average capacity will lead to congestion during peak hours. With DRT-services, certainly those with a P2P-ride-sharing scheme, the supply of vehicles could be increased during peak-hours by offering drivers higher pay, or demand could be decreased by increasing pricing to its customers.

Operating a public transportation service has historically always been unprofitable and deficits were solved by subsidies provided for by the government because public transportation provides many benefits on other aspects (environmental, less accidents, social (making transportation available to a population with lower income)) ([19], [21] and [22]). Nowadays this business model is more and more criticized and, like many governments [23], the Flemish government is also searching for a possibility to make public transportation more profitable by investing in new and innovating mobility concepts [11].

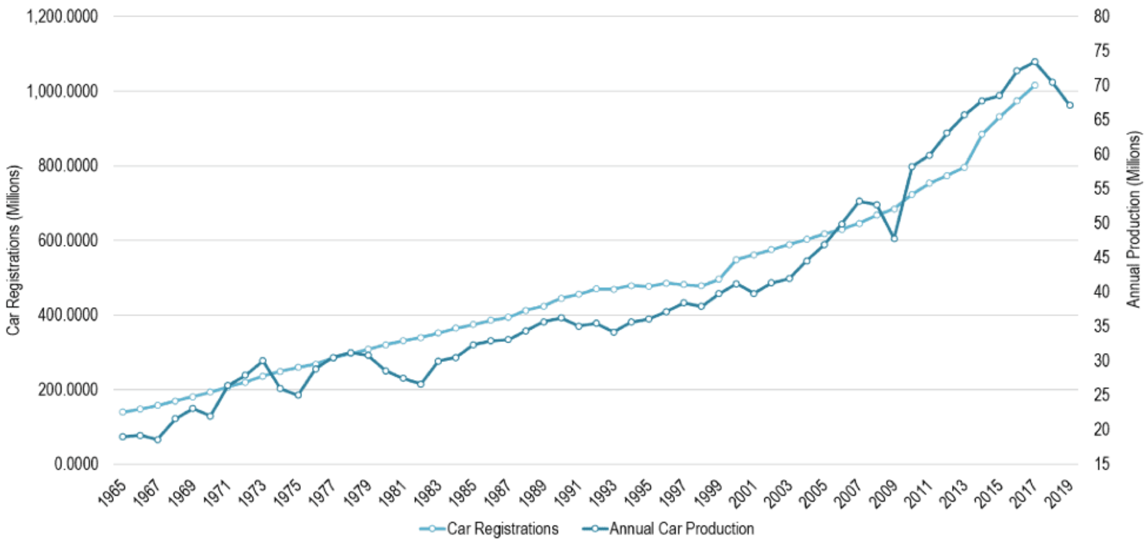


Figure 2.1.1: World Automobile Production and Fleet, 1965-2019

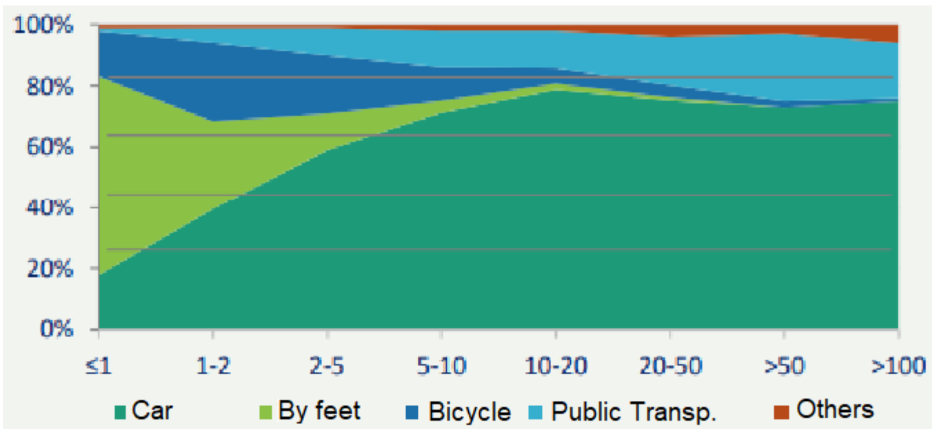


Figure 2.1.2: Transportation means by distance in Belgium (km, 2016)

2.1.3 Demand responsive transportation as a mobility solution

One such mobility innovation that is becoming more and more popular are ride-sharing services providing on-demand responsive transportation. Enabled by ubiquitous connectivity, ever more powerful smartphones, and cloud hosted applications these services are transforming urban mobility landscape for good. An overview of the changes mobility on-demand went through is given in figure 2.1.3 [1]. Most of its history, presented as stage one in the figure, was already explained in subsection 2.1.1. During this stage most services heavily relied on assets and human skills, such as driving and planning of trips. It was also the computational limits and the lack of telematics during this time period that left little to no space for innovation in the market. On-demand 2.0 is driven by the enormous technological advances of the late 20th century and a rise in popularity for mobility on-demand, explained by several factors such as:

- Motivations for car ownership are changing: The car is the second most expensive item that most of us will buy, and yet it is parked 96% of the time [24]. Younger people in particularly still tend to regard cars as necessary (e.g. for their work), but they do not particularly value the perceived autonomy, status or prestige that car ownership is thought to offer ([25]). This moves the idea from owning a car to sharing one. A forecast done by Deloitte Belgium ([26]) predicts that 31% of all kilometres driven in Belgium will be shared by 2030, yet currently ride-sharing trips are reported to represent only about 1 percent of the overall number of kilometers traveled in the world [1]. This comes to show that ride-sharing services are expected to grow rapidly and have an increasing impact on urban mobility systems as users warm to the new paradigm.
- "In a successful modern city, the car must no longer be king" [27]. Although walking and cycling have the most social benefits and fewest negative effects, they are often under-represented in people's mobility behaviour. Therefore cities are now encouraging walking and cycling through infrastructural and policy changes. These changes make it even more important to implement a well working public transportation service. An example in Belgium is the so-called "circulatieplan" introduced in Ghent [28]. This new policy introduced so-called "knips": borders which normal cars were not allowed to cross in contrast to buses, taxis, pedestrians and cyclists. This example shows how a city tries to reduce to ease of car travel in favour of a more environmental friendly alternative.
- Changes in our society such as working from home become more and more popular. As owning a car is often justified by needing it for work, working mostly from home will make it less economically viable to own a car compared to sharing one [29].
- Technological advances: improved DRT-algorithms, fast-telecommunications and the introduction of telematics opened up a great opportunities for DRT-services. Not only for

the provider, whose efficiency is increased by new algorithms, but also for the passengers using the service. Arranging a trip nowadays is as simple as visiting a website or application and clicking some buttons. This makes the on-demand services very user-friendly and therefore potentially more popular.

- Environmental changes: Most people now accept the fact that climate change is happening [30] and scientist around the world are clear that this change is mostly caused by humans [31]. The need for more environmentally friendly solutions is rising in a quest to reduce carbon emissions and other forms of pollution [32].

The third phase representing a future in which further developments in demand responsive public transformation, autonomous and self-driving vehicles and the convergence of multiple different mobility providers, both privately as publicly owned will further increase efficiency, viability and popularity of DRT services.

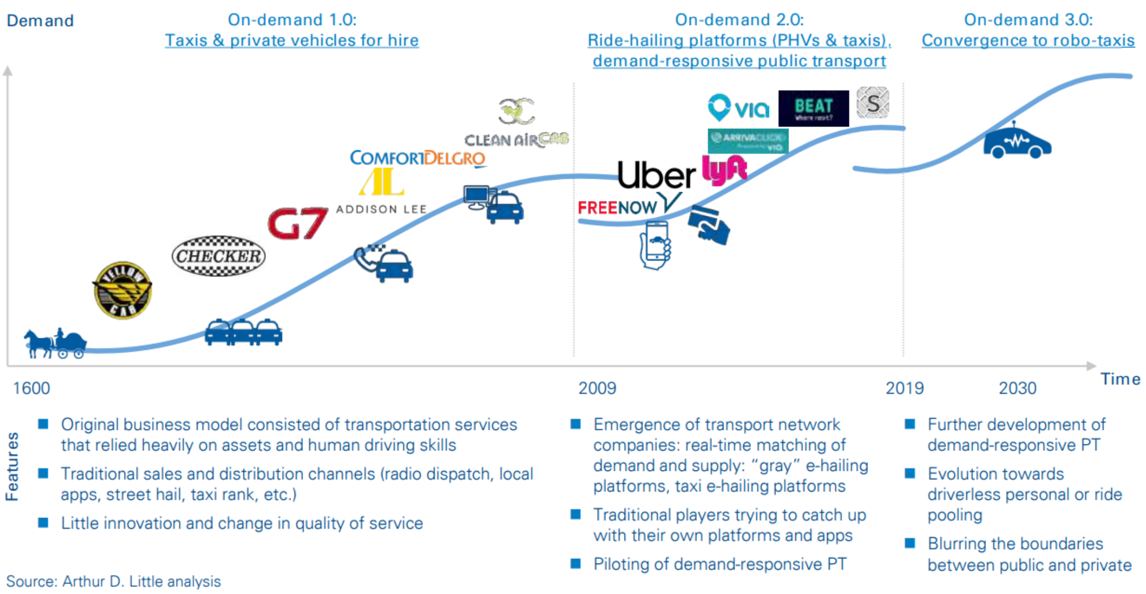


Figure 2.1.3: On-demand mobility market evolution

2.1.4 Current flexible transportation services

First, lets introduce a new emerging term used for DRT-providers: Flexible Transport Services, in short: FTS. FTS covers services provided for passengers (or even freight) that are flexible in terms of route, vehicle allocation, vehicle operator, payment schemes and type of users. The flexibility can vary along a continuum of demand responsiveness from fixed-route services (conventional public transport) to fully DRT-services. FTS are thus the operators that provide DRT-services, but from this point on, when talking about FTS, highly DRT-services are meant.

To conclude previous sub chapter, improved DRT-algorithms, fast-telecommunications , the introduction of telematics and a shift in both policy as well as environmental decisions shifting the idea of owning a car to sharing one represent great opportunities for FTS-providers. and many new and innovative services came into existence. Examples exist for different type of providers. There are providers working with private-hire vehicles (PHV) (UberPool, lyft Line) in which drivers can register with their personally owned vehicle and earn money by ride-sharing. Other providers work together with licensed taxi-services to provide ride-sharing to its customers (Wecab, Collecto). In other cases, FTS-providers also develop partnerships or collaborate actively with public transport authorities or operators to offer services that complement, or even partly replace, public transport. These joint services offer “demand responsive public transport”, in short DRPT (Kutsuplus). FTS-Providers are flexible in many aspects, see table 2.1.1, yet their inner way of working is always similar. As described by C. Mulley and J.D. Nelson [12]: "Telematics-based FTSs are based upon organisation via Travel Dispatch Centres (TDCs) using booking and reservation systems which have the capacity to dynamically assign passengers to vehicles and optimise the routes. Automated Vehicle Locationing (AVL) systems are used to provide real-time information on the status and location of the fleet for the route optimising software."

Many DRT-providers are also interested to emerge as a cornerstone of future Mobility as a Service (MaaS) schemes. MaaS combines different modes of transport seamlessly and offers prospective users both payment and ICT integration. By operating together with other operators, providing different forms of transportation inside a MaaS scheme, the potential user base for the DRT operator is larger then when operating stand-alone. This can be explained due to the fact that MaaS eases the usage of different modes of transport thanks to the integration it provides, facilitating the inclusion of the considered modes into new mobility patterns. As a result, the likeliness that an individual who considered using DRT will be even more inclined to use DRT when this is part of a MaaS scheme. These are results found by Alonso González (2017, [33]). This could possibly provide an answer to the first major problem which FTS-providers face: their need for high demand in order to work cost efficiently.

Question	Answer
How does the user book their journey?	- Telephone call - Internet (website/App) - ...
When is booking required?	- On the day/when required - In advance - Repeating booking - ...
How frequently should the service run?	- When requested - Fixed number of journeys a day - ...
How flexible is the route?	- Fully set, but only runs when there is demand - Deviations possible within a set corridor - fully door-to-door
What area is the service covering	- Rural - Suburbs - City center - Mixed
Who are the main users?	- All public - Disadvantaged groups - Private groups
What size of vehicle should be used?	- Car - Minibus - Bus
What is the price for the user?	- Free - Fixed price - Pricing per km - ...
How is the DRT system financed?	- Subsidised - Partly-Subsidised - Commercial

Table 2.1.1: Flexibility of different parameters for FTS-providers, based on [5]

2.1.5 difficulties of current flexible transportation services

After introducing its history, presenting the need for DRT today and giving an overview of the flexibility and providing some examples of FTS-providers, this section will introduce and shortly discuss the difficulties which many FTS-providers face. In contrast to the early days, technological barriers do no longer obstruct the potential of FTS-providers, although further development of AI, smart demand-planning and self driving vehicles could further increase the efficiency of their services. DRT services however still face some important barriers. Most of the following examples are based on the report "Rethinking on-demand mobility" by Arthur D.Little [1].

First lets introduce the term ride-hailing: ride-hailing refers to an act when a customer orders a customised ride online usually via a smartphone application. As opposed to ride-sharing, the driver generally does not make any stops between the starting point and destination. Ride-hailing and ride-sharing are not exactly the same, yet both terms are often used interchangeably. Luckily ride-hailing services can be extended with a ride-sharing nature if customers accept traveling together without much investment costs other then implementing ride-sharing algorithm to its dispatcher unit.

Local regulations DRT and other forms of shared mobility are heavily influenced by local regulations. This has prevented services like Uber to scale-up to its full potential, as is the case in Belgium ([34]). Every local government imposes its own regulations on these services such as licensing and labor laws for drivers, often to protected local traditional taxi services. It is very costly and time consuming for for DRT operators to try to keep abreast of all the different local regulations in a fast-changing market. Some local regulations represent such high entrance barriers, that DRT-providers simply choose not to enter. This is one of the reasons why the DRT market remains highly fragmented and introduced many different operators worldwide, making the DRT market a highly competitive market, which can definitely be seen both an opportunity as an additional difficulty presented in the next paragraph.

Acquisition of customers The economics of PHV-operators (Private Hire Vehicles), taxi ride-hailing/sharing and DRPT (Demand Responsive Public Transport) services are quite different (shortly explained in section 2.1.4) . Still, all business models rely on what is called a "network effect", which means that large scale is needed to be profitable. To gain market share, each type of service provides highly competitive pricing and gives discounts to new passengers. This aggressive pricing is fueled by the fierce competition in the ride-sharing market, where it is also expected a “winner-take-all" will take place. Companies like Uber require large amounts of liquidity due to a high “cash-burn”. Uber is currently losing about $3 for each $1 they make, even without the need to invest in an own fleet or in the recruitment, training and supportment of full time employed drivers [35]. Figure 2.1.4 presents a simplified economics on PHV ride-hailing platforms . It shows that Customer Acquisition Costs (CAC) represents a large part of the OPEX for such a platform (40 to 80%). It can be expected that Customer Acquisition Costs will be lower for DRTP platforms and taxi ride-hailing/sharing, certainly if they operate in partnership with more traditional public transportation platforms or existing taxi operators. However this does not mean that DRT platforms are by definition more profitable, as other costs are important:

Acquisitioning and costs of drivers To be operational, PHV, DRPT and taxi ride-sharing services currently depend on drivers. With PHV, drivers are usually less expensive compared to the other alternatives. This is simply explained due to the fact there is no need to train and support full time employed drivers nor do PHV-services have to provide, and invest in, vehicles. To convince new drivers to work for them, PHV-services provide lots of benefits (for example free trips as passengers) and even cash to their newly acquisitioned drivers. Drivers also receive a higher pay when demand for trips is high. This way, operators try to cope with demand. While customer acquisition costs are typically lower for taxi ride-sharing and DRPT compared to PHV, driver costs tend to be higher. Both DRPT and taxi ride-sharing services have to invest more in assets (vehicles) and drivers, who are licensed taxi or bus drivers, which are more expensive then PHV-drivers, who often have to pay for licensing themselves. As an example, taxi ride-sharing platforms typically take a 10–15 percent fee per trip (as opposed to 20–30 percent with PHV ride-sharing platforms), while the remaining revenue is kept by the traditional taxi operator. Moving forward, Moving forward, if and when the development of self-driving vehicles is successful, DRT-providers will be able to dramatically reduce their costs and become more profitable.

Questions rise if DRT-services are reducing congestion In contrary with the story Uber, Lyft, and their peers like to tell, ride-hailing services are not reducing traffic in American cities [36]. Nor will they, even if they meet their goals for converting solo passenger trips to shared rides, according to study done by Mr. Schaller [37]. This is mainly allocated to the fact most users switch from non-auto modes. The study suggest that policy makers who are striving to reduce congestion should limit low-occupancy vehicles, increase the shared-ride percentage of DRT-services (both for PHV-services and taxi ride-hailing) and ensure frequent and reliable bus and rail service. This shows that next to being economically viable, DRT-providers should also strive to become more environmental friendly by increasing the amount of shared-rides. Therefore in this paper, the shared-ride KPI will often be discussed as an important KPI.

Flexibility leads to questions Many different options can be considered for DRT platforms, and it is difficult to predict what model will dominate in the future. Will it be a model based on PHV, or will people remain skeptical about being served by untrained and unprofessional drivers in private cars which are possibly less safe? Will it be acceptable that private companies operate public transport or will we prefer to invest in a DRPT system, regulated and subsidized by the government? Should we operate alone or cooperate in a MaaS network? Will DRT complement or replace current public transportation?

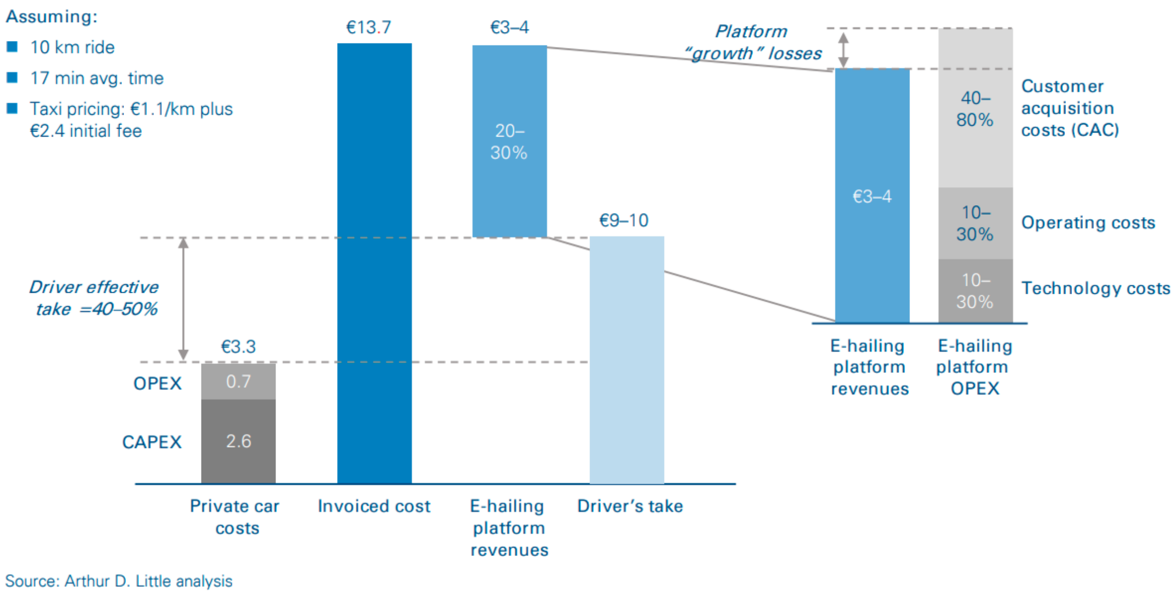


Figure 2.1.4: Simplified economics of PHV ride-hailing platforms (€/trip) ([1])

2.1.6 conclusion

DRT as a concept stems from the early days of public transportation, in which it was presented as a possible solution for public transit in rural areas or as a service for passengers with disabilities. Nowadays, urbanization and the related problems ask for new mobility-solutions to reduce the car ownership. Luckily, driven by technological advances and motivational changes on car ownership and environmental issues, DRT and other mobility solutions such as MaaS are gaining more and more support. But, as the mobility market is highly competitive and the options for DRT-implementations are vast, most DRT-providers are not yet capable to reach a high enough user base to operate cost-efficiently.

2.2 Case study: Kutsuplus

In the next chapter we present a case study on Kutsuplus, to illustrate the workings, opportunities and difficulties of an FTS-provider. Operating in Helsinki, Kutsuplus was the world's first fully automated, real-time demand-responsive public transport service operational in Helsinki, which made it also one of the first FTS solution active in an urban area. Kutsuplus was developed by Helsinki Regional Transport Authority (HSL) and Split Finland Ltd. (earlier Ajelo Ltd.) and operated in coexistence with the other modes of public transportation. Most of this case study is based on insight gathered from the final report on Kutsuplus [2] and an ex-post evaluation done by Nils Haglund [4].

2.2.1 Background

Although the absolute number of journeys with public transportation in Helsinki increased over a period of almost 50 years, its share among trips had been decreasing. This trend had ceased in 2012, as the share of public transport had increased from 42% in 2008 to 43% in 2012 (fig 2.2.1). However, the number of private car trips was still increasing. The basic idea of Kutsuplus was to provide a service that could tackle congestion, parking problems, and other environmental problems caused by non-shared private car trips in the metropolitan area. Based on the fact that every second almost 50 trips were made in the Helsinki metropolitan area the potential of combining trips was recognised. Also, evolutions is ICT, including accurate positioning technologies, enabled real-time optimization of shared trips in a large-scale service. All these factors drove Aalto University into researching the possibility of a new and cost-effective mode of public transport that could compete with the luxury of owning a private car. The project was funded by the Finnish Funding Agency for Innovation (TEKES), Helsinki City Transport Innovation Fund, Helsinki City Transport (HKL), and the Ministry of Transport and Communications. The results of the initial research were very promising and it was decided to start a novel transport service to offer shared rides enabled by an automated control and service system. This lead to the launch of Kutsuplus on April 3th 2013.

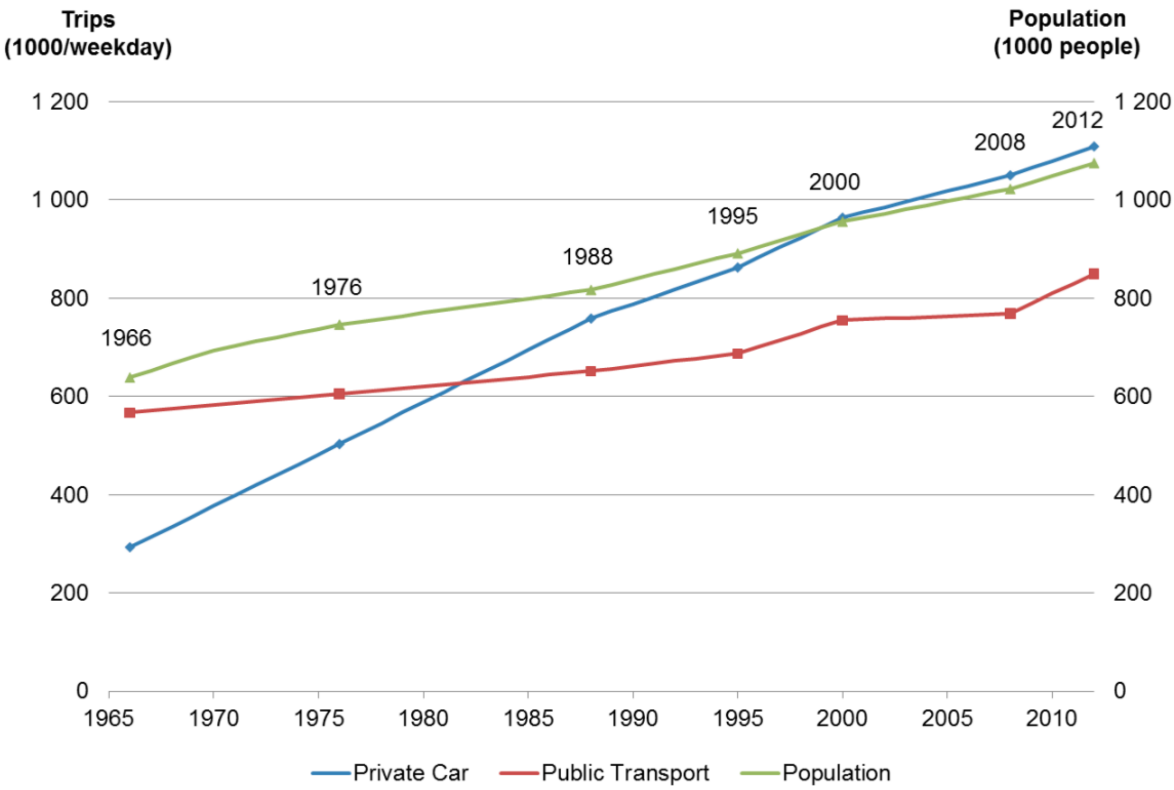


Figure 2.2.1: Helsinki region traffic survey 2012 (HLJ2015) ([2])

2.2.2 Objectives

The objectives of Kutsuplus were simple: increase the number of private car users switching to public transport. This would decrease congestion, release parking space and reduce pollution in the city. To do so, the service had to be time-efficient, more so than traditional public transportation, it had to offer a good solution to orbiting traffic and it had to compete in areas where regular public transport had not been competitive. The new service was to become a flexible and personal form of public transport, enabling door-to-door journeys, while competing with the private car in terms of time-efficiency, ecology and economy. Simulations of the new service in an area with the same characteristics as Helsinki showed that extending the number of vehicles would increase the efficiency of the service. Kutsuplus started with 15 vehicles. The goal to expand up to 45 vehicles by may 2014 was not met due to challenging financial situations.

2.2.3 Implementation

Kutsuplus worked with a centralized optimization algorithm that received trip orders from customers and optimized the route planning over all available vehicles and trips in real-time. Passengers could choose the desired level of service and the fare they payed was determined on the basis of their selections. They received real-time information on their drive and guidance to the bus stop where they would be picked up. Passengers traveling in the same direction were picked up in the same vehicle (ride-sharing) to spread the expenses over multiple passengers.

2.2.4 How the service would become profitable

Kutsuplus knew, supported by the simulations and predictions it made, that the service could only become profitable when achieving significantly scale of service. To do so Kutsuplus presented three key objectives: First, the service had to be easy to use and provide high-quality service. Secondly, the correct positioning of the service between taxi-like services and traditional public transportation was mandatory. And lastly, it was of high importance to be as cost efficient as possible, especially on dominant cost factors such as transport costs. Dynamic pricing was used to spread demand over the day, to reduce congestion and limitation of the service during peak-hours. As Kutsuplus was a service provided by the government it was also important to consider certain environmental and social benefits to the society when evaluating the economic feasibility, these are profits that private firms could never include in their cost model, making it harder for them to be profitable. The cost model of Kutsuplus included factors such as the decrease of traffic accidents and public parking spaces. The impact on the environmental costs can be found at [38]. An overview of some of the long-term saving potentials is given in figure 2.2.2. This comes to show that more aspects can be taken into consideration when calculating profits for a service ran by the government. Overall in Helsinki, they calculated that over 700 million euros could be saved annually with a fleet of 8000 vehicles.

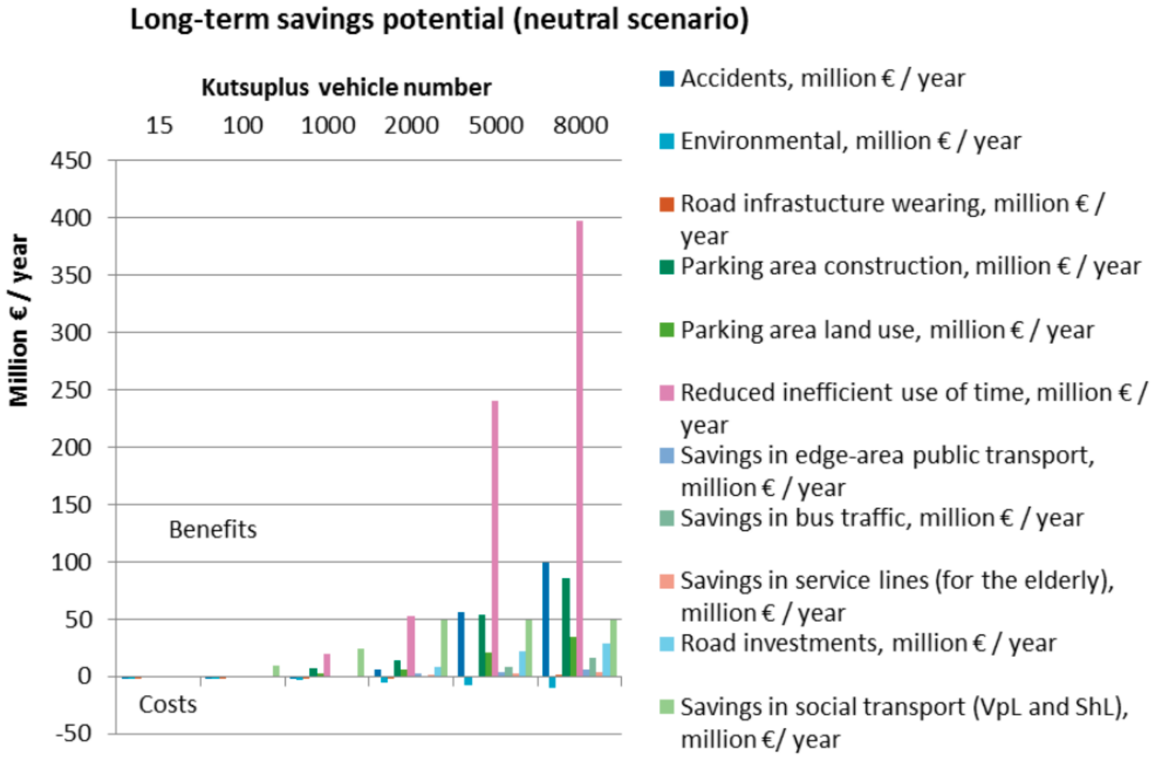


Figure 2.2.2: Long-term savings potential in a neutral scenario for Kutsuplus

2.2.5 Real-world implementation as a public transportation service

After field testing and adjusting the service, Kutsuplus operated with a fleet of 15 vehicles between 6am-11pm starting in November 2013. Passengers originally paid €3,5+€0.45/km, but this was increased by approximately 17% in January 2015. This mainly because the service could not expand its vehicle fleet of 15 vehicles and dynamic pricing was introduced to flatten the morning and evening rush-hour peaks. Overall the number of trips was vastly increasing, at a pace of several hundred per cent annually (even when the operational area and vehicle fleet stayed limited), showing the potential of the service, see figure 2.2.3. With the increase in demand the efficiency of the service also rose. This is easily explained by the fact that the probability of combining trips became much higher, fig 2.2.4. Compared to a taxi-service it seemed clear that if the scale, costs, and regulations of two comparable transport services are equalized, it is evident that a service that is capable of taking even only one passenger at a time when necessary, and that can also at other times effectively combine trips in real time within the price and time-limits desired by less busy individuals, will be better off when compared to the one trick pony taxi-service.

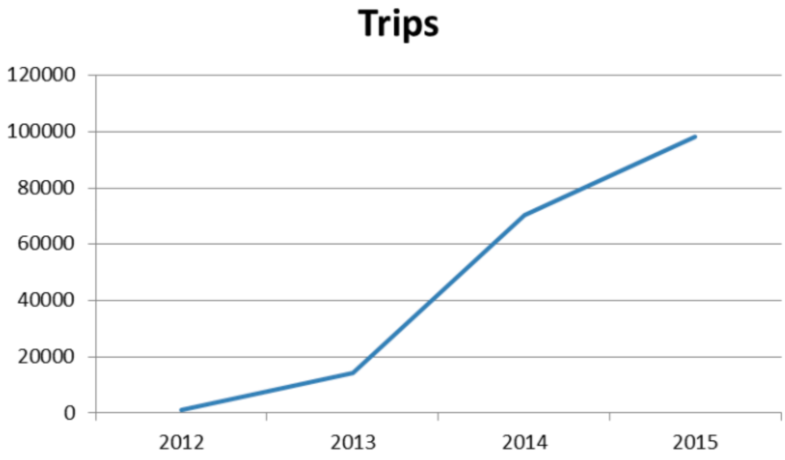


Figure 2.2.3: The number of trips annually

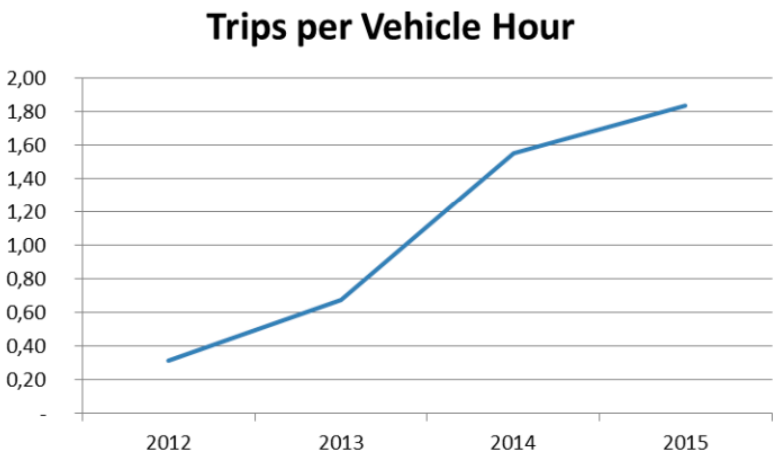


Figure 2.2.4: Trips per vehicle hour

Overall the feedback of customers was excellent. The service even achieved an overall rating of 4.7/5. This comes to show that a well supplemented DRT-service could really achieve scale and be a viable alternative to owning a personal vehicle. When customers are happy it will also increase word-of-mouth marketing and this will consequently further increase the user base.

2.2.6 Termination of the service

Despite the strong growth in demand and the excellent ratings of the service demanding for an increase in capacity by 2014, the service could not receive enough funding by the municipalities. This led Kutsuplus operating with 15 vehicles even if the capacity should have been tripled to 45 vehicles to improve efficiency of the service. This decision severely hurt the further developments in terms of efficiency, economics, and quality development. Despite this decision, the positive development and excellent ratings of the service continued. This drew worldwide attention, and services resembling Kutsuplus started to emerge. By 2015, HSL prepared a financial and operational plan for 2016-2018, in which the subsidy level of Kutsuplus would already be lower than any other HSL transport service by 2018. However in the early years of the proposed expansion, the amount of subsidies still increased, which the member municipalities didn't accept. This led to the decision to determine the service by the end of December 2015.

2.2.7 lessons to be considered for cities pursuing mobility-on-demand systems:

Findings as found in [39]:

The first lesson that could be drawn is the fact that Kutsuplus was build with greater density in mind. This density was not reached because the service area was considered way to big for the small amount of vehicles present. This resulted in low ride-sharing numbers and an expensive to operate service.

The second lesson was the lack of marketing. Other then offering free-rides during valentine 2014, Kutsuplus never tried to obtain new passengers. In Helsinki, many people were only vaguely aware of Kutsuplus.

The last lesson should be that many of the issues that plagued the system were issues that could be addressed if Helsinki would have continued the service. Cities should really consider the longevity when starting up a DRPT.

2.2.8 conclusion

This case study was presented to show the true potential of DRT/DRPT-services. Kutsuplus, while being world's first first DRT-service, already performed exceptionally well. First it showed that passengers were glad to use the service. A survey in 2013 even showed that current customers were already convinced to further use the service and only 1.4% stated that they would stick with other means of transportation. This result is very encouraging for cities that try to reduce the personal vehicle ownership. Secondly, it also showed that, when implemented correctly, DRT can handle high levels of demand. Kutsuplus, during its life-time, was load-tested several times with real passengers in heavy demand situations by introducing free-rides. During these tests the central system worked reliable, showing computational limitations are now something of the past for DRT. Thirdly, and possibly most important, Kutsuplus also seemed on its way to become economically feasible. The positive trend on-demand would continue, provided sufficient marketing and an increase in both vehicle capacity and service area was offered to customers. Also important in the report of Kutsuplus was the fact that almost two-third of the costs are based on driver wages. Autonomous vehicles will thus be one of the most important changes in the near-future for DRT-services. Overall Kutsuplus was a highly appreciated catalyst for DRT, and it has shown the world that DRT is economically feasible, increasing the worldwide efforts to achieve a more demand driven form of public transportation.

Chapter 3

Methodology for an economic feasibility analysis on-demand responsive transportation services

The goal of this paper is to assess the economic feasibility of demand responsive transportation services. To do so it is first required to build a representable dynamic cost model. This model is dynamic in terms of the services lifespan (eg. how long does each vehicle last), vehicle fleet, vehicle type and level of demand. An explanation on how the cost model is build and an overview of each of the cost drivers is given in section 3.1 and 3.2. This model is build inside *Microsoft Excel*. It is important to notice that this paper focuses on a potential DRT company situated in Flanders. Therefore all cost values are chosen to be representable for a Flemish company, bound to Belgian or Flemish regulations and laws. These costs may, as already explained in sub chapter 2.1.5, differ between different regions and cities.

To feed the cost model different DRT-services are simulated inside the simulation testbed, which is fully explained in chapter 4. These services differ on their available vehicle fleet, vehicle type (Sedan/Minivan) and level of demand. The outputs of the simulations, different Key Performance Indicators (KPI) are then imported inside the cost model.

Combining both the cost model and the simulation output a cash flow is generated representing the different expenses the service will make over its lifespan, taking into account inflation rates. With these estimated future cash flows the Present Value (PV) [40] is calculated, this value represents the present value of all future expenses, taking into account the time value of money. In other words, this value represents the total revenue a provider has to earn over his lifetime if he plans to run break-even. The PV itself is then used to calculate the equivalent

Annual Worth (AW), Daily Worth (DW) or Hourly Worth (HW) of the company. This means that all incomes and disbursements (irregular and uniform) are converted into an equivalent uniform (end-of-period) amount, which is the same each period. Using both the DW or HW and the simulation results considering the amount of successful trips and the distribution on the amount of taxi vehicles driving around each hour, a break-even pricing for each provider will be calculated, this can by done on a daily or hourly rate. By comparing providers of different sizes, the effect of scalability on the break-even pricing of DRT will be derived.

3.1 Cost modelling approach

To begin cost modeling it is often suggested to start building a work breakdown structure, WBS, a basic tool for getting a cost overview [41]. Each level of a WBS divides the cost elements into increasing detail. A WBS helps classification of different costs and gives a good overview, allowing for a better cost modeling approach. The total cost of a DRT-service - presented at the top level of the WBS- is the sum of all costs in its sub-categories. Figure 3.1.1 shows the WBS build for a general DRT-service provider, working as a taxi ride-hailing service. The categories used are: Vehicle Fleet, Office space, Taxes, administration, direct labor wages and the platform costs.

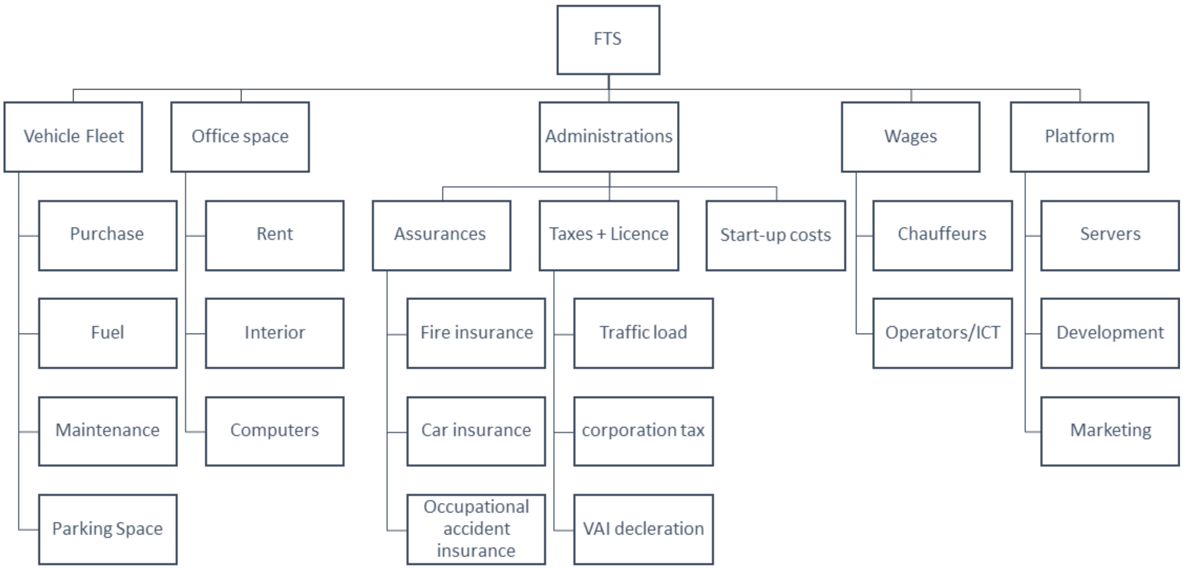


Figure 3.1.1: Work breakdown structure for a DRT-service

To build a dynamic cost model, it is also necessary to classify costs as either an operational or capital expense. Capital expenses, referred to as CapEx, is defined as a cost for development or purchase of non-consumable parts of a product, system or investment. Operational expenses, also called OpEx, are recurring costs a business incurs through its normal business operations, these could include insurances, wages, fuel-costs, rent, maintenance, etc. Next to CapEx and OpEx, costs can also be classified as either fixed costs which remain the same no matter the output of a business, and variable costs, which are costs that change as the quantity of the good or service that a business produces changes. A division of all costs based on these two properties is given in the cost matrix in Table 3.1.1

	CapEx	***OpEx***
Fixed	-Application development -Office: interior and computers	-Office: rent -Web hosting -Utilities -Platform: server
Variable	-Vehicle purchase -Parking space	-Assurances -Maintenance -Taxes -Wages -Fuel -Licensing -Marketing

Table 3.1.1: Cost Matrix

To investigate the viability of a DRT-service, the model will first be time-invariant. Here, a break-even pricing is calculated. A sensitivity analysis on the break-even pricing will be done to hopefully show how the increase in demand increases the service efficiency. Estimations of all costs is done by performing desk (internet) research on existing, or failed, DRT-providers.

3.2 Data input and assumptions

Table 3.2.2 gives an overview of all costs and their actual values as used in the viability analysis of an DRT-provider. As stated above, all values are based on actual prices found for similar enterprises in Flanders. Assumptions are made by averaging over a multiple of different input possibilities, such as a variety of different sedan type vehicles in search for a possible vehicle seating four passengers. The same logic applies to: Minivan, computers, parking space (uncovered parking in Ghent, bought in bulk), fuel prices, office space (rent in Ghent) and assurances. A quick test for these values was done by running a first simulation using the simulation software (Chapter 4). In the area of Ghent, a small taxi business (no ride-sharing) is modelled. As inputted in the software: 300 daily passengers with demand distribution as explained in 4.3.6, 20 taxi vehicles during day shift (13 hours) and 5 vehicles during night shifts (remaining 11 hours), with two personnel in the office during the day shift and none during the night shift. Given these input values a 86% success rate (the percentage of successfully finished trips) is achieved, a total of 4973km s driven each day. Assuming this would be the mean performance for each day (365 days a year) and a life span of 7year, a trip would cost (break-even) around €3/km, Assuming a profit margin of 15%, this would result in a price of €3.5/km. In Ghent, the average price for a taxi is between €1.6-2.3/km + base fee of around €9 (including first 3km). This comes to show that the assumed input values for the cost values are are likely in the correct range.

3.2.1 time-variant assumptions

To generate a net present value over a short time horizon on DRT-providers it is necessary to implement both an inflation as well as a discount rate. In Belgium, the targeted inflation is 2% [42]. Costs (and revenues) that occur in the future are discounted with a discount rate of 15%. Notice that when using a time window of ten years, the purchase of vehicles will be done two times, once at year 0 and once during year 5.

Assumptions	**unit**
Discount rate	15 % (annual)
Inflation rate	2 % (annual)
Time window	10 years
Vehicle lifetime	5 years

Table 3.2.1: Time-variant assumptions

Input	Unit	Amount	reference
Purchase Vehicle, Sedan	€	36 250,00	Assumption
Purchase Vehicle, Minivan	€	42 014,15	Assumption
Interior office	€ /m²	448,40	[43]
Development Application	€	100 000,00	[44]
Computers - office	€ /computer	1 500,00	Assumption
Parking	€ /parking (CapEx)	3 775,00	Assumption
Fuel (Diesel)	€ /l	1,40	Assumption
Fuel (gas)	€ /l	1,36	Assumption
Maintenance	€ /km	0,04	[45]
Taxes Vehicles	€ /year	243,22 or 154.31	[46]
Insurance vehicle	€ /year/veh	2 500,00	Assumption
Labour cost chauffeur	€ /hour	24,70	[47]
Labour cost IT-dev	€ /hour	53	[48]
Labour cost other	€ /hour	40	Assumption
Office space	€ /m²/month	6.8	Assumption
Office: utilities	€ /year	3 533,70	[49]
Insurance office	€ /year	1 000,00	Assumption
Insurance employee	€ /year/FTE	500,00	Assumption
Taxi Licence	€ /year/vehicle	300,00	[50]
Software	€ /year	130,00	Assumption
Servers to run app	€ /month	4 000,00	[51]
Start-up costs	€	1500	[52]
Company contribution	€ /year	850	[52]
Marketing	€ /year	150000	[53]

Table 3.2.2: Input parameters for a DRT-provider, assumptions as based on the average of different possibilities

3.3 Important KPI and output parameters of the simulation

To assess the viability of DRT-providers the following Key Performance Indicators are taken into consideration:

- Success rate: percentage of requests that get accepted.
- Total distance traveled: Total distance driven by all vehicles during the day, a summation of total distance with and without passengers.

- Shared distance: When multiple passengers are boarded their shared distance is multiplied by the number of passengers boarded minus one. Example: 100 km driven with two passengers boarded = 100km shared, 100 km driven with three passengers boarded = 200 km shared. The shared distance is an indicator on how much distance is saved by ride-sharing.
- vehicles average productivity rate: average amount of passengers driven per vehicle hour.
- occupancy rate: average amount of passengers on board per vehicle hour. This will not take empty vehicles in consideration, so occupancy rate is always higher or equal to 1. The simulation software uses a dictionary to keep track of the occupancy rates during each time of the day of all taxis. So during each hour the software calculates the time zero passengers were boarded, one passenger was boarded,... .
- taxis required each hour: The amount of taxis required each hour represents the amount of taxis that are assigned to one or multiple requests plus a safety factor of 10%. This indicator is used to calculate the driver wages per hour.

The success rate, total distance traveled and the amount of taxis required each hour will produce a break-even pricing for the service. By comparing pricings for different services, the scalability-effect will be discussed. Next, different policies will also be compared. One such policy is the maximum allowed increase in the passenger's travel time caused by deviating to pick up or drop off another passenger. Another policy is the accepted time window in which passengers have to request their trips in advance.

After discussing break-even pricing, it seemed also important to include other parameters such as the total distance shared between customers and the taxi's occupancy rate. These indicators show how many trips are actually shared and therefore give an indication on the environmental impact of the service.

Chapter 4

Simulation

Simulating a Demand Responsive Transportation service under various conditions is a necessity to evaluate its economic feasibility. In this section an introduction to the simulation software will be given. Next, an overview of the implemented centralized DARP-Algorithm (Dial A Ride Problem Algorithm) that steers the virtual driving-agents is provided. To conclude this section, different scenarios are simulated to show the performance of the demand responsive transportation service under various conditions. These results will be used to drive the cost modeling in the next chapter.

4.1 Simulation software

The open-source simulation software build by Michal Certicky, Michal Jakob, and Radek Píbil. [54] is provided by the Czech Technical University. It is an interactive simulation tool for testing and evaluating control mechanisms for traditional demand-responsive transport services (Dynamic Dial-A-Ride Problem) as well as next-generation flexible mobility services (exemplified e.g. by Uber or Lyft). Installation instructions can be found on the GitHub page, but is has to be noted that for the software to work it seems that only Java Platform, Standard Edition 7 can be used. Higher versions result in various errors, and Eclipse will not be able to handle the software. The testbed is implemented on a Ubuntu 18.04 machine running java version "1.7.0_80". Further information about the testbed can be found on the GitHub page, as well as a very detailed overview given in article "Analyzing On-demand Mobility Services by Agent-based Simulation" [55].

4.2 Control Mechanism

The testbed allows to incorporate and study a variety of control mechanisms. These can be divided into centralized or decentralized mechanisms, based on the degree of autonomy of the drivers. Also a distinction between dynamic and static control mechanisms is made, each suitable for the transport demand with different temporal structure.

Static vs. Dynamic: Static control mechanisms (sometimes called 'offline'-mechanisms) need to know the passengers demand in advance (eg. demand over the next day), after which they use linear programming to optimize the complex routing problem. This is the go-to option in situations where demand is typically known in advance. A well known and studied example for such a routing problem would be the routing of trucks that need to transport goods from a centralized warehouse to diffused local warehouses which require a certain amount of goods each day (demand is known at least a day in advance), in which one tries to minimize the overall cost. Sadly for DRT-providers, customers that want to make use of short-distance transportation services will typically not generate their requests a long time in advance. Dynamic control mechanisms (sometimes called "online"-mechanisms) process the travel demand requests when they come in. Such mechanism will be used for our study on DRT. Each time a request is made, the algorithm will try to find the most suitable vehicle to serve the customer based on the passengers already on board or queued (accepted passengers, but not yet picked up), without knowing any of the future demands.

Centralized vs. Decentralized: In a demand-responsive transport system, the behaviour of driver can be governed either centrally by a (single or multiple) dispatcher agent, locally by the drivers themselves, or the combination of both. Decentralized mechanisms are suitable in situations when communication capabilities are restricted, or when the drivers are independent and self-interested but can still benefit from collaboration. Centralized mechanisms are more suited in situations where drivers work together to maximize the total profit. This comes at a higher cost to both the memory and time complexity of the algorithm, in which the mechanism now has to store all the diver-agents information (location, current and future passengers + destinations) and has to iterate over all available drivers to find the best suited solution to the new transportation request. While in decentralized mechanisms each driver only has to store its own trajectory and validates if he can pick up the new request at an acceptable cost. For this analysis, the focus will be on centralized control mechanisms, in which a centralized dispatching-agent will steer drivers based on the overall best performance. To minimize the time complexity, certain decisions and eliminations will be taken by the algorithm, such that the time between a request and its acceptance is limited, so passengers don't have to wait considerable time before getting accepted by the service.

4.2.1 Implementation of the DRT control mechanism inside the testbed

Currently, the simulation model presented by Michal Certicky, Michal Jakob, and Radek Píbil on their github has not yet implemented a ride-sharing DRT-algorithm. The centralized control mechanism provided for in the software is a simple standard taxi-algorithm, in which ride-sharing is not yet possible. When a request arrives the dispatching agent simply selects the closest free taxi vehicle and assigns it to the passenger, after which the taxi is set to "busy" and no new requests can be handled by the vehicle until it drops of its passenger. A big part of this project was thus the implementation of a working DRT-algorithm. To do so multiple classes in the software were altered to work with a ride-sharing scheme. As this paper doesn't focus on the technical implementation of a DRT-algorithm, only the most important classes are discussed in this subchapter.

4.2.1.1 DispatchingLogic

First, since the simulation is done with a centralized control mechanism in a sense that the dispatcher agent has complete power over the behaviour of all the vehicles, it is necessary to extend the abstract class DispatchingLogic and implement its method processNewRequest(Request r), which is called every time the passenger announces a travel request. Pseudo code can be found at Algorithm 1 and 2

Control Mechanism Input:

The request argument that enters the processNewRequest function represents the new passenger's request, it's a class-object containing following information:

- PassengerId (String): Each passenger has his specific id.
- callTimeInDay (Long)For a dynamic implementation, the requests are event-triggered: when the callTimeInDay is reached. Please remark that the same algorithm could be used for a static implementation, by setting the callTimeInDay of all requests to 0. However, existing static linear programming algorithms would probably perform better. This because requests would still enter the algorithm one-by-one and it would still not take following requests into consideration.
- fromNode and toNode (Long): The passenger requests to be driven from his fromNode to his toNode, these locations are represented as Long-values on the implemented users area.

- timeWindow (List[Long]): each request has a list representing the passengers earliest + latest departure and arrival time.
- additionalRequirements: Not used for this implementation, but this could represent requirements such as wheelchair support, which only specific drivers could provide for.

In the PROCESSNEWREQUEST(Request r), each of these items can be called upon using a *request.get-"item"* function.

Control Mechanism Memory:

Next to the new incoming request-argument, the control mechanism has to store and call upon different objects stored in its memory when assigning a new passenger to the best available driver. A brief overview of these objects:

- Map of taxi Ids with their current location.
- Map of taxi ids along with their current passengers on board and passengers in queue
- Map of taxi ids along with their current trip plan (nodes they are visiting in a chronological order) also containing information of each node, see figure 4.2.1 for more information on nodes. The nodeFunction is a binary representation if the node is a pick-up or drop-off point.
- Information about all previously handled requests and passengers.

In the PROCESSNEWREQUEST(Request r), each of these items can be called upon using a *taxiModel.get-"item"* function.

Node: PassengerId; nodeFunction; arrivalTimeAtNode; departureTimeAtNode; [earliestDeparture, latestArrival/Departure]

Table 4.2.1: information stored at nodes

Control Mechanism Algorithm reasoning and Output:

When a request arrives, the control mechanism first calculates and stores all information it needs for this specific passenger. This includes the passenger's latest arrival time to his destination as well as a latest + earliest departure time from his pickup point. The latest departure time is equal to the latest arrival time minus the travel time for a direct route between his from- and toNode. If the driver arrives to the pickup point after the latest departure time, the passenger could never reach his destination on time, even if given full privilege over all

Algorithm 1 process new request

```
procedure PROCESSNEWREQUEST(request)                ▷ assign a taxi to the request
    initialize and log different parameters;
    for taxi in listOfAllTaxis do
        if taxi could handle request given full privilege then
            listOfAvailableTaxis.add(taxi):
        end if
    end for
    initialize sorted dictionary closestTaxis
    for taxi in listOfAvailableTaxis do
        location = location of vehicle at earliestDeparture time of request
        distance = calculateDrivingTime(location, request.FromNode)
        closestTaxis.put(distance, taxi)
    end for
          all available taxis now sorted based on distance to the new request
    while closestTaxis.hasNext() do              ▷ iterate over the taxis in closestTaxi
        if taxi has no current tripplan then           ▷ no other passengers assigned
            assign taxi to passenger
            generate route for taxi to drive
            inform passenger of his acceptance
            break
        else
            currentTripPlan = taxi.getCurrentTripPlan
            if insertionAlgorithm(request, currentTripPlan) = possible then
                assign taxi to passenger
                update tripPlan of taxi
                inform passenger of his acceptance
                break
            else
                continue with next taxi
            end if
        end if
    end while
    No taxi found = reject request
end procedure
```

Algorithm 2 insert passenger in taxi's tripPlan

```
procedure INSERTIONALGORITHM((request, currentTripPlan)    ▷ check if insertion is possible and if so return the new tripPlan
    extraDistanceOptimalNewTripPlan = ∞
    for (i = 1; i < nodesCurrentTripPlan.size()+1; i++) do
        Add FromNode at currentTripPlan[i]
        No changes done to all nodes before new pick up (no need to update)
        check if arrivalTime at FromNode < request.latestDeparture
            (else break)

        now the new fromNode could, theoretically, be added
        for (j = i + 1; j < nodesCurrentTripPlan.size()+2; j++) do
            Add ToNode at currentTripPlan[j]
            if j == i+1 then                          ▷ drop off immediately after pickup
                check if arrivalTime at ToNode < request.latestArrival
                    (else break)
            else
                calc drivingtime between ToNode and currentTripPlan[j-1]
            end if
            if j > nodesCurrentTripPlan.size()+1 then
                toNode is last node
            else
                Calculate driving time from toNode to currentTripPlan[j+1]
            end if
            Now check all other nodes
            if j != i+1 then
                increase = newArrivalTime(currentTripPlan[i+1]) -
                               originalArrivalTime(currentTripPlan[i+1])
            else if j not the last node then
                increase = newArrivalTime(currentTripPlan[j+1]) -
                               originalArrivalTime(currentTripPlan[j+1])
            else
                increase = 0
            end if
            pas = calculate number of passengers before FromNode
            pas += 1 (add new passenger)
```

```
        for (k=i+1; k < nodesNewTripPlan.size(); k++) do
            check if pas < maxPassenger
                (else error = 1 and break iteration of k)
            if node at k is ToNode and j == i+1 then
                pas -= 1
            else if node at k is ToNode and j != i+1 then
                calculate arrivalTime at ToNode based on node (k-1)
                check if arrivalTime < request.latestArrival
                    (else error = 1 and break iteration of k)
                pas -= 1
                if k not at the last possible node then
                    increase = newArrivalTime(currentTripPlan[k+1]) -
                            originalArrivalTime(currentTripPlan[k+1])
                else
                    increase = 0
                end if
                update node at k and continue iteration over k
            else                    ▷ we arrive at a node of queued/boarded passengers
                newArrivalTime = increase
                        + originalArrivalTime(currentTripPlan[k])
                function = check whether node is pick/drop off
                check if new arrivalTime still acceptable for this passenger
                    (else check if k<j, if so break iteration over j)
                    (else error = 1 and break iteration over k)
                Now we have three important possibilities:
                if function = pickUp then
                    if newArrivalTime < earliestDeparture then
                        increase = 0 (we have to wait, just like before,
                                no need to increase further nodes)
                        pas += 1
                        departureTime = originalDepartureTimeOfNode
                    else                    ▷ We arrive between earliest-latest departure
                        increase = newArrivalTime - originalArrivalTime
                        pas += 1
                        departureTime = newArrival
                    end if
                else                                        ▷ node not a pickup
```

```
                    incrase stays the same
                    pas -= 1
                    departTime = newArrivalTime
                end if
                update node at location k with new timings and continue
            end if
        end for
        if error = 1 then
            current j not possible: continue itteration with next j
        else
            Boolean found = True
        end if
        extraDistance = to and from FromNode + to and from ToNode
        if extraDistance < extraDistanceOptimalNewTripPlan then
            this iteration is currently the best
            extraDistanceOptimalNewTripPlan = extraDistance
            store this tripPlan as the currently best one
        else
            continue iteration on j
        end if
    end for
  end for
  return Boolean found + (newOptimalTripPlan (if found))
end procedure
```

the other passengers on board or queued by this agent. Note that this latest departure time is also equal to the pickup time a traditional taxi service would communicate to the passenger (including some safety time for possible delays). The earliest departure time stems from the fact that passengers will accept a longer travel time for a ride-sharing taxi compared to a direct taxi-service, if this is reflected in a lower price. Yet, this increase in travel time has to be limited. In our model, it is is calculated as a percentage of the travel time for a direct connection (without deviations caused by ride sharing). If there would be no earliest departure time, passengers could be picked up by a driver the moment they generate their request, and spend hours inside a taxi, which of course can't be the case in real-life. The reason why the increase of travel is calculated as a percentage of the direct travel time, and not as a specific fixed value can be explained by a simple example: if a passengers direct route is only a couple of minutes long, a 30 minute extra travel time would most probably be unacceptable, yet when the direct travel time is 2 hours, a 30 minutes increase of travel time (25%) could be acceptable. The influence of this percentage on the amount of accepted an rejected passengers will be tested during simulations in chapter 5.

Next, the control mechanism determines which drivers are available for the request, and stores stores this info in a list, sorted by the forecasted distance to the *fromNode* at the earliest departure time of the new request. A taxi is declared "available" if it is possible to transport the passenger within the requested time limits, without considering any passengers currently on board/queued by the driver (as a traditional taxi service). If this is not possible, it makes no sense to try to combine this new trip request to already accepted trips by this taxi vehicle. The reasoning to store available taxis based on their distance to the new fromNode (at the earliest departure time) is of course to try to minimize the total distance travelled (to reduce costs). The current mechanism will try to assign drivers by iterating over the sorted list of available taxis. Once a possible solution is found, this iteration stops and the passenger gets accepted. This means that the assigned taxi is possibly not the best taxi to assign to this new passenger based on the overall distance traveled, yet it decreases time needed to accept the request. As the list of available taxis is sorted by their forecasted distance to the new pick-up location, the solution will be near-perfect. Alternatively, the algorithm could be adjusted to try to find an optimal solution by iterating over all available taxis and selecting the one with the best balance between cost and time.

Once all available taxis are listed based on their distance to the new request around the earliest departure time, the mechanism will iterate over this list until it finds a possible taxi to assign to the new passenger. Two possibilities for each taxi arise:

Empty trip plan : When a taxi has no passengers boarded or queued at the time of the new request, he has an empty trip plan and is parked at his current location. This means he can simply drive and board the passenger without any detours. Its easy to decide whether or not to accept the new request, and is solely based on the fact that the taxi can drive to, and pick up the passenger before his latest departure. As this taxi was in the available taxi list, this should not be an issue, yet a double check will be done. The taxi will then be assigned to the passenger. The passenger receives a notification his request is accepted, and the taxi is sent to the location of the passenger, where he will wait until the passenger is available for boarding. The PROCESSNEWREQUEST(Request r) function is finished until a new request arrives and the assigning-process starts again.

Non-empty trip plan : This is where the DARP will prove its value by combining trips of different passengers to reduce the overall cost of the service per costumer, and thus allowing for a decrease in price compared to traditional taxi services while still being able to satisfy the constraints of each customer. A trip plan is an array of integers, representing the different way- points (locations determining the current route for the taxi). Based on the current (optimal) trip plan of the taxi the insertion algorithm tries to add this new passenger to the trip in the most optimal way. Because a current trip plan is always optimal, there is no need to re-calculate a new trip plan for all passengers currently boarded or queued by the taxi, drastically decreasing time complexity of the algorithm. The insertion algorithm simply has to check where to add the new fromNode and toNode without exceeding constraints of previous passengers. The easiest way to understand the algorithm is by illustrating its working: As already explained, each taxi has his own trip plan, an array of nodes, representing real life locations. Table 4.2.1 shows a visual representation of the data associated with the trip plan. Each node contains the passengerId and an integer representing if the passenger will be picked up (1) or dropped off (0). Next, the calculated arrivalTime and departureTime are stored. These times are only different when the taxi has to wait for a passenger. These arrival and departure times can change when new requests arrive, yet they are constrained by the requested earliest and latest Arrival/Departure time, which are also stored for each node. For a pick-up point, both earliest and latest departure times are stored. For a drop-off point, only the latestArrival is stored, as we assume that any earlier time will be accepted by the passenger. Next, the algorithm iterates over this list, and checks if the new fromNode and toNode can be inserted, while still satisfying all constraints. To do so, the algorithm will first check if the capacity limitation of the taxi is not passed by inserting the new passenger(s). Next, the new arrival times and departure times are calculated and checked for each node in the potential trip plan. Of course, only the nodes after the new fromNode have to be recalculated and checked. For each node during the iteration an increase in time is applied and checked against all constraints. The initial increase in time is set to be the difference between the original and the new arrival time at the first node after the new fromNode. If the new arrival and departure times at this node satisfy all constraints, the new increase in time for the next node is calculated. This is done for all nodes and the increase in time for the next node is always calculated based on the current node which is already checked to satisfy all his constraints.

- Current node is the new toNode: The algorithm calculates the time increase for the node directly after this node (difference between the new and original arrival time).
- Current node is a pick up node and the taxi arrived between the earliest and latest departure: The new increase is equal to the difference between the new arrival time (which is also the same as the new departure time) and the original departure time (stored in nodeInformation). It's quite easy to see why the original departure time is used instead of the arrival time. For most of the situations these times are equal (passenger is present, and taxi is not required to wait). The only exception is when the node used to be a pick up node where the taxi had to wait, the increase is not the difference between the original arrival time and the new arrival time, as the taxi already had to wait until his earliest departure time.
- Current node is a pick up node and taxi arrives before the earliest departure time (as stored in nodeInformation). In practice, this can for example be the case for a node were the taxi was already scheduled to wait for the passenger. The current increase will not influence any further nodes as the departure time at this node stays the same (earliest departure time). Therefore the new increase is set to zero.
- Taxi is at a drop off point: No need to change the current increase.

If multiple possible new trip plans exist for a specific taxi, the algorithm chooses the solution in which the total distance driven is minimal. It is chosen for this initial setting that the first taxi that can handle the request is assigned to it. Therefore not all taxis in the available taxi list are checked (all taxis after the assigned taxi are not checked anymore). This could probably be done to further optimize the DARP-algorithm (minimize distance traveled or increase ride-sharing by comparing all taxis) but this would increase the time complexity. The passenger receives a notification his request is accepted, and the taxi is sent to the location of the passenger, where he will wait until the passenger is available for boarding. The processNewRequest(Request r) function is finished until a new request arrives and the assigning-process starts again.

4.2.1.2 calculateTravelTime

This function calculates the shortest travel time between two nodes. Most of its function is available in the model by Michal Certicky, Michal Jakob, and Radek Píbil. A shortest-path algorithm (A-Star) is ran to find the shortest path between both nodes and based on the average moving speed, set to 30km/h in this paper, the travel time is calculated.

4.2.2 process VehicleArrivedAtPassenger

When a taxi driver arrives at a pick-up node where the passenger is not yet present, the taxi driver has to wait. In this case, the time between the arrival and the earliest Departure time is calculated (=delay). An event is created with releasetime = currentTime + delay. When this release time is reached, an event is triggered that will start the *passengerGetInvehicle* procedure.

4.3 Experiment Process

To simulate DRT-services inside the testbed a three-step process as explained in [55] is followed, as depicted in Figure 4.3.1.

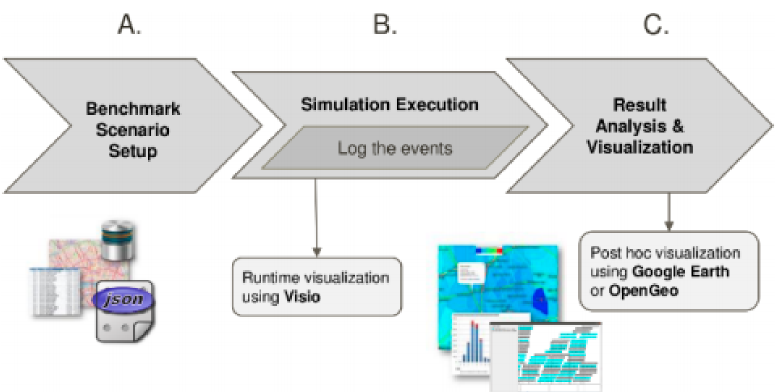


Figure 4.3.1: Three-step process of the experiment

4.3.1 Scenario Definition and Setup

First, we have to set up and configure the scenario under which we wish to test a specific control mechanism. This scenario consist of following files:

Road Network - The road network represented in the OpenStreetMap (OSM) format.

Driver agents - Description (in JSON) of all the relevant drivers with their initial position and the properties of their vehicles including capacity, fuel consumption, CO2 emissions or specialized equipment (e.g. wheelchair accessibility).

Travel demand - The exact representation (in JSON) of travel demand, containing all the passenger agents with their associated trip details: coordinates of their origin and destination, announcement time and special requirements.

4.3.2 Simulation Area

To test whether Flanders makes a good candidate for demand responsive transportation services, the city of Ghent and its surroundings was selected as the simulation area. Ghent is the capital and largest city of the East Flanders province, and the third largest city in Belgium. Together with its surroundings represents a typical Flemisch scenario for DRT solutions: Ghent has a busy city-center with various tourist attractions, shops, offices, schools, homes, restaurants and bars. A place where people live, work, study an visit. There is a train station with direct access to other Belgian towns and cities, including to the main airport in Belgium (Brussels - Zaventem). Ghent also has a harbor where lots of industrial activities are situated e.g. Volvo and ArcelorMittal. The surroundings also included in this area are Drongen, Mariakerke, Wondelgem, Vinderhoute... typical Flemish urban sprawl areas populated by the Belgian working middle class. An .osm file was generated for this area of $156.58km^2$ and implemented into the testbed in the **main.java** file in eclipse, and as **scenario.goovy** file in the experiment directory.

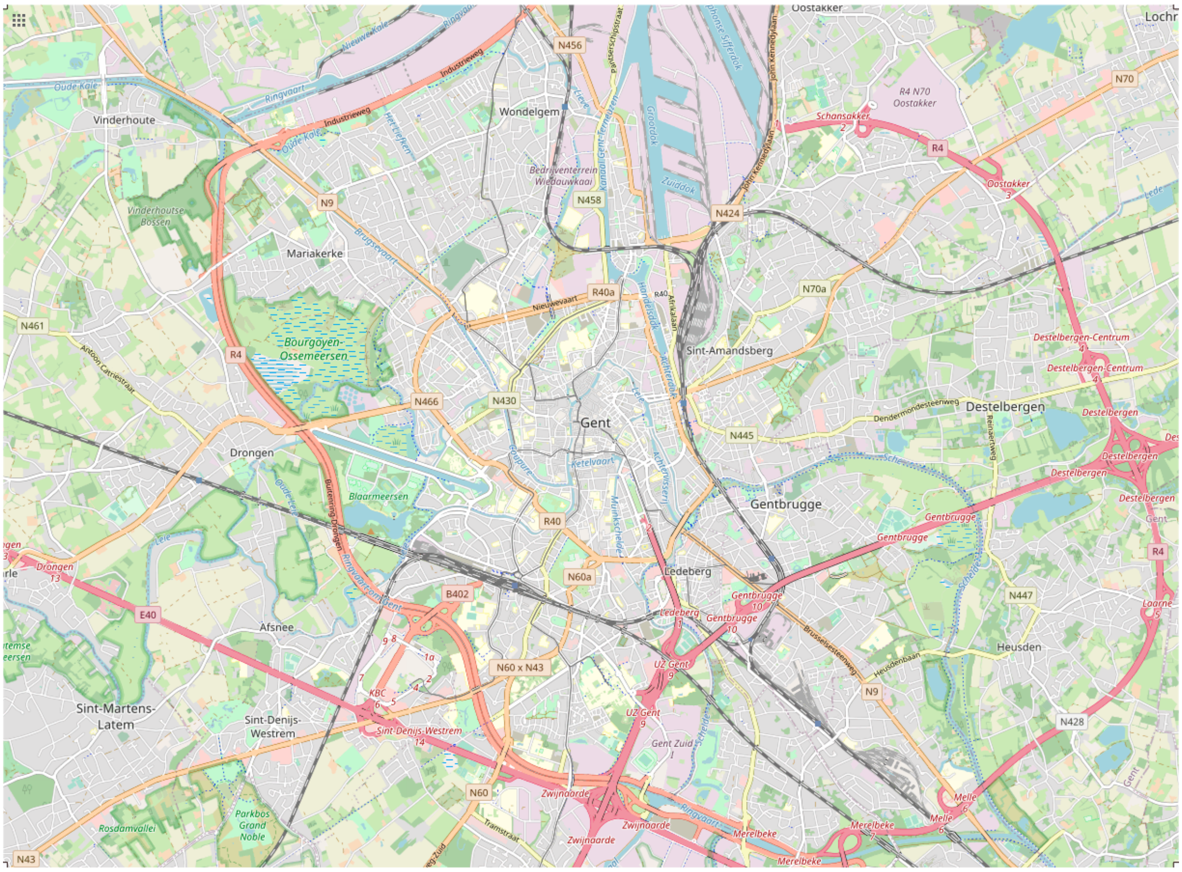


Figure 4.3.2: Simulation Area

4.3.3 Travel demand

Simulating a DRT-service in Ghent requires simulating passengers requesting realistic trips: trips should have a minimum distance (longer than walking distance), and the expected time between a request and pick-up should be acceptable.

To generate demand, different generators are included in the simulation software. For this paper, the generator **LenientRequestGeneratorApp.java** was adjusted and used to generate a given number of daily requests for a given time-period. These requests objects are explained in section 4.2.1.1.

Daily demand distribution: Using the lenient request generator gives the user the possibility to implement a daily demand distribution. The generator will simulate demand following this distribution. This allows for a more realistic setting as demand will generally not be uniformly distributed over a given day. To simulate a realistic demand, the daily demand in Ghent is based on an analysis of Berlin's taxi services (Bischoff, Maciejewski and Sohr) [3] and an ex-post evaluation of on-demand micro-transit pilot

in Helsinki (Kutsuplus) [4]. Overall, this paper will focus primarily on weekdays.
First, let's take a look at figure 4.3.3, which shows the number of taxi requests during one week in Berlin (2014). During weekdays demand follows a clear pattern with a major peak around 9 am and a smaller one during the afternoon. Figure 4.3.4 shows the hourly average number of departures of the Kutsuplus service in Helsinki. The most representative phase of the Kutsuplus service (2014 and 2015) show a typical peak structure, with a narrow morning peak and a broader afternoon peak, which is similar as the distribution in Fixed Public Transport (FPT) services. During the fourth phase, a clear midday peak is also visible, during which pricing was 20% off.During that phase, Kutsuplus had a total of around 100000 trips [2]. As this paper wants to simulate a mature service, only this forth and final stage will be taken into consideration when generating demand. Comparing both illustrations shows clear similarities. As Kutsuplus was a DRT system it seems most representative for the DRT simulations. Therefore this distribution was used to generate the daily demand during day time (6u00-23u00). As Kutsuplus only operated during the daytime, The distribution of the Berlin taxis was used to generate the nighttime demand. figure 4.3.6 shows the demand distribution used for all experiments used in this paper.

Time windows for the requests: Working with the daily demand generator it is also important to understand how the different time values are determined, a visual representation is also given in figure 4.3.8. The actual departure and arrival times can not be assigned to a request. Yet, the actual departure time is bound between the earliest and latest departure time. In this experiment the latest departure time will be equal to the sampled value from the demand distribution. The earliest departure time is set to be the latest departure time minus the chosen allowance-percentage times the direct driving time. Note that the latest departure time should be compared to the pick-up time communicated by a traditional taxi-service (which normally includes some safety time to accommodate possible delays). The earliest departure time comes down to the fact that passengers are willing to accept longer travel times for a ride-sharing services, in return for a lower price compared to a direct taxi-service. Yet this increase of travel time can't be infinite, and it is based on a percentage of his direct driving time, named the time-allowance. Next the earliest and latest arrival times are set to be the earliest/latest departure times plus the total driving time. Each request also has a release time: this is the time at which the passengers contacts the service. For the DRP-algorithm, this release time is the time at which the request enters the PROCESSNEWREQUEST(Request r) function, also called the callTimeInDay. To determine the relation between release time and the departure times, we analyzed the data in the Kutsuplus case [4] (figure 4.3.7). Notice how short of a delay between acceptance and the actual pick up time

[b]0.7

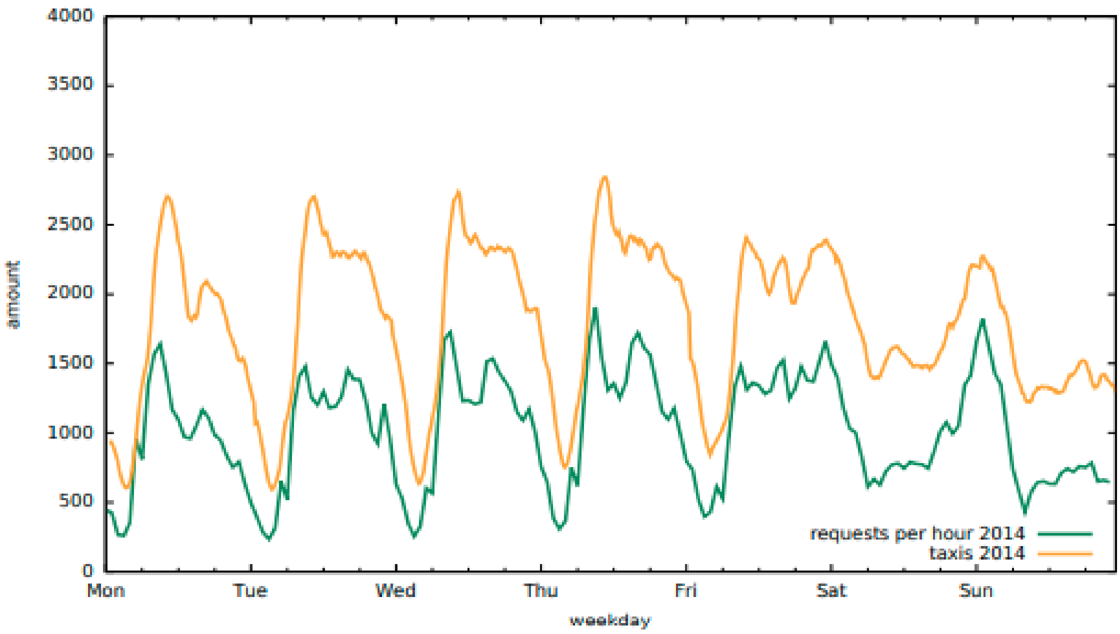


Figure 4.3.3: Request submissions per hour and active taxis in Berlin over a week in 2014, figure provided by [3]

[b]0.7

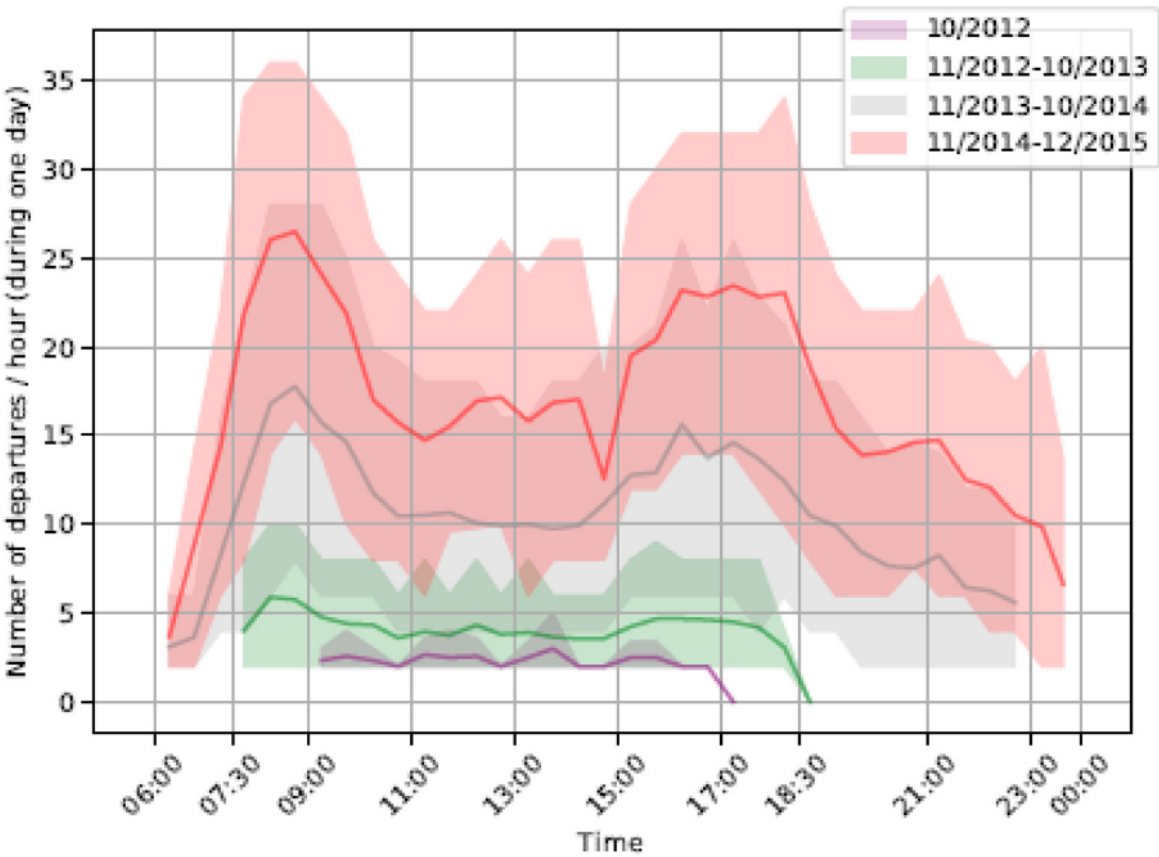


Figure 4.3.4: Hourly average variation (with 10th and 90th percentile area as background) of Kutsuplus journeys by service phase , figure provided by [4]

Figure 4.3.5: Different inputs for the daily demand distribution

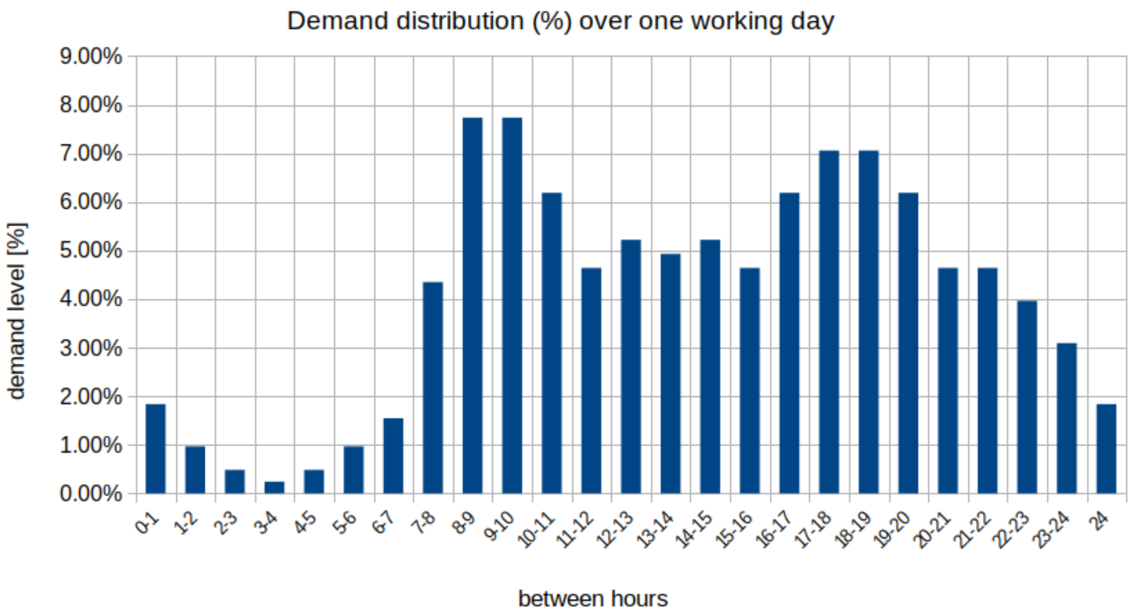


Figure 4.3.6: generated daily demand levels in percentage

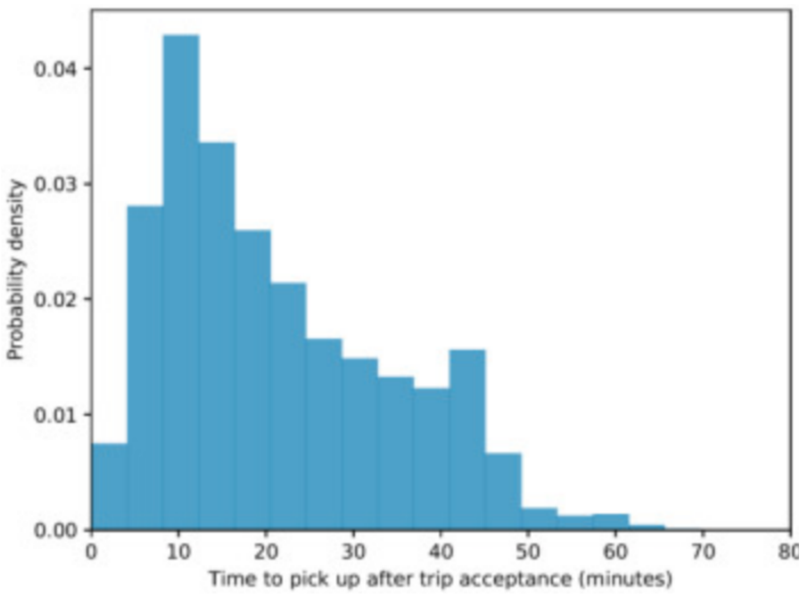


Figure 4.3.7: time delay between acceptance of order and pick up time reached by Kutsuplus

Kutsuplus could reach, with a mean value around 21 minutes. Remark also that quite frequently this delay is only 10 minutes or less. Therefore it is important to keep a low difference between the passengers from time and his callTimeInDay, again to mimic this real life behaviour of DRP-services. In the initial setting the release time will be set between 60 and 30 minutes before the latest departure and this policy will be discussed and compared in chapter 5.

trip - origin and destination: Given the scope of this project, the logic used to generate the origins and destinations is quite basic. When the user loads the ".osm" map inside the model, the testbed generates a simplification of the area. This simplification is, of course, again a network of nodes and edges, but the number of nodes is reduced compared to the original input. The edges represent connections between different nodes and are weighted with the distance between both nodes. Each node is represented by a long value in the software, and when the user defines a location (longitude and latitude), the software will search for the closest node that represents this location. Generating a demand distribution can be done in a multiple of ways. For this paper we defined highly visited locations in Ghent, based on our knowledge of the city. These so-called "center points" are highly touristic places, train-stations, or places were lots of businesses are located. Some examples of these points are: Korenmarkt, Dampoort, Zuid, DokNoord, Sint-Pietersplein, Station Ghent-Sint-Pieters, Volvo Car Ghent (harbor) and Zwijnaarde Industriepark. The user has to define his preferred locations as longitudes and latitudes inside the testbed, which will then generate a normalized distribution over the area, representing the probability of a specific longitude and latitude to be chosen when random samples are drawn from the distribution. These distributions are implemented under the GPS generator class inside the testbed. So when generating a trip-demand, the testbed first chooses, fully random, one of the gps-generators (with its specific dis-

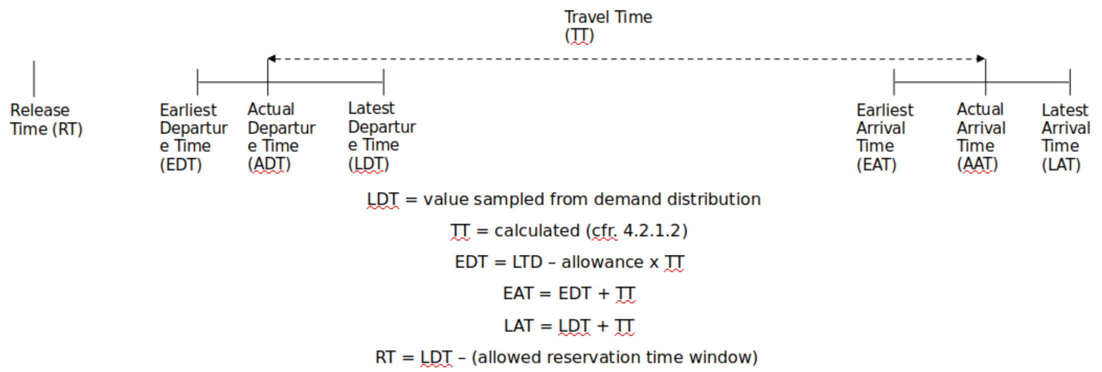


Figure 4.3.8: Graphic representation on requests time- window

tribution around the center-point) and samples both a longitude and latitude for the trips origin and destination. Next the closest nodes to both the origin and destination are generated, these represent the trips from and toNode. The main disadvantage of this method is the disability to generate trips given a specified distribution for the trip lengths as both to and from node are sampled randomly. This could be an interesting topic for a further analysis. The only condition set to the length of trips is that this has to be minimum 1km, otherwise passengers would probably prefer walking the short distance. To check whether trips are acceptable in the current stage of the software, 100000 requests were generated. The results are represented in figure 4.3.9 and a heatmap of the first 250 generated origin nodes in 4.3.10. The average distance is $9.62 \pm 0.14 km$ *CI 99%*, the max distance is 24.5 km and is only limited by the area in which we simulate. This average distance seems acceptable for this specific situation (travel in and around the city of Ghent).Note this average travel distance is somewhat higher then the 5km average found in the Kutsuplus case. [4].

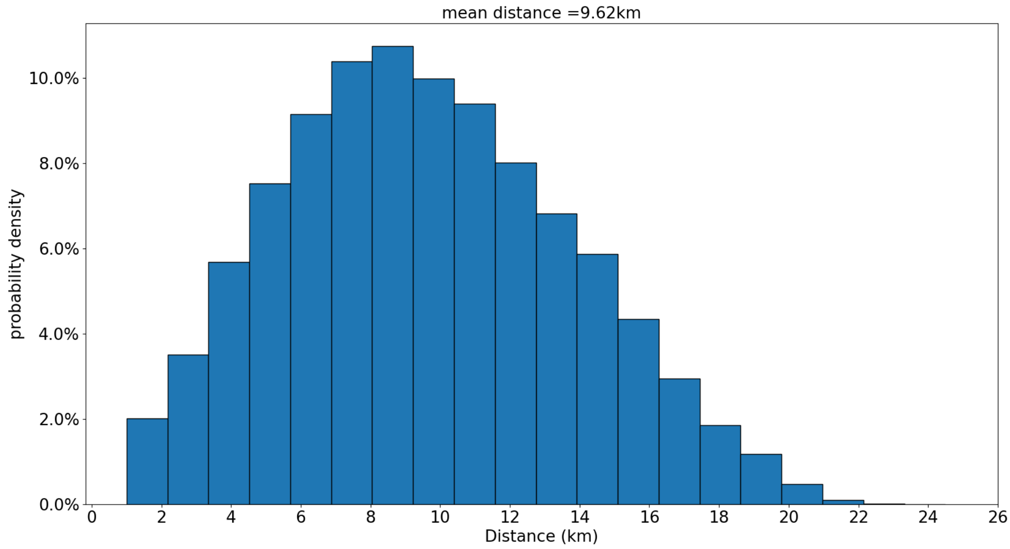


Figure 4.3.9: Distance distribution of generated trips

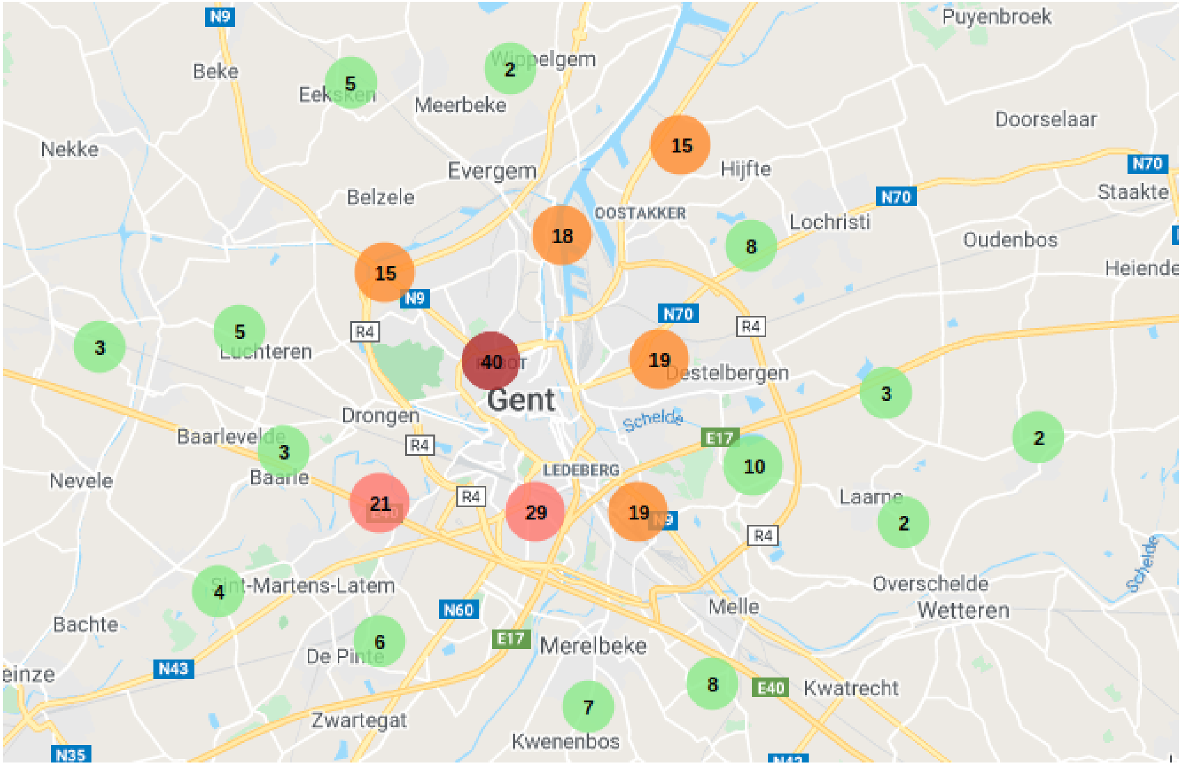


Figure 4.3.10: Heatmap of the first 250 generated OriginNodes. The numbers shows the number of trips that started in the vicinity of that point.

4.3.4 Driver Agents

Driver agents are defined by their ID, their position and the properties of their vehicle: capacity, fuel consumption, CO2 emissions, specialized equipment (e.g. wheelchair accessibility). Their initial position will also be sampled from the GPS distributions explained in the previous sub chapter 4.3.3. For this experiment the only important input will be the vehicle capacity, fuel consumption and corresponding co2 emissions, while no further attention will be given to non-standard equipment.

4.4 Concluding notes on the simulation software

The simulation software provided by Michal Certicky, Michal Jakob, and Radek Píbil was extended to handle dynamic ride-sharing transport services. While the software provided a vast array of classes and tools, it was still necessary to implement and extend a multiple of classes and functions to handle dynamic ride-sharing. Overall, the simulation software requires a lot of calculations and memory, and therefore the use of powerful computers. While passengers requests are handled in a couple of ms (avg 670ms) the software itself must handle a vast amount of memory on each of the taxis driving around. By increasing the amount of taxis, the simulation time increases drastically. Therefore the computational resources of UGent were used as much as possible for generating large amounts of data. Only for smaller experiments we could use our own personal PC. Overall, the results generated by the simulation software and cost model (as discussed in chapter 5) can be considered in the correct/acceptable range.

vehicles	demand	simulation time (h:min:sec)
50	500	0:02:01
	750	0:03:30
	1000	0:05:23
	1250	0:08:21
	1500	0:10:51
	1750	0:13:25
	2000	0:17:19
100	1750	0:12:25
	2000	0:14:58
	2500	0:23:03
	3000	0:30:51
	4000	0:50:34
	5000	1:17:10
200	4000	2:48:23
	5000	4:27:03
	6000	3:45:30
	7000	3:18:30
	8000	4:25:21

Table 4.4.1: Simulation real-time: Intel(R) Core(TM) i5-6600K CPU @ 3.50GHz, 16gb-ddr4: 2133Mhz

Chapter 5

Scenario Analysis

5.1 Introduction: simulating Kutsuplus

To explain the process of assessing DRT-providers and show that both the simulation software and cost model are generating outputs that can be considered in the correct range, will first perform a limited simulation on the Kutsuplus case, using input parameters close to those of Kutsuplus at the end of its service.

5.1.1 simulation

During its last year, Kutsuplus served around 300 people a day, totaling to around 100000 trips / year [53]. The service was available between 6am and 12pm, resulting in a 19 hour working day. Kutsuplus also operated in an area roughly the same size of the simulation area handled in this paper [53]. Demand is generated as discussed in sub chapter 4.3.3 with the only exception that no demand can be generated before 6am and trips end before 12pm. An overview on the input is given in table 5.1.1.

Input parameter	amount
Demand	300
Drivers	15
Operating hours	6am-11pm

Table 5.1.1: Input for simulation

A first simulation of 3 operating days resulted results in an average success rate of 93% adding up to a total of 3652km traveled. This means, on average, around 270 passengers are transported each day and each of them accounts for around 13.1 km of distance traveled. The average distance for the direct trips is 9.62 km, so this means a taxi has to travel around

3.48km extra on average to pick up its passenger. Table 5.1.2 gives an overview on the most important KPIs. One can see that the overall occupancy stays rather low, indicating not much rides are ride-shared. This comes as no surprise as Kutsuplus also faced low occupancy rates with over 90% of trips serving only one or two passenger at the time. The overall occupancy of trips was 1.26 [4], but notice how the simulation result is even less. This can be explained by the fact that each request in the simulation serves only one passenger (no groups traveling together), while in real-life some requests were made in group. The total distance traveled was 3652.9km, of which 2917.9km served passengers, and only a total of 56km were ride-shared, which comes down to only 1.92%.

Time in day	Avg. pas per vehicle hour	Taxis needed	Occupancy	TotalKm	Shared km
0h-1h	0.00	0.00	0.00	0.00	0.00
1h-2h	0.00	0.00	0.00	0.00	0.00
2h-3h	0.00	0.00	0.00	0.00	0.00
3h-4h	0.00	0.00	0.00	0.00	0.00
4h-5h	0.00	0.00	0.00	0.00	0.00
5h-6h	0.00	0.00	0.00	3.90	0.00
6h-7h	1.38	14.00	1.00	167.27	0.00
7h-8h	1.78	15.00	1.01	170.94	2.38
8h-9h	1.87	15.00	1.00	263.08	1.19
9h-10h	1.67	14.00	1.03	119.69	2.58
10h-11h	1.60	13.00	1.01	167.16	2.76
11h-12h	1.63	13.00	1.00	155.46	0.00
12h-13h	1.14	13.00	1.02	161.68	5.05
13h-14h	1.00	13.00	1.00	139.44	0.00
14h-15h	1.67	15.00	1.00	127.66	0.00
15h-16h	1.38	15.00	1.05	191.97	12.35
16h-17h	1.78	15.00	1.00	168.56	0.00
17h-18h	1.73	15.00	1.04	206.63	10.33
18h-19h	1.96	15.00	1.02	225.81	7.81
19h-20h	1.40	14.00	1.00	157.96	0.00
20h-21h	1.75	13.00	1.00	136.56	0.00
21h-22h	1.29	13.00	1.07	187.75	11.52
22h-23h	1.00	12.00	1.00	151.79	0.00
23h-24h	1.00	0.00	1.00	14.56	0.00

Table 5.1.2: KPI-output for a service with the same scale as Kutsuplus

5.1.2 Cost overview

The actual operating costs and revenues of Kutsuplus for its first four years op operations can be found in figure 5.1.1. "Operating costs" consist of the payments for the transport contractors. These include compensation for supplying vehicles and drivers, as well as compensation based on passenger count and driven kilometers. "Other purchases of services" include ICT costs, expert consultations, subcontracting, service development, and marketing of the novel service. Notice that the purchase of 15 vehicles, office space and parking space is not included, while this is still taken into account in the cost model build for this specific project. Tables

5.1.3 and 5.1.4 give an overview on both the CapEx and OpEx as found with both the cost and simulation model build for this project. With these values the PV and AW are calculated by building a 4 year cash flow diagram for the service. Of course, it makes no sense to compare this simulated steady-state PV and AW with the first 4 years of Kutsuplus, as this service was just starting up and in full expansion. Rather, it is compared with a "steady-state" situation built on extrapolating the Kutsuplus 2015 operations and using the same inflation and discount rates as in our simulation. Overall this results in a great comparison and, as visible in Table 5.1.5, the new results found are very comparable. This shows that both the cost model and simulation software are generating results in an acceptable range.

Kutsuplus	**2012**	**2013**	**2014**	**2015**	**2012 - 2015**
Operating revenues	**3 000**	**62 700**	**321 800**	**507 900**	**895 400**
Ticket revenues	2 600	61 700	319 200	507 700	891 200
Other operating revenues	400	1 000	2 700	200	4 300
Purchases of services	**-316 800**	**-1 521 400**	**-2 750 200**	**-3 233 000**	**-7 821 400**
Operating costs	-164 200	-1 004 000	-2 186 400	-2 626 600	-5 981 200
Other purchases of services	-152 600	-517 400	-563 800	-606 400	-1 840 200
Personnel expenses	**-119 600**	**-276 100**	**-256 100**	**-256 000**	**-907 800**
Other expenses	**-15 500**	**-12 700**	**-10 600**	**-1 500**	**-40 300**
Depreciations	**-1 600**	**-11 100**	**-13 200**	**-13 200**	**-39 100**
Net income	**-450 500**	**-1 758 600**	**-2 708 300**	**-2 995 800**	**-7 913 200**

Figure 5.1.1: Kutsuplus: operating costs and revenues (2012-2015) [2]

Category		*units*	*Cost/unit*	*Amount [€]*
Vehicle fleet	Purchase Vehicle, Sedan	15.00	36250	543750
	Purchase Vehicle, Minivan	0.00	42014.15	0
	Parking Space	15.00	3775	56625
			subtotal	**€600375**
Office space	Interior	14.00	448.4	6277.6
	computers	2.00	1500	3000
			subtotal	**€9277.6**
Platform	Development application			150000
Administrations	Start-up Costs			1500
			Total Capex	**€761152.6**

Table 5.1.3: Overview CapEx cost model input Kutsuplus

Category		*units*	*Cost/unit*	*Amount [€]*	period
Vehicle fleet	Fuel (Diesel)	621.67	1.40	868.48	day
	Fuel (gas)	0.00	1.36	0	day
	Maintenance	3,652.32	0.04	146.9	day
			subtotal	**€ 1,014.57**	**day**
Office space	Rent			650.00	month
	GEW			294.48	month
			subtotal	**€ 944.48**	**month**
Platform	Servers			4,000.00	month
	Software			10.00	month
			subtotal	**€ 4,010.00**	**month**
Wages	Drivers	271.00	25.00	6,575.00	day
	office personnel	16.00	40.00	640.00	day
			subtotal	**€ 7,215.00**	**day**
Administration	Company contribution			850.00	year
	Insurance vehicles	15.00	2,500.00	37,500.00	year
	Taxes Vehicles	15.00	243.22	3,648.30	year
	Insurance personnel	17.00	500.00	8,500.00	year
	Insurance office			1,000.00	year
	Licencing	15.00	300.00	4,500.00	year
	Marketing			150,000.00	year
			subtotal	**€ 205,998.30**	**year**

Table 5.1.4: Overview OpEx cost model input Kutsuplus

Case	Result	Amount
Kutsuplus: cost model	PV	€ 11,062,898.76
	AW	€ 2,905,617.19
Kutsuplus: 2015-2019	PV	€ 10,271,659.82
	AW	€ 2,697,581.84

Table 5.1.5: Results for PV and AW Kutsuplus

5.1.3 discussion on the PV and break-even pricing

Figure 5.1.2 gives an overview of the PV of the different cost categories. It is clear that wages (mostly for drivers) present the most significant cost with an overall percentage of 75%. This could be expected as was already discussed in the literature study.

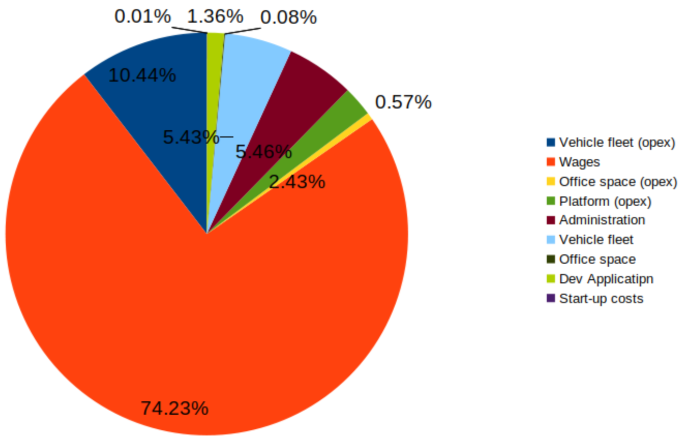


Figure 5.1.2: cost categories based on PV (4years) [2]

To generate a break-even price, the AW was converted to a DW and a HW. This is done the same way as the AW, but now for a period of 3650 (10-year) days. To calculate HW, the DW without driver wages is divided by the daily operational hours of the service (a cost shared between all passengers) and then added to this value will be the HW of driver wages as calculated by the amount of drivers needed at each instance. This way not only an overall break-even pricing is found, but also one to indicate how much passengers traveling at different times during the day should pay if drivers wages were not divided over all passengers. An overview of break-even pricing is found in Table 5.1.6. By the end of the Kutsuplus service the average trip fare was € 5.8 [2]. But Kutsuplus was still receiving subsidies, which represented around € 20 per trip. This indicates that the break even price for Kutsuplus was around 26 € / trip.

Time in day	Hourly worth [€]	Passengers taveling	Break-even pricing [€]
6h-7h	422.04	12.37	34.12
7h-8h	422.04	23.94	17.63
8h-9h	422.04	21.29	19.82
9h-10h	422.04	16.53	25.53
10h-11h	422.04	13.80	30.59
11h-12h	422.04	14.71	28.70
12h-13h	422.04	13.36	31.59
13h-14h	422.04	15.62	27.02
14h-15h	422.04	14.91	28.31
15h-16h	422.04	17.96	23.50
16h-17h	422.04	20.26	20.83
17h-18h	422.04	20.61	20.47
18h-19h	422.04	19.11	22.09
19h-20h	422.04	13.12	32.16
20h-21h	422.04	13.80	30.59
21h-22h	422.04	12.05	35.02
22h-23h	402.24	9.91	40.59
23h-24h	303.24	4.16	72.85
Total	**7,458.06**	**277.50**	**26.88**

Table 5.1.6: break-even pricing as found by simulating Kutsuplus

5.2 Impact of different policies

The range of policies operators can use is vast, and it was never the goal of this paper to conclude on which would be the most beneficial DRT-service in Ghent. But, before assessing the economic viability of DRT-services in Ghent, it would be necessary to make some policy decisions such that it would even begin to make sense to validate the service. In a way this section gives an overview to the reader on which decisions are taken to mimic a reliable service. It also shows how the model could be used to simulate policy decisions before applying them in the real world. It should be clear that the policies discussed in this paper are just a small share on the vast array of policies that could be taken to improve upon a DRT-service and I would like to recommend further investigation on different policies as a possible subject for further theses topics. For this section the DRT-provider is set to be a newly introduced taxi ride-sharing service that operates with licensed drivers. Later in section 6 more type of services will be discussed, yet the findings of the different policies here will remain the same.

5.2.1 Impact of centering taxis

This subsection will shortly discuss how centering empty taxis, after dropping off their last assigned passengers, impacts KPIs of the service.

In the first simulations, there was no specific instructions for taxi drivers who dropped off their last passenger. This meant taxis simply stopped driving, parked and waited until they get assigned a new order. It is easy to see that this became a problem when a taxi dropped off his last passenger far from the city center. As less trip origins are generated further from the center points (4.3.3), it was less likely that a new incoming request would be assigned to this taxi. This problem was noticed during early simulations when the amount of fulfilled trips differed greatly between the different taxis. It seemed an opportunity to increase the service efficiency by reducing this variety. Therefore this section will now handle and compare two new policies.

The first policy is to sent empty taxis, that have no assigned requests, back to a central location in the simulation area. For this experiment that location is set to be the Korenmarkt, as it is located more or less in the center of the simulation area. Directly comparable is the second policy, in which taxis are send back to the closest of the eight discussed center points (4.3.3), this way it is expected to even further improve the 'total distance driven'-KPI. Both policies are easily implemented inside the testbed and simulations are set for 50, 100 and 150 taxi vehicles, each on a different set of daily trips.

As explained in the introduction, these policies are introduced to reduce the difference between the number of successfully assigned passengers per taxi. To compare the different policies, box plots are created on the amount of successfully assigned passengers per vehicle. The wider a box, the more scattered the data it presents and vice versa: a narrower box means that the difference on the amount of assigned passengers between taxis is smaller. Figure 5.2.1 shows the box plots for each of the different policies on the different daily inputs and service sizes (50, 100 and 150 drivers). For 50 drivers it seems less convincing, but for the larger services the variety between taxis gets reduced by the new policies. This comes to show that both policies are performing as they were intended. Do notice that for less loaded services (high number of taxis for a low number of daily trips) and high loaded services (high number of daily trips for the service) the difference between policies seems to disappear, this is mostly visible on the plot with 100 drivers as the other services are not tested on such low/heavy loads (see fig 5.2.2 on the success-rates). Regarding less loaded services, the spread of the boxes is always high, even with the new policies in place. This is explained by the fact that each taxi of the service is always present during each hour of the simulation, yet, more then often, only a few taxis are necessary to handle the low amount of requests during some hours. Therefore lots of taxis are empty most of the time. Next to this, the ride-sharing algorithm as used for this experiment also aims to first try and assign taxis with other passengers on-board to new requests, this is done by by putting a point/weight on boarded and queued passengers to the closest 10 taxi vehicles. In the cost modelling aspect this problem of empty vehicles is highlighted by introducing a KPI which presents the number of taxis required each hour (explained in section 3.3). For a high loaded service the spread is always low, this is explained by the fact that there are almost always new requests available for each taxi regardless if they are driving inside the city center or in a more rural location and regardless of the policy in place. The simulations did not provide a clear indication on which of the centralization policies perform best. Also, the difference on how many passengers handled per taxi isn't really such an important parameter to predict the feasibility of a DRT- service, it simply indicates a disproportionately between taxis that will affect other more important KPI such as break-even price and success-rate. These are the KPI now considered.

An important consideration is the success-rate of the service, it highly influences pricing by spreading costs over more passengers and it gives the customer a far better experience if trips are accepted more often. Presented in figure 5.2.2 are the success-rates obtained by each of the different policies for all considered instances. For less loaded services the success-rate of the different policies is more or less equal to 100%. There are plenty of taxis available for each requests at all time, and little to no ride-sharing is taking place. Even without sending taxis back to a more central or critical location the service is easily serving all requests. This changes when more daily trips are generated, and a clear difference grows between the initial (no centering) policy and both new centralizing policies. Gains of over 10% are found, showing how great the service is improved by returning empty taxis. The bigger the vehicle fleet and daily trips, the more important this effect shows. Between both new policies it is again difficult to decide which one performs best. For 50 vehicles the one-location centralizing policy seems to outperform the closest-centering policy, but this changes when the amount of vehicles grows. To further decide on the optimal policy the break-even price will now be considered for services performing with at least a 90% success, this way less realistic and under-performing services are eliminated.

As expected, break-even prices found with the new policies are usually better (lower) then those without a drive-back policy, see figure 5.2.3. Now it also becomes clear that centralizing to one location (in our case to De Korenmarkt) seems a better option than centralizing to 8 points. To better understand this, let's can take a look at the other KPIs for the different options (with minimal of 90% success-rate) in figure 5.2.4. Attention should be given to the scale on the y-axis in which the minimal values differ between different service scales. First of all, while the policy to return to 8 center points was introduced because it was expected that this would reduce the total distance driven (compared with the 1 point centralization policy), simulations show the opposite for most of the situations. Of course this could also be caused by a greater success rate, therefore closer attention is given to the the amount of km traveled per passenger (total km divided by all passengers). Again it shows that the 1 point centralization policy outperforms the 8-point centralization policy (8 times out of 13 instances). This could indicate less ride-sharing is taking place when taxis are returned to the closest of the eight center point even tough the amount of successful requests is higher. This presumption is confirmed when comparing the shared-distance (%) KPI. In almost all cases there is more ride-sharing (as a % of total distance traveled) for the one-location centering policy. Because of less taxi-sharing, the closest-centering policy has a negative effect on costs per passenger (cost per passenger increases). This also shows in the total hours driven, in which the one-center policy is always outperforming the closest-centering policy. The driver wages are the most important cost-factor so it is easy to conclude that the higher break-even prices for the closest-centering policy are a result of less ride-sharing. The average vehicle productivity also seems to benefit from a one-location centering policy. Notice that this KPI is somewhat off putting as it filters out empty taxis each hour (eg. if only 1 taxi drove 1 passenger and the other 99 taxis were empty during this hour, the avg productivity would be 1 passenger/vehicle hour), this would be the reason for the sometimes higher averages when there is no policy in place.

It seemed a good solution to implement the closest-centering policy to reduce the overall distance by sending vehicles back to the closest of the eight most visited locations. But it now seems the DRT-provider is better of sending his vehicles back to a more central-location that is closer to all other "hot-spots". In this setting, the Korenmarkt is not only also one of the eight center points, it is also considerably close to all other center points. Meaning that when a taxi is at the Korenmarkt, he could also handle requests from the other 7 center-points quite easily. In contrast, when taxis are send back to the closest of the eight center-points he could be at a long distance from the other center-points, which reduces the probability for him to be assigned a new passenger. Overall it seems most beneficial to find a central location on the DRT-service area which is close to each of the "hot-spots" for trips as compared to sending taxis back to a specific hot-spot.

To conclude this subsection: Both centralization policies reduce the variation in amount of passengers transported by the different taxis. However, it is clear that the one-location centering policy outperforms the closest-location centering policy if other KPIs such as break-even pricing and shared distance driven are taken into consideration. Although the closest-centering policy has an overall better success-rate, the increase in passengers does not seem to positively effect the ride-sharing nature of the service. As this paper tries to give an analysis on the economic feasibility of a DRT-service, is it chosen to opt for the solution that minimizes total-costs over a policy that introduces greater success-rates. Therefore, future simulations will always be performed with the use of one-location centralization policy.

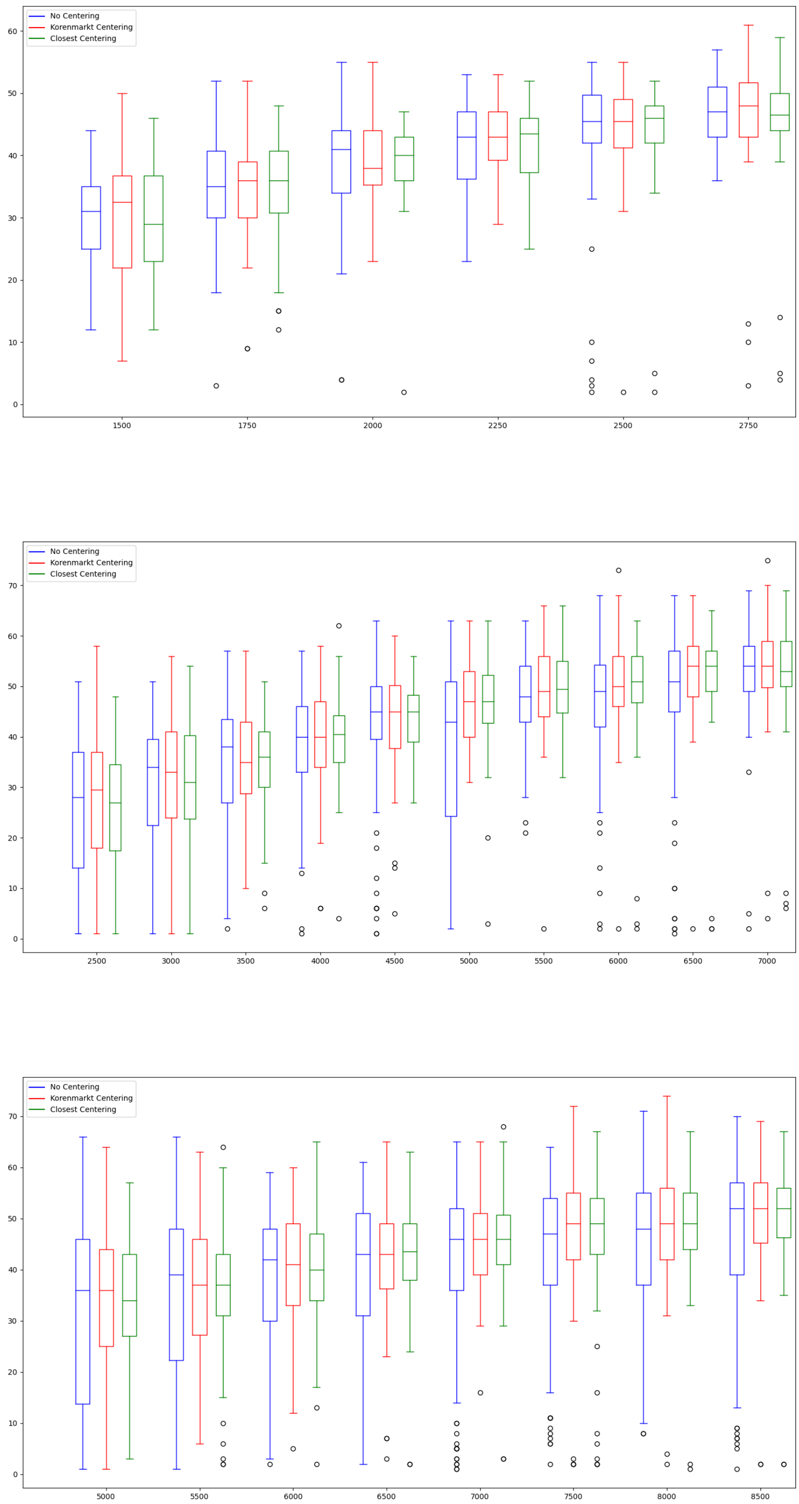
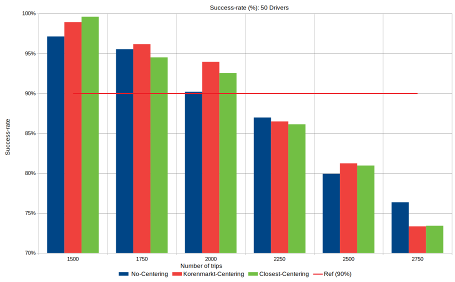
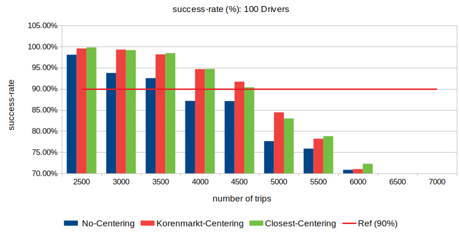


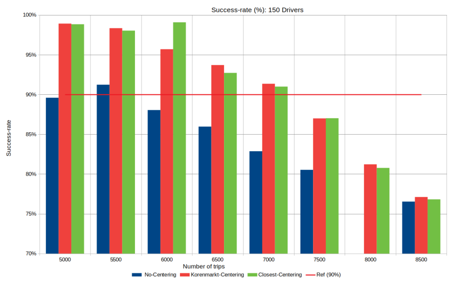
Figure 5.2.1: Box plots for respectively 50, 100 and 150 drivers. X-axis represents number of handled trips per taxi, Y-axis represents the amount of daily trips.



(a) 50 drivers

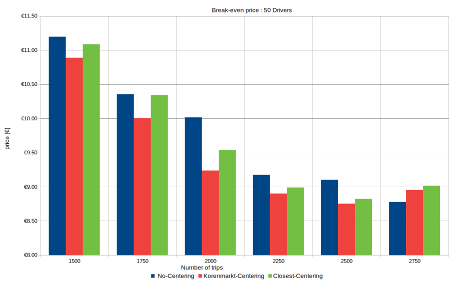


(b) 100 drivers

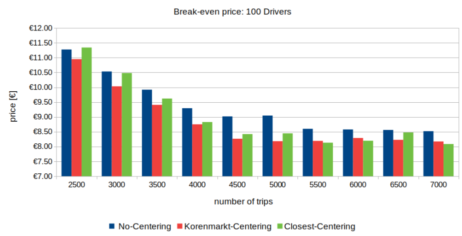


(c) 150 drivers

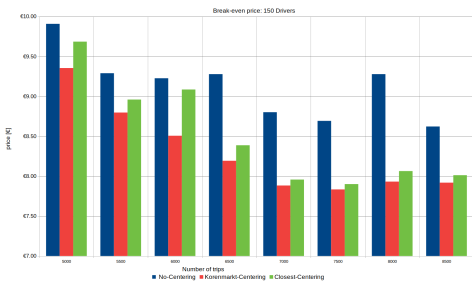
Figure 5.2.2: Success-rates for the three policies



(a) 50 drivers



(b) 100 drivers



(c) 150 drivers

Figure 5.2.3: Break-even prices for the three policies (with 90% success-rate)

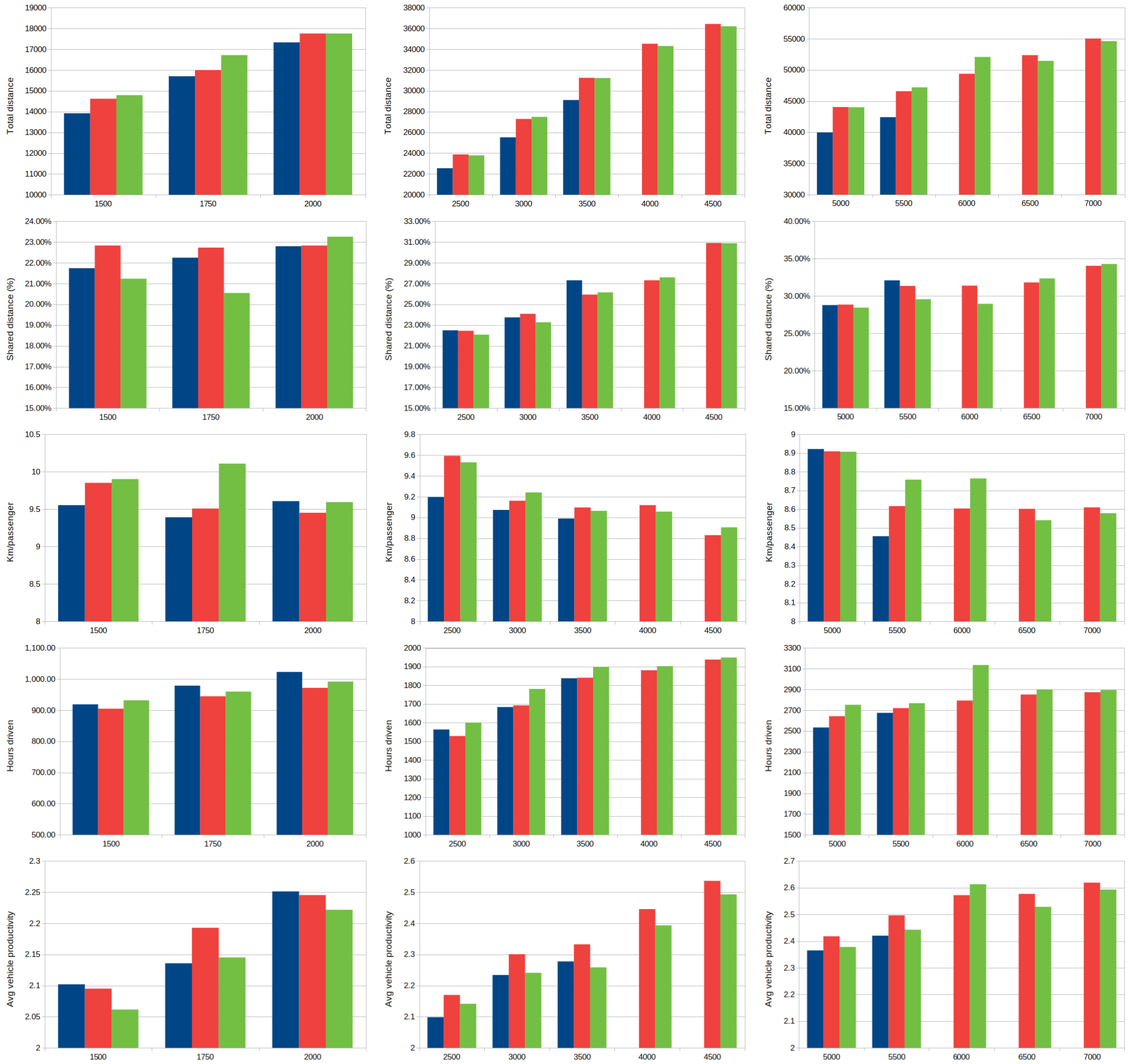


Figure 5.2.4: Graphs on other important KPI for different policies, corresponding with services of respec. 50, 100 and 150 vehicles, each for a given amount of daily trips with at least a 90% success-rate.

5.2.2 Impact of the extra allowed travel time

Compared with traditional public transport, travelling by car or taxi will typically be less time consuming. To be competitive, DRT should also provide its users an acceptable travel time, which of course will be somewhat higher then a direct travel time because of its ride-sharing nature. Yet, this time increase should remain reasonably limited. An interesting question for the DRT-provider is: "If we allow extra travel time, will the gains in success rate and break-even price be important enough to offset the negative impact on the comfort level of passengers"

To answer this question, it would be interesting to compare the reduction in break-even price with the passenger's money value of the extra travel time. If the reduction in price is greater then the money value of the extra travel time, it would be acceptable for most of the service users to indeed increase the maximum allowed travel time. This section will now discuss multiple instances of this allowed extra travel time and show the impact on both pricing as well as the environmental benefits.

As discussed in Section 4.3.3 the average trip length is 9.62km. Direct travel of this distance at an average speed of 30km/h (as used in the simulator) takes about 19 minutes. For ride-sharing to take place, it is a necessity that each passenger accepts an increase in travel time. This accepted/allowed increase is defined as a percentage of the direct travel time between the request's origin and destination and can be altered inside the testbed when generating demand. To show how the extra allowed travel time impacts both pricing and environmental concerns, simulation is done alternating between four different values for this allowance: 30, 50, 70 and 100%. It is important to understand what average speed means for the simulation testbed: when the simulator calculates the travel-time (s) between two nodes, it uses the distance in meter and the average travel-speed (m/s). To calculate a maximum on the tested allowances it was chosen to calculate how much time a bus (of "The Lijn") would take, including the time it takes walking to and from the bus stops and waiting time for switching buses (if needed). Different trips were considered inside the application of the provider "de Lijn" ([56]) and by averaging over a multiple of routes during different times of day it seemed that 15km/h was an acceptable approximation. Therefore it seems needless to consider allowances above 100%, as passengers would probably not accept the service when travel times exceed those provided for by the probably less expensive service of public bus travel.

To show how these different allowances impact the different KPIs, both a service operating with 50 and 100 vehicles are tested each of them with various numbers of trip requests. First the average and maximum on-board travel times are discussed. Notice how both the average and maximum on-board travel time increase in tables 5.2.1 and 5.2.2. This consequence was to be expected as an increased allowance will never result in a decrease of the average trip length but will only allow for longer on-board travel times. The important question is how much the on-board travel time increases with increasing allowance. Luckily, this seems to be limited. On average, a 20% increase of allowance increases the average on-board time with 00:01:04 (=1 minute). This value will later be used when deciding on which allowance to use. Next to the average increase of travel time in absolute numbers, it is also interesting to consider the relative (percentage) average increase in travel time. This increase is also defined as a percentage of the direct travel time. For each executed trip the travel time is compared to its corresponding direct-travel time and the overall average value is calculated, see Table 5.2.3. These values are of course highly connected with the average increase in the on-board travel times. Notice that an allowance of 100% only has an average relative increase of travel time by 15,3%. This shows that on most trips are not drastically impacted by an increase in the allowed extra travel time. Interesting as well is how the average increase is distributed over all trips. Figure 5.2.5 shows a histogram on how the increase is distributed over all trips, for two simulations (3000 and 3250 daily passengers) with 100 drivers and an allowance factor of 100%. Most of the trips (>60%) only see a maximum increase of 5% which could indicate that lots of trips are not ride-shared (around 30% has a 0% increase) and that the ride-sharing algorithm quite efficient in combining trips (only combining trips in case when the trips are compatible) (+30% of trips see less then 5% increase). Also interesting is the fact that the distribution is quite uniformly distributed for values higher then 5%. Figure 5.2.6 shows the same histogram as fig 5.2.5 excluding all values below 5%. What could raise concerns is the fact that this average increase becomes higher when generating more trips. The more daily trips, the more likely ride-sharing takes place and, as a consequence, more travellers see an increase in their on-board travel time. Luckily, if we only consider services with acceptable success rates, the overall average increase in travel times stays acceptable.

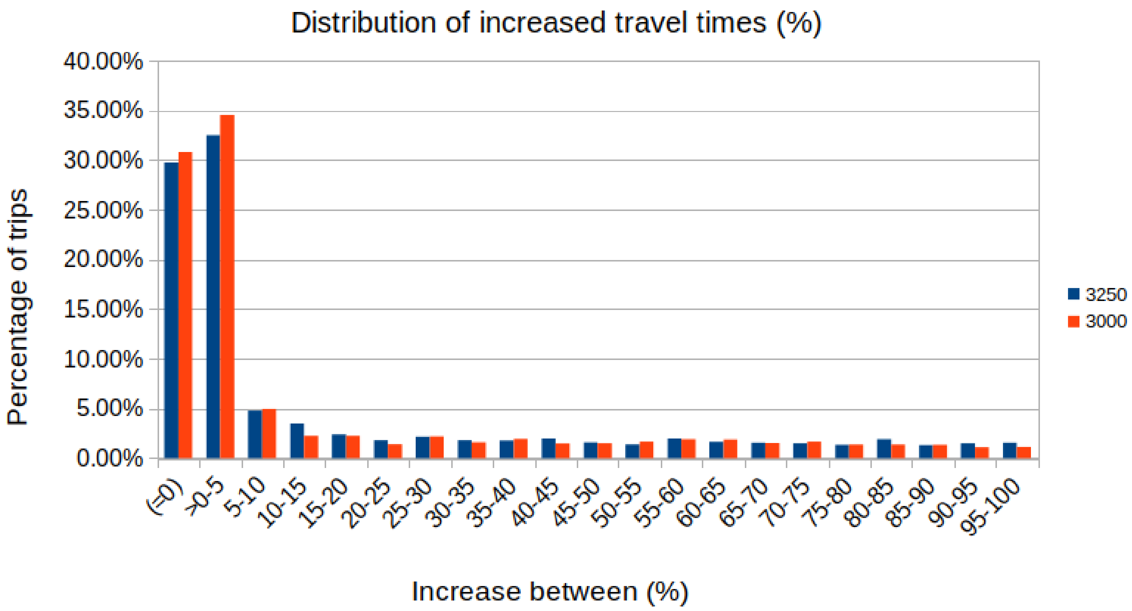


Figure 5.2.5: Histogram on the increase in travel times as a percentage of direct travel, including 0%-5%

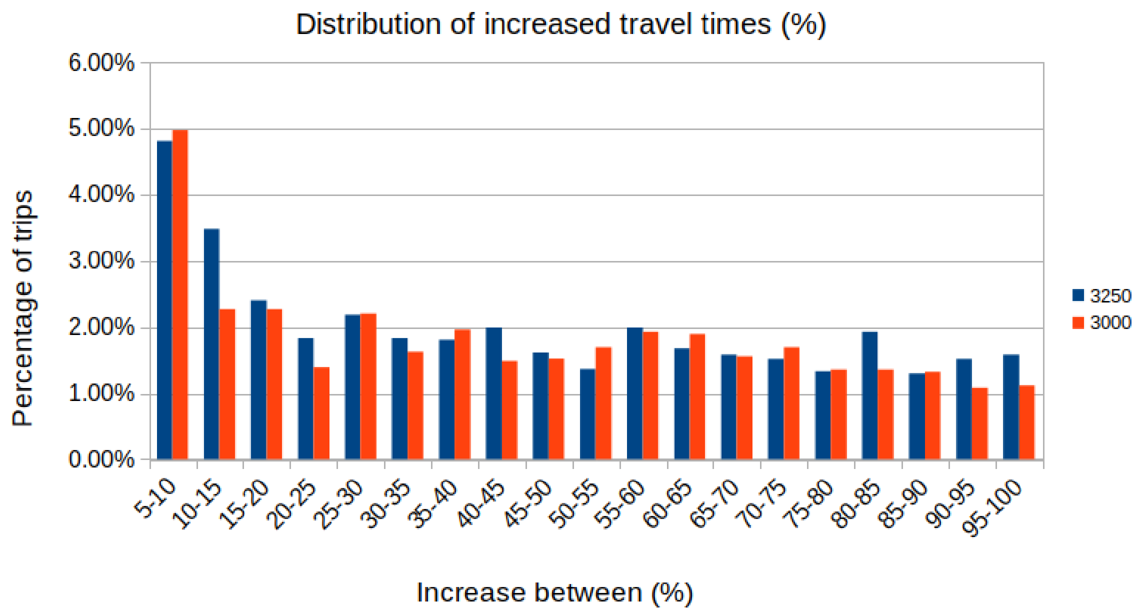


Figure 5.2.6: Histogram on the increase in travel times as a percentage of direct travel, excluding 0%-5%

Figure 5.2.7 shows the impact on break-even pricing and success rate if the allowance is increased. It is very clear that a higher allowance is beneficial for both the success-rate and break-even price. By allowing longer on-board times, the amount of ride-sharing is increased, this is visible when comparing shared-distance between the instances as shown in figure 5.2.8.

The service operator choosing which policy he would implement, as discussed in the introduction, should consider the money value of the extra added time compared to his reduction in break-even pricing. The average wage in Belgium is around €2100 [57], considering people work around 38h a week and 4.28 weeks a month, the price value for one minute is set to be around €0.21 (of course highly dependable on each passengers perception). Another reasoning could be because services are only simulated for weekdays (Monday-Friday) that people work 50% of their time awake (8h sleep-8h work-8h free time). This way the price value decreases to $2100/(30 * 24 * 60 * 0.5) =$ €0.1. On average, as already discussed, a 20% increase of the allowance increases the average on-board time with 00:01:04 (=1 minute). To benefit both the service as well as its passengers, the break-even price should drop with at least €0.1 to €0.2 for each 20% increase in allowance. This is most definitely the case. On average, the price drops between 50% and 30% is €0.89. Increasing from 50% to 70% makes it drop around €0.5. From 70% to 100% the average drop is €0.81. The gained decrease in cost out-weights the increased travel time cost, therefore it should be considered highly advisable to increase the allowed travel time as high as possible (for this setting 100%). Another interesting idea for further analysis would be extend the simulation model to communicate to the potential customer both the actual time cost for the requested trip with a traditional public transport bus, next to the offer presented by the DRT-service, this way the maximum allowance could be increased.

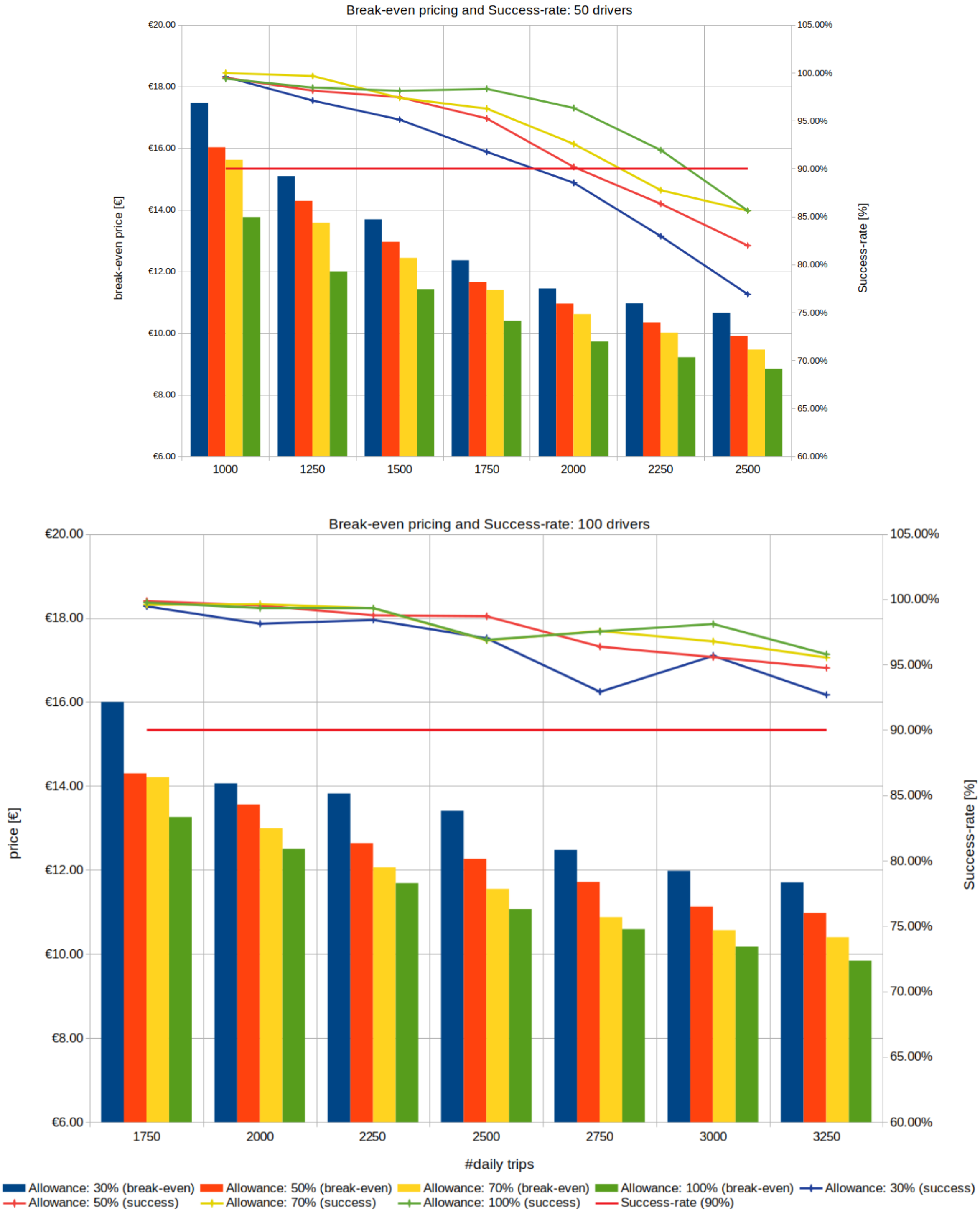


Figure 5.2.7: Influence of the allowance of on-travel time on break-even pricing and success-rate

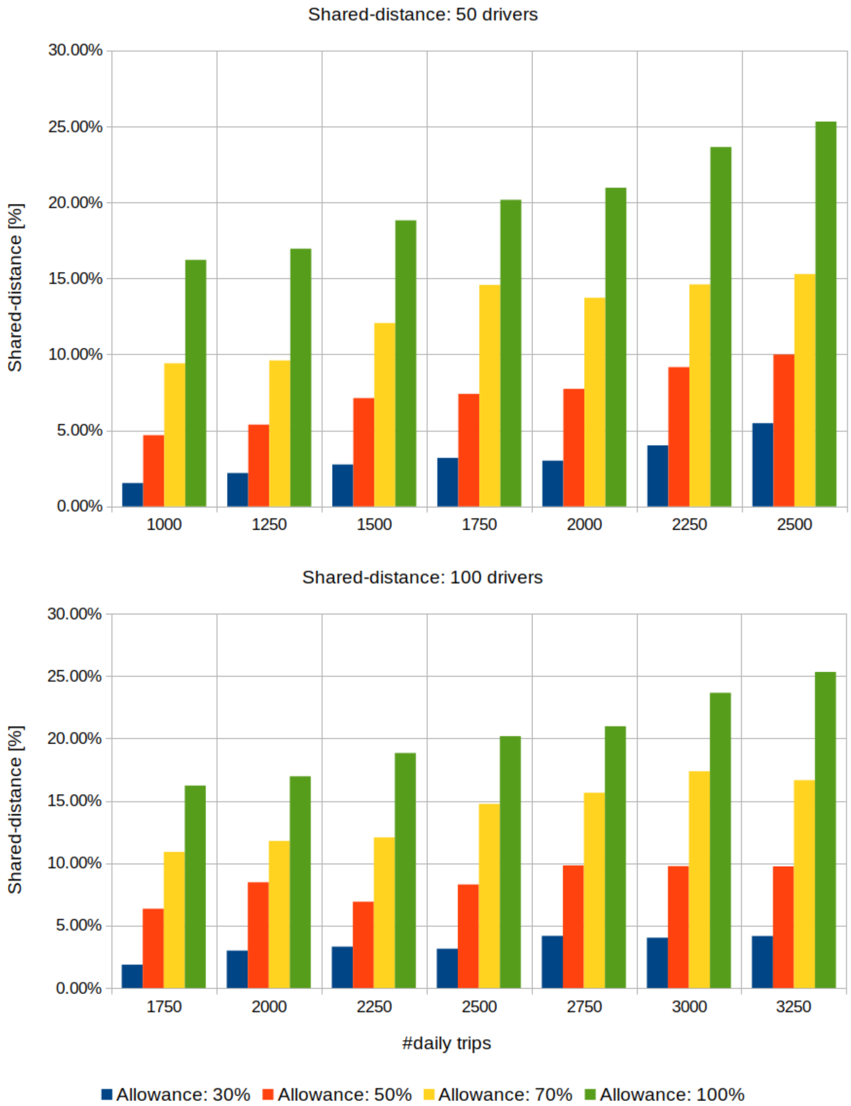


Figure 5.2.8: Shared-distance as a percentage of total distance traveled for different allowances

		30%	50%	70%	100%
	1000	00:19:24	00:20:07	00:20:57	00:22:12
	1250	00:18:58	00:20:22	00:20:32	00:22:19
	1500	00:19:40	00:20:26	00:21:20	00:22:34
50,00	1750	00:19:28	00:20:28	00:21:39	00:22:09
	2000	00:19:13	00:20:13	00:21:23	00:22:26
	2250	00:19:27	00:19:47	00:21:25	00:23:15
	2500	00:19:46	00:20:35	00:21:04	00:22:44
	1750	00:19:33	00:20:16	00:20:47	00:22:22
	2000	00:19:27	00:20:19	00:21:13	00:22:50
	2250	00:19:23	00:20:04	00:20:27	00:22:33
100,00	2500	00:19:37	00:20:17	00:21:32	00:22:55
	2750	00:19:32	00:20:20	00:21:18	00:23:03
	3000	00:19:55	00:20:14	00:21:22	00:22:43
	3250	00:19:27	00:20:16	00:20:57	00:23:17

Table 5.2.1: Average TravelTimes with increased time allowance

		30%	50%	70%	100%
	1000	00:45:15	01:00:50	01:08:03	01:11:25
	1250	00:48:45	00:56:19	00:59:02	01:16:23
	1500	00:52:01	00:57:26	01:09:26	01:10:41
50,00	1750	00:51:02	00:59:41	01:05:56	01:11:40
	2000	00:49:58	00:57:08	01:05:13	01:14:20
	2250	00:51:49	00:55:38	01:08:38	01:12:20
	2500	00:53:57	00:58:18	01:06:19	01:14:59
	1750	00:53:54	00:57:46	01:06:38	01:13:34
	2000	00:48:22	01:00:44	01:05:49	01:19:40
	2250	00:51:27	00:53:20	01:07:34	01:16:45
100,00	2500	00:55:17	01:05:14	01:06:48	01:27:22
	2750	00:54:12	00:59:31	01:07:01	01:19:17
	3000	00:50:02	00:56:33	01:09:50	01:17:14
	3250	00:52:10	01:00:20	01:03:43	01:14:53

Table 5.2.2: Maximum TravelTimes with increased time allowance

		30%	50%	70%	100%
50,00	1000	1.71	3.34	6.89	12.46
	1250	1.88	3.99	7.76	13.35
	1500	2.07	4.60	8.54	14.63
	1750	2.26	5.01	9.48	15.59
	2000	2.28	5.12	8.83	14.96
	2250	2.50	5.62	9.69	17.12
	2500	2.93	5.96	9.51	16.41
100,00	1750	1.84	4.55	7.06	12.80
	2000	2.18	4.86	8.14	14.90
	2250	1.99	4.53	7.81	15.47
	2500	2.26	5.24	9.45	15.36
	2750	2.41	5.46	9.39	16.82
	3000	2.57	5.63	9.85	16.38
	3250	2.39	5.32	9.74	17.43

Table 5.2.3: Average increase in travel times as a percentage of direct travel

Just like break-even pricing, the environmental impact of increasing the maximum allowance is clear. As the probability of ride-sharing is increased by allowing longer trips (fig 5.2.8)the service reduces its environmental impact per person. This is clearly visible if the distance per passenger is compared. Figure 5.2.9 shows the total distance traveled, the distance per passenger and the average vehicle productivity for each of the tested allowances. Notice that it is hard to make any assumptions on the total distance traveled based on a service with 50 drivers: sometimes an increased allowance increases the total distance traveled, sometimes it does the opposite. But for 100 drivers there is always a reduction when the allowance gets increased. The same applies to the average distance per person (total distance/total passengers). Overall the conclusion is that with increased allowance the avg distance per passenger is decreased, indicating the service is reducing the environmental impact per passenger. This is a great discovery and a tipping point can be discussed. If the total distance divided by the total amount of successful trips is below the average trip length of direct travel (in this case 9.62km) it should be clear that the service is working efficiently in reducing overall emissions compared to direct non-sharing car travel.

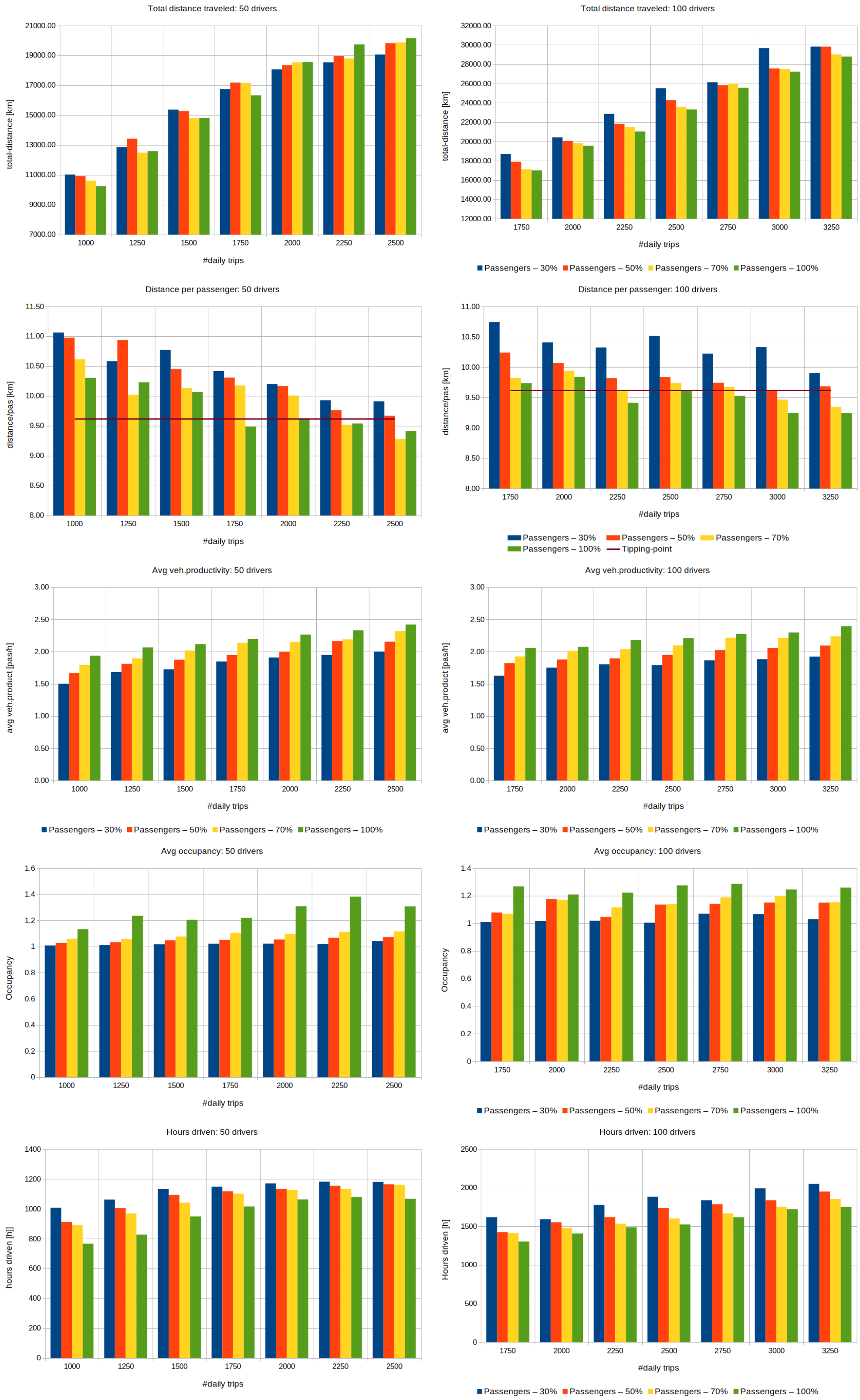


Figure 5.2.9: Influence of the maximum allowance on different KPI

The total impact on all other KPI is positive, and the overall efficiency of the service is greatly increased. The average occupancy and vehicle productivity are positively effected by the policy change (figure 5.2.9) and the total amount of vehicle hours decreases. Conclusion of this experiment: when the provider of DRT can persuade his passengers in accepting some extra travel time by offering them a decrease in price, he should definitely do so. As discussed, the limitation of this increase can be calculated by predicting the money value of time and comparing both the price reduction with the increased average travel time. With variable pricing this logic could be implemented even further. When passengers have higher travel times the fare which they have to pay should be reduced by offering a discount based on the money value of time and their detour time. For all following experiments, the maximum allowance will be set to 100%.

5.2.3 Impact of an increase in the allowed reservation time-window

Kutsuplus used a maximum allowed reservation time of 45 minutes before the actual earliest departure, this way the service tried to be as efficient as possible whilst still providing accurate travel times to its customer. This is described by [53]: "Kutsuplus used a maximum allowed reservation time of 45 minutes before the requested departure time." This way of working seems quite bizarre, as one could argue the service would benefit from an increase in the allowed reservation time-window. Also, when using data analysis, it should become increasingly easy to predict travel times, even if reservations are made days in advance. To simulate an increase in allowed reservation time, the initial setting in which requests have to submitted between 60 and 30 minutes before the requested departure time is first increased to 120 and next increased to 180 minutes (still at least 30 minutes in advance). Notice previous discussed policies are in place: centralizing empty taxis to the Korenmarkt and a maximum time allowance of 100%.

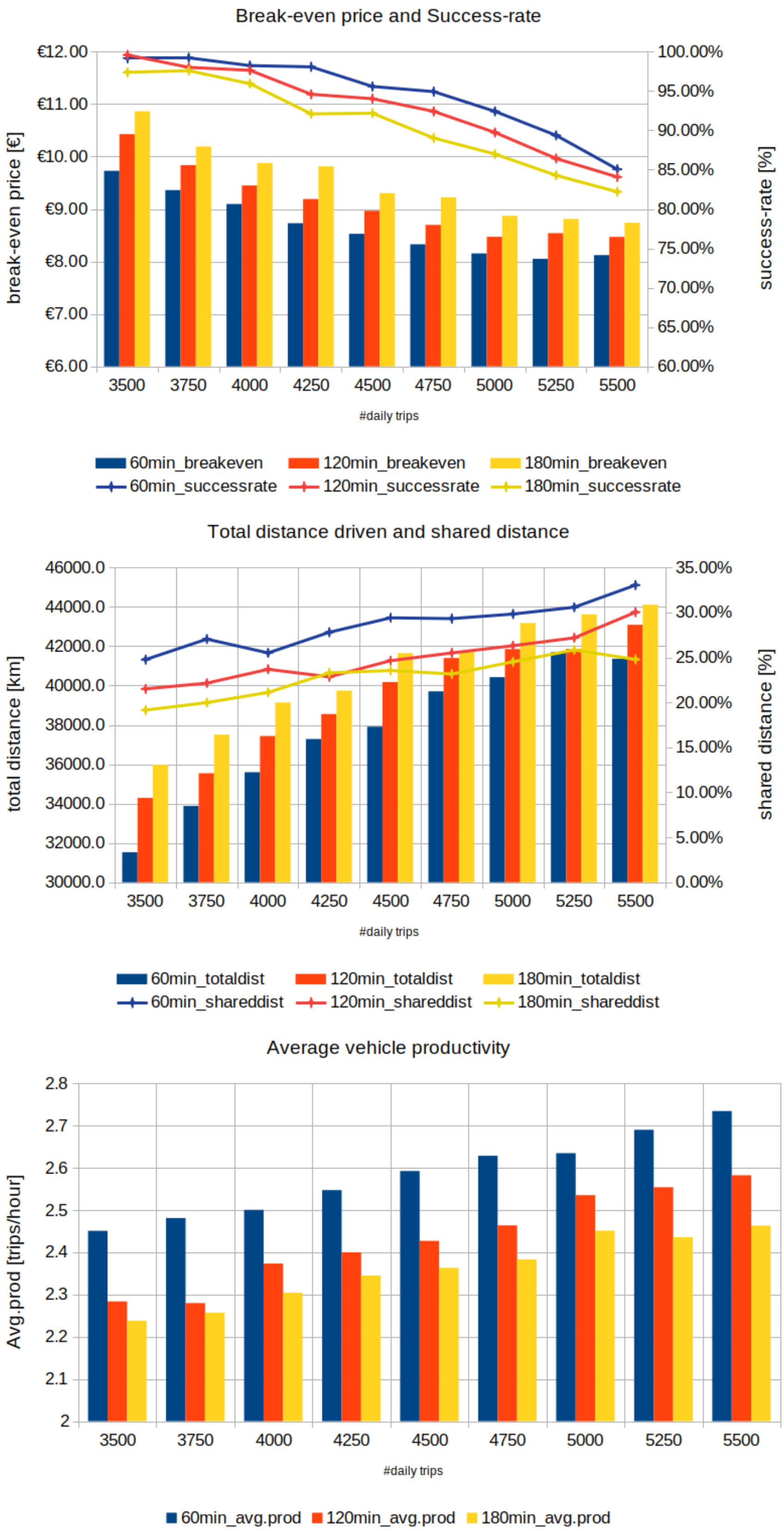


Figure 5.2.10: Influence of the maximum allowed reservation time on different KPI

Taking a look at figure 5.2.10, the performance of the service clearly decreased with an increase in the allowed reservation time-window. While this may seem contra-intuitive, this can be explained by the fact that it's harder for the algorithm to predict which vehicles will be closer to the request at the time of its earliest departure. This makes it increasingly harder to efficiently combine passengers (as also seen in the decrease of the shared distance), resulting in a higher total distance driven even with a lower success-rate and less daily passengers, also generating higher relative costs and break-even and lower vehicle productivity.

Thinking about possibilities to overcome this phenomena, an extension to the algorithm could probably be implemented that re-releases previous accepted requests. Rejecting the old request would now be impossible, but it becomes easier to predict which taxi will be closer to the request. If a more appropriate taxi is found it could be assigned to the old request and the originally assigned taxi is then released from its duty to pick up this passenger. While this would increase computational power needed, the passengers gain some extra levels of comfort by allowing them to make earlier reservations. Some passengers, such as the elderly, would most definitely highly appreciate this option, as human beings could be scared off by the fact that their request wouldn't get accepted if released too short in advance.

A small note on this topic. If a request would generally be submitted considerable time before the requested departure time or if demand could be more precisely predicted by analysing previous requests (Big Data Analytics) it could become appropriate to also implement a static DARP-algorithm to assign these requests. New requests could then be inserted by the dynamic routing algorithm. This way the overall efficiency would start increasing with an increased allowance on the reservation time-window. I would suggest reading "The Dial-a-Ride Problem (DARP): Variants, modeling issues and algorithms" (Jean-François Cordeau, Gilbert Laporte [**?**]) for those who are interested in implementing such an algorithm.

5.2.4 Impact of a flattened demand-curve

Flattening the daily demand distribution of a DRT-service could possibly increase the efficiency of the service by reducing the bottleneck of the service during peak-hours and spreading those passengers over other, less busy, times. This prediction seemed interesting enough to try and simulate. Flattening the daily demand could be done by implementing a variable pricing which would stimulate passengers to travel during a less busy time of the day. This paper will not focus on how big the impacts of variable pricing would be on the customers demand-curve, but will only use use different demand curves to compare the KPIs.

Flattening the curve is expected to impact multiple KPIs, both on a positive or negative way.

It can be expected that to achieve the same success-rates, flattened demand could reduce the amount of vehicles needed, vice versa, if the same amount of vehicles remains constant, flattened demand would probably increase the overall success-rates. This would have a positive effect on the break-even price as more passengers are now paying for the service. On the other side, it could possibly also negatively affect the total distance driven and require more taxi vehicles and taxi drivers during less busy times. This would increase the total costs and thus increase break-even prices...

The model is not build to release new taxi vehicles to achieve a predetermined success-rate, and so it would be impossible to check the difference on the amount of vehicles needed to achieve certain success-rates in a normal or in and more flattened daily demand distribution. This experiment will thus only test the second hypothesis: that a flatter demand increases the overall success-rate, if the number of vehicles remains constant.. Three different experiments are ran on services operating with either 100 or 150 vehicles with daily demand ranging from 3500 to 9000 trips. Figure 5.2.11 shows how the daily demand compares between the experiments, notice that unaltered (normal) distribution is the initial distribution as used by previous experiments.

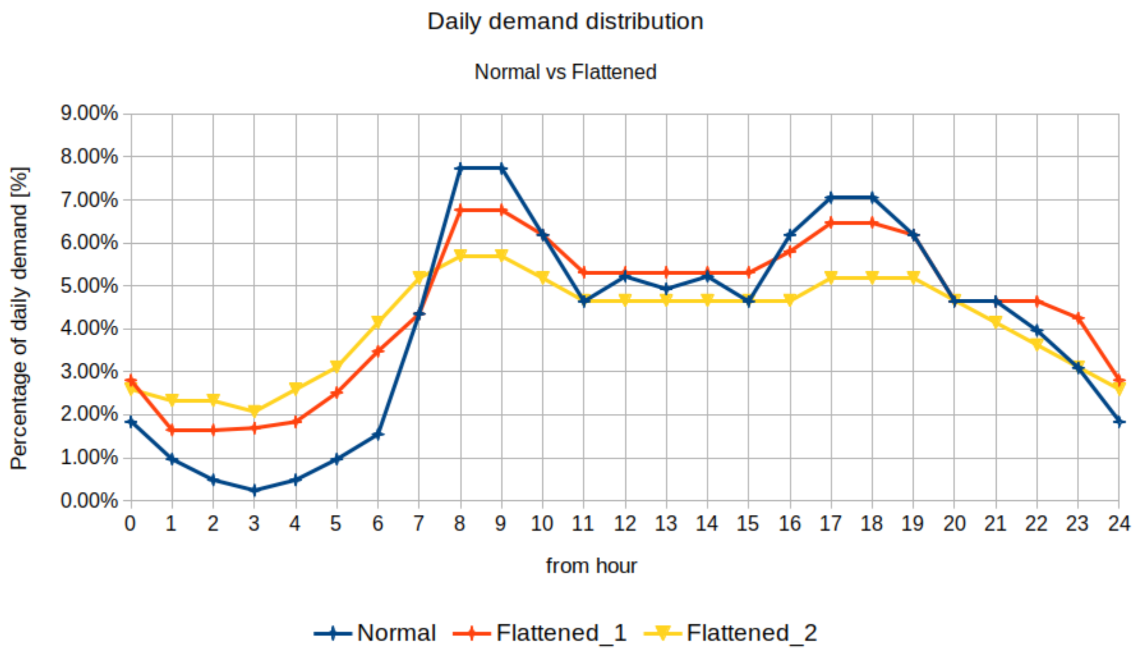


Figure 5.2.11: Flattened daily demand compared to normal distribution

The results of this experiment really depend on the service size and demand levels reached and a difference can be made between less-loaded and high-loaded services. Figures 5.2.12, 5.2.14 and 5.2.13 compare different KPIs for the different services.

First, considering less-loaded services: it is noted that break-even prices rise when demand is flattened. By flattening the demand for less-loaded services the opportunity to share rides during those peak-hours is reduced. Passengers that used to share rides during these hours are now spread over less busy hours, and the net gain in ride-sharing during those hours is less then the loss of ride sharing during peak-hours. Figure 5.2.15 shows the percentage of shared-distance for each hour for the different demand distributions as an average of 3500 to 4500 daily trips. Notice that this distribution is quite similar to the daily demand distribution. Less ride-sharing indicates more vehicle hours are needed to reach the same levels of success and this combined by the fact driver wages have the most impact on the costs of the service, the overall break-even price increases.

In contrast, high-loaded services can benefit from spreading demand. The net gain in the amount of ride-sharing during non-peak hours now outreaches the net losses of ride-sharing during peak hours, this combined by higher success-rates now reduces break-even prices for the customers.
It can be concluded that the impact is positive for services that are overloaded because they can now transport the otherwise rejected passengers at less busy times, while ride-sharing is often still taking place. For lower loaded services, the opposite is noted. There is now less ride-sharing during peak hours because possible combinations are no longer found because one of the two players is now traveling at a different time, were also less other passengers are traveling. To conclude on this experiment, only when the service faces low success-rates rates it could be beneficial for the service to flatten its demand distribution by implementing a variable pricing scheme.

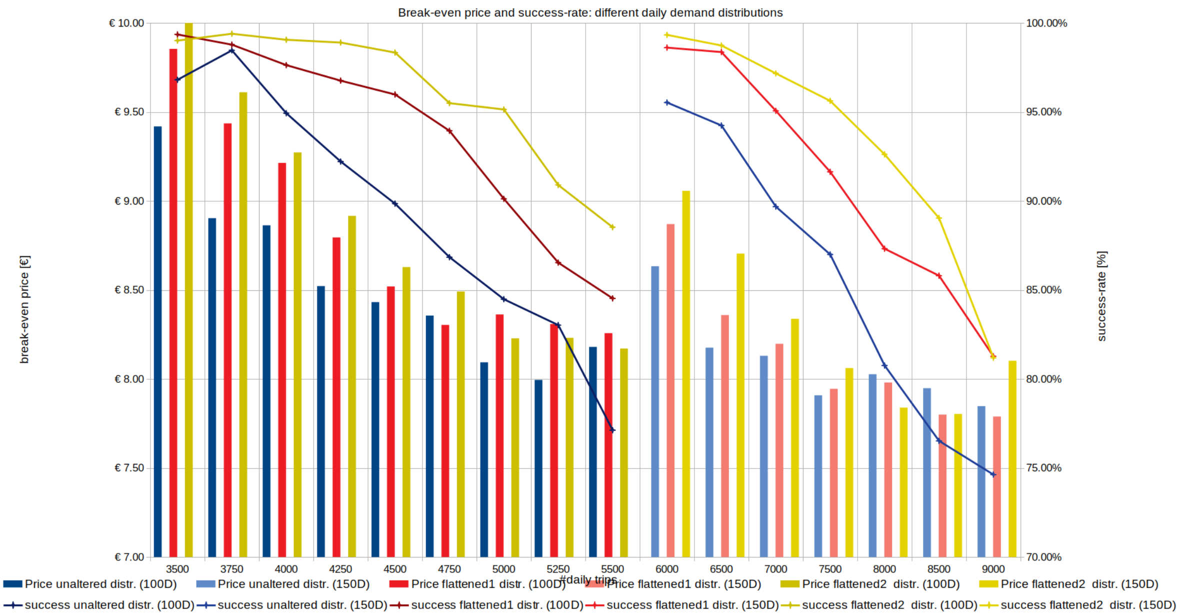


Figure 5.2.12: Break-even price and success-rate for the different daily trip distributions

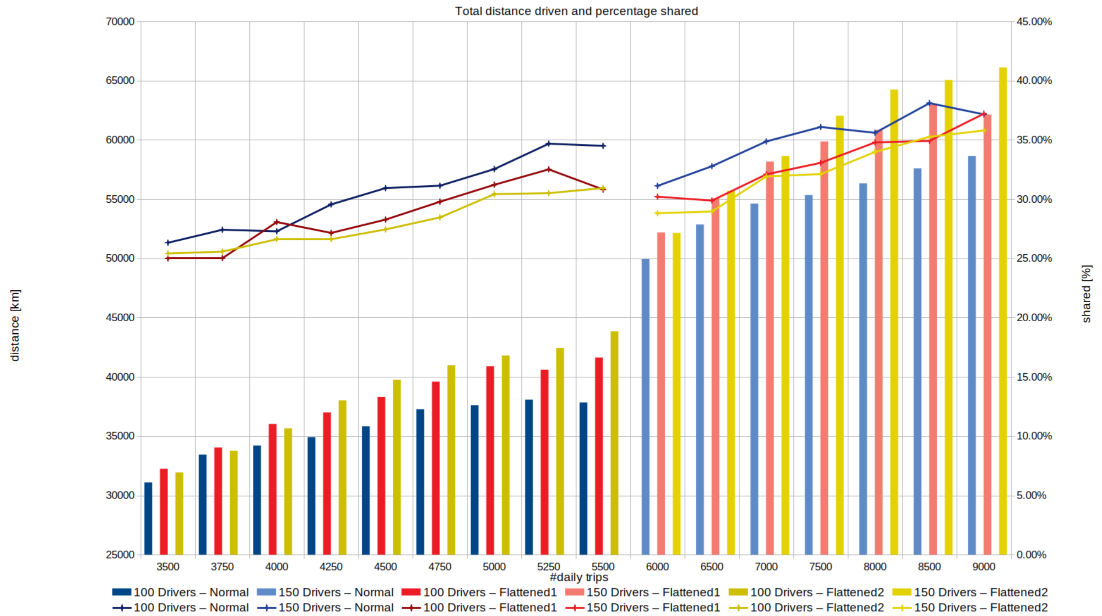


Figure 5.2.13: Total distance and shared distance for the different daily trip distributions

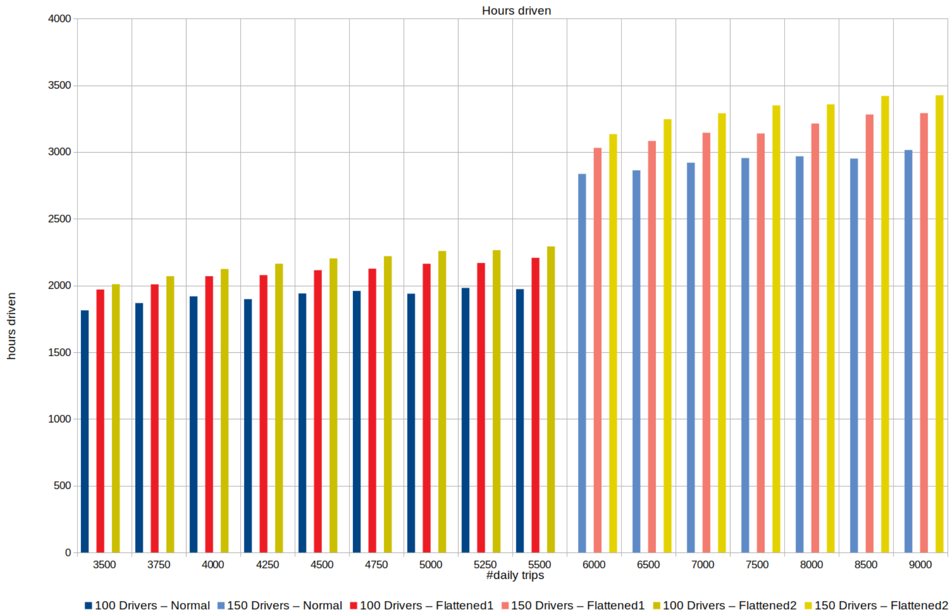


Figure 5.2.14: Hours driven for the different daily trip distributions

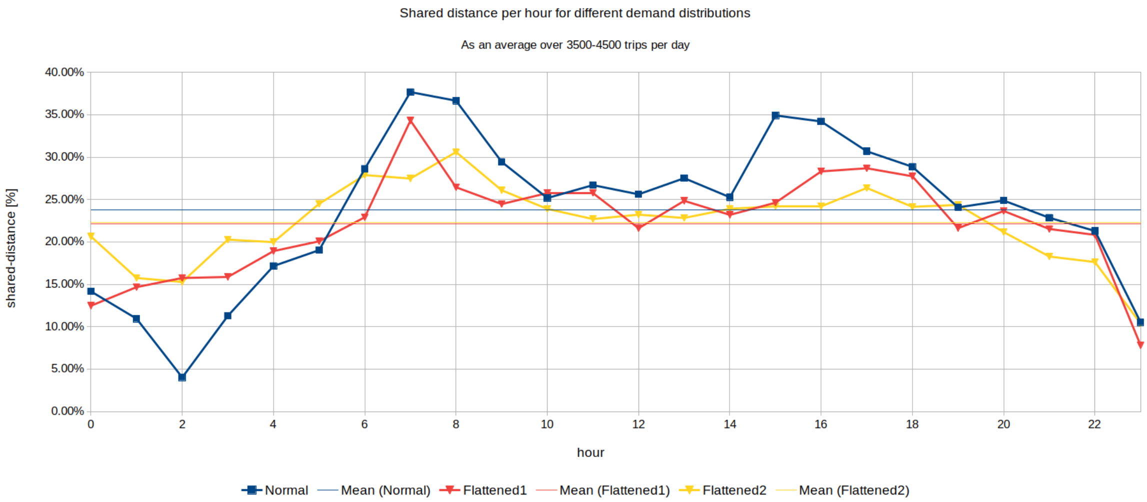


Figure 5.2.15: Shared-distance [%] over each hour during the day as an average of 3500-4500 daily trips

5.2.5 Is it economically interesting to offer a night service?

In previous settings the DRT-provider operated 24hours a day. This provides its users with a great experience but it seems economically less beneficial for the service. In previous experiments, break-even price was always calculated as the daily total cost divided by the daily total number of passengers. This was thus the fixed price each passenger would have to pay, if the service wanted to operate break even. It is also possible to further investigate on break-even prices by keeping track of the amount of drivers and passengers present each hour. This way a break-even price per hour can be calculated. In this way, the DRT-service has a more detailed overview on how his prices to offer the service vary during the day. As an example figure 5.2.16 shows how this price differs during the day for a service operating with 100 vehicles and having a daily demand of 4000 trips. If all passengers payed the same price, €8.86 would be needed to cover all expenses. Looking at figure 5.2.16 it seems that passengers traveling during the day time would be able to much less, but they are "punished" to pay for passengers traveling between 23 and 5 hour in the morning. This section will now analyse the impact of operating a DRT-service only between 5-24h. Between 0-5h it is estimated (analyzing the daily demand distribution used) that only 4.7% of trips happen. It is therefore important to compare services that operate only during the daytime with services having 4.7% more trips if they operate also at night. To generate demand, the same daily distribution is used with demand between 0 and 5h set to zero.

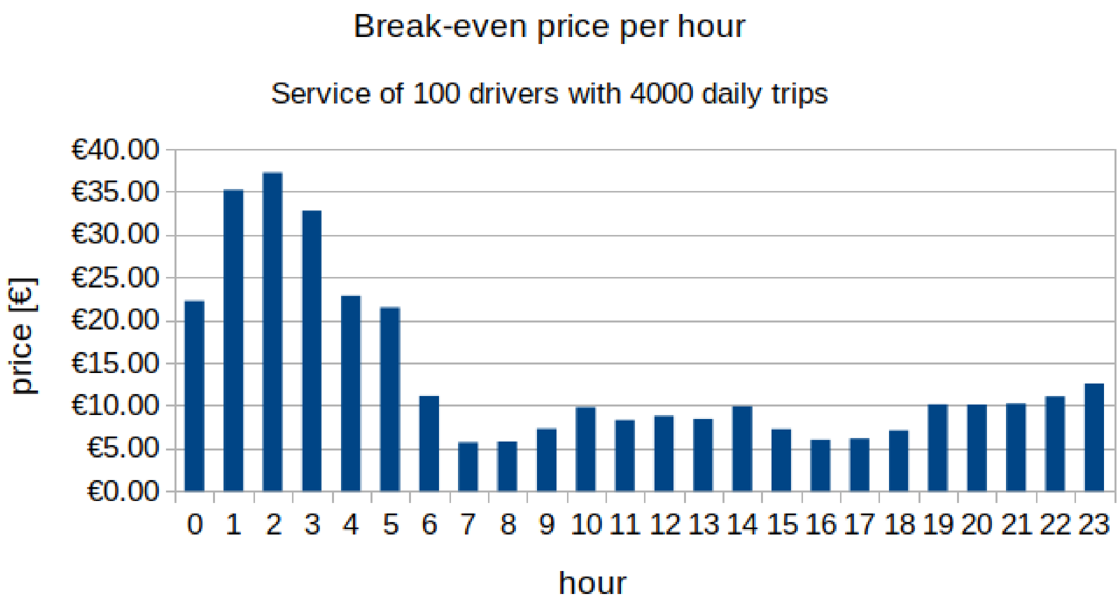


Figure 5.2.16: Break-even price per hour for a service operating with 100 vehicles and experiencing 4000 daily trips

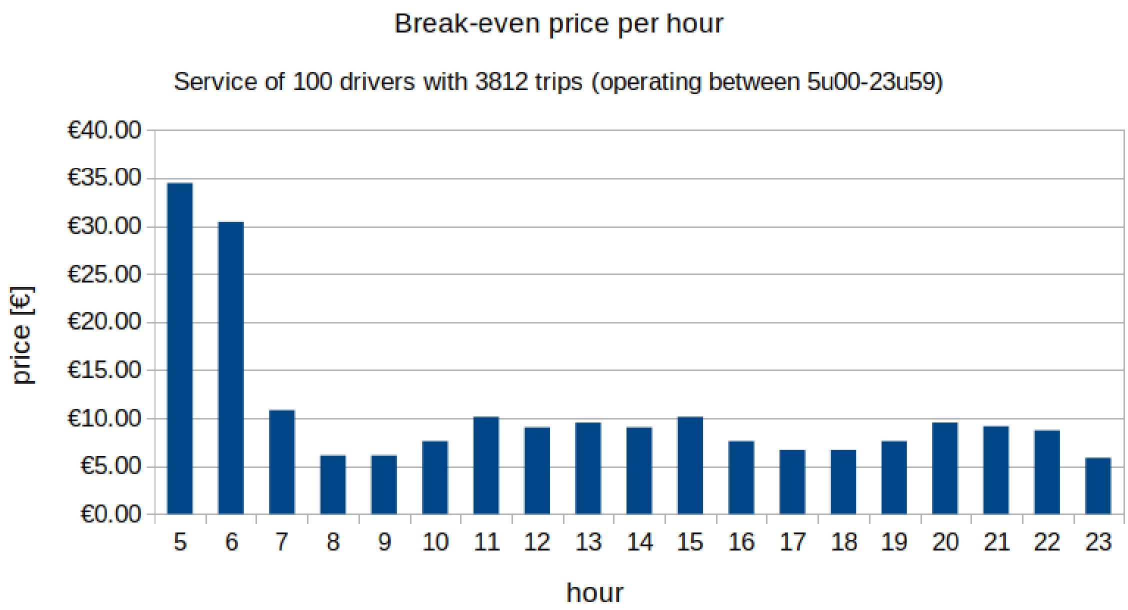


Figure 5.2.17: Break-even price per hour for a service operating with 100 vehicles and experiencing 3812 daytime trips

First, let us consider this service operating with 100 vehicles, having a daily demand of 4000 trips and 3812 daily trips if only active during the daytime. If the service would only operate during the daytime the hourly worth of the service without driver wages is increased (from €244 to €293), as the daytime service still has the same expenses as the 24h service, only now divided over less active hours. But, as expected the service now has less driver wages to pay (1740h vs 1941h) over this shorter period. Overall this results in a service that is a little less expensive for the customers (€8.66 vs €8.86). An overview on the hourly break-even price for a daytime-service is also given in figure 5.2.17.

Comparing the results found for a multiple of simulations (fig 5.2.18) it can be concluded that it is (almost) always cheaper for the service to only provide a daytime service. But, overall the difference in pricing is small and averaging the price-reduction as found for all simulations this comes down to a 2.46% reduction in price. For these simulated services (operating at around €9) the average price reduction is around 20 euro cents. Given this small price-reduction, operating only at day would not drastically change the economic viability of a DRT-service and therefore the rest of the paper will make use of 24h-services.

Notice also the similarities for success-rate comparing the daytime-service to its 24h-service "brother". This shows that the 4.7% reduction on the amount of passengers was a correct assumption if comparable services are required.

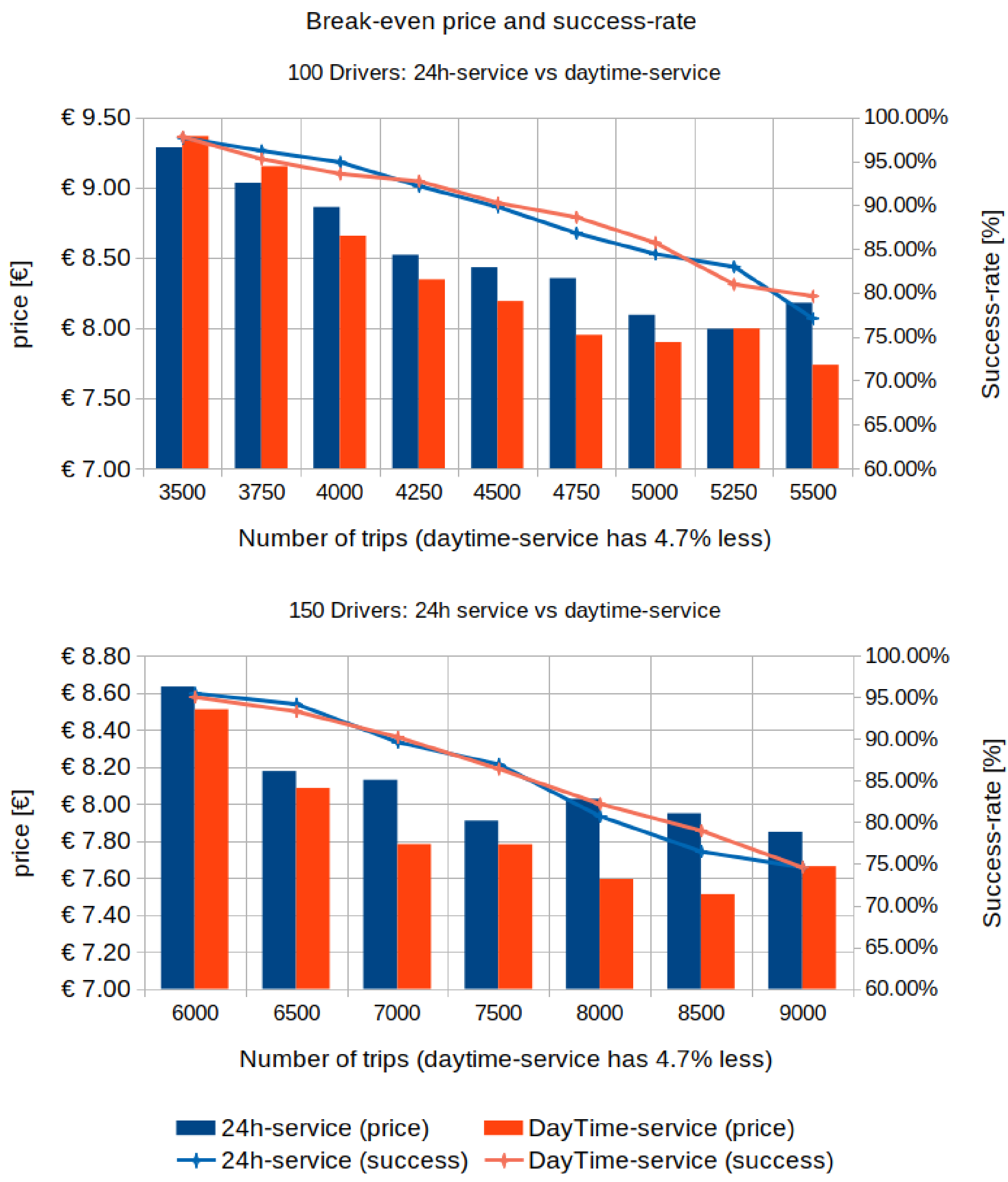


Figure 5.2.18: Break-even price and success-rate difference between 24h-service and its "daytime"-brother

5.2.6 Impact of an increased vehicle capacity and vehicle type

All previous simulations were done with taxi-services operating with sedan-type vehicles, offering a capacity limited to four passengers. It seemed also interesting to simulate situations in which the capacity was increased by driving around with minibuses, increasing the capacity up to eight passenger. As stated in chapter 3 the cost model already includes the possibility to adjust the vehicle type by simply changing the vehicle type inside the input values. This automatically changes all cost factors to those as found for minibuses. Inside the simulation model, the user has to adjust the capacity of the taxi vehicles up to eight. Now the model is ready to simulate this higher capacity. This will be done for services with 50, 100 and 200 drivers having a daily amount of trips ranging from 3500 to 9500.

First let us consider services which operate at the same scale regarding vehicle fleet size and daily trips. It is expected that increasing the capacity would increase success-rates because a capacity limit is increased , but it isn't sure if this would benefit pricing as the vehicles also introduce different costs. Figure 5.2.19 shows the price and success-rates found for the two different DRT-operators. The expected gain in success-rate is not found. This comes at a bummer but can somewhat be explained by a combination of two reasoning's. First: all current generated trips/requests are lone travelers, while in real-life it would often occur that friends, families and colleagues travel together. It could be interesting to extend the simulation model to include an extra attribute for each trip request representing the amount of passengers traveling together. This way it would probably occur more often that a higher capacity vehicle is needed. Secondly, the maximum allowance, as discussed in 5.2.2 (set to be 100%) limits the probability to be able to combine lots of trips. By extending the simulation model it is also possible to see the share of how many passengers are traveling together when ride-sharing is taking place. Averaging over all instances simulated with 150 drivers following result is found: in 85% of cases ride-sharing is taking place with two shared rides, in 14% of the cases ride-sharing takes place with 3 shared rides. This shows only 2% of ride-shared trips consists of 4 or more combined trips. These results are consistent with those found in real-life implementations [58] (Wenxiang Li, Ziyuan Pu, Ye Li and Xuegang) in which it is concluded that over 90% of shared-rides consist of only two shared rides. Overall it can be concluded that while extra capacity would help services that see their customers traveling in group it does not seem to benefit the amount of ride-sharing in the scale of services as simulated in this section.

If the increased capacity has no real benefits for the service, the answer to why the price of the service operating with minibuses is on average lower is really a result of the lower price for gas compared to diesel even if the minibuses have a lower efficiency (increased l/100km). This difference is somewhat limited due to a higher purchase price of minibuses. On average a service operating with minibuses only sees his price drop with 0.27%, with the given price range of around €8-€9 this comes down to price change of €0.02 which would probably never persuade more passengers. If sedans and minibuses would have exactly the same fuel efficiency and fuel price the only reasonable explanation for higher price-differences would by that the daily trip requests was more generous for one of the two services. If an average over all simulations is done (minimizing impact of generous trip generation) and if the vehicle type was changed from sedan to minibus inside the cost-model (while still being simulated as if it were sedan taxis), the price difference of 0.27% sacks to a difference of only 0.21%. This shows that for realistic demand inputs the service would not really achieve greater economic and environmental results.

The previous reasoning is also the answer to why a service operating with minibuses isn't really able decrease his fleet-size while still successfully handling the same amount of daily requests. This is shown in figure 5.2.20.

To conclude on this section: it stays an interesting pricing question weather to opt for minibuses or sedans, but this is not because of the increased vehicle capacity. In contrast, it could maybe be interesting to reduce the sedan-type from a comfortable four-seater to a comfortable 3/2-seater (eg from BMW model 5 to model 3) if most of the handled trips are expected to be lone traveling passengers. Therefore this section shows that the minimization problem (to reduce costs) comparing vehicle types is more influenced by the vehicles purchase price, expected lifetime, fuel-efficiency and fuel-type rather then the vehicles capacity. This should thus be the focus for DRT-services.

Figure 5.2.19: Break-even price and success-rate compared between sedan and minibus with same input size

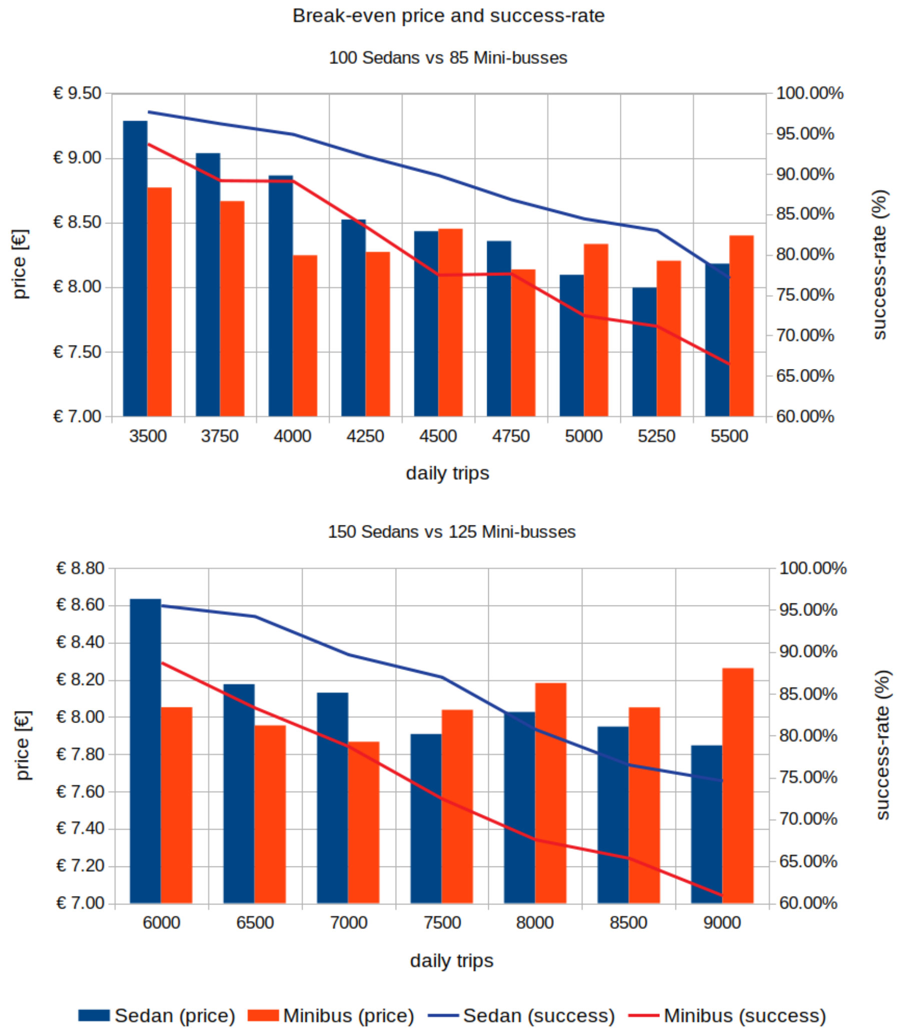


Figure 5.2.20: Break-even price and success-rate compared between sedan and minibus with same amount of trips but different fleet-size

5.3 Scalability effect on pricing for DRT-services

In this section the impact of scalability will be validated in a fixed service area. This is done by calculating break-even prices for different inputs varying on both demand and vehicle fleet size. Of course, each of the simulated services operates within the same general assumptions and their values of all cost factors is kept constant. From previous experiments it was chosen to use a centering policy (to the Korenmarkt), a maximum allowance of 100%, a reservation time window of 60-30minutes and provide a 24h/day service with minibuses (capacity 8).

In this experiment it was chosen to fix the total daily number of passengers per driver. This way different service sizes could be compared based on a fixed ratio. Four scenarios were simulated: 30,35,40 and 45 passengers/driver. From figure 5.3.1 two conclusions can be drawn. First, by increasing the amount of passengers per driver, prices drop.. This was expected as the vehicle is now serving more passengers per day and the operational expenses are spread over more passengers. Next, with increasing number of drivers (and passengers) the costs also initially seem to drop substantially, but this drop is stabilized and it seems that the prices converge to a minimum.

The most gains can be found in situations in which the success-rates of the service is relatively low. There is lots of demand and the probability to share rides is relative high. Ride-sharing really is the main driver to reduce break-even prices. The most cost-efficient DRT-service would be a service operating with far more requests for trips than available taxis can provide. If the computational power was not limited it would be interesting to see what the amount of passengers per vehicle would have to be to reach a minimum price. This would in real-life be the situation in which every taxi is almost always full. Figure 5.3.2 shows that the increase in the pas/veh ratio with 5 new passengers is almost always resulting in a stable increase in the amount of shared distance. On average the increase is 6.54% per 5 daily passengers added per taxi. This estimation can help to estimate how many passengers should be present per taxi in which the service would reach a 100% shared-distance. For 55 drivers the initial setting of 30 passengers per vehicle resulted in a shared-distance of 21%. To increase to 100% it is estimated a ratio of $(100 - 21)/6.54 + 30 = 90$ would result somewhere in reach of 100% shared distance. Services operating with more vehicles seem to be able to achieve this desired percentage more easily, eg 450 vehicles are estimated to achieve 100% shared distance with an 80 pas/veh ratio. This would indicate that for large scale services, the desired ratio (pas/veh) to reach a 100% shared distance could possibly be reached with sufficient success-rates. For the setting in which 500 vehicles are serving 25000 passengers following distribution is found on the shared rides that occur: 80% of shared rides see two passengers on board, 17,5% happen with three boarded passengers, 2% have four boarded passengers and the amount of rides with more then 5 passengers is only occur in less then 0.7% of cases. Indicating again that minibuses are not considered a necessity for DRT-services.

Figure 5.3.2 shows the success-rates for the same fixed ratios. Notice that for a low number of passengers per taxi the services success-rate is stable at around 100%, for larger rates it seems that by increasing the service size, success-rates initially increase after which they also converge to a maximum. Sadly, this maximum success-rate is not the desired 100% and the maximum seems lower for larger ratios (passengers/driver). This would mean that larger services, with more vehicles, are not becoming more and more efficient in combining the fixed amount of passengers per vehicle. As an example, it seems that with a fixed ratio of 45 passengers per taxi, the real amount of passengers handled over the day will never exceed 42.5, regardless of the number of vehicles available.

Overall the above results seem to indicate previous results indicate that the scalability of DRT-services should not be overestimated. This result is unfortunately not what was had hoped for and it is hard to validate the scalability effect on DRT-services based on this experiment, and with the used simulation software. However, it can be stated that the scale on which was tested here is still not very significant. This is due to a relatively time-inefficient algorithm combined with extremely high demand. There are still lot of opportunities here that could help reduce calculation time. However, these will not be elaborated here because the scale of this experiment would lead us too far from the economic feasibility analysis for which this paper was intended. A number of ideas are presented here:

- Instead of beginning to focus on the taxis driving around, it could be an idea to first search compatible other requests already boarded or queued by the service. This could be implemented using a list of all queued and boarded passengers with their from and to-node. Next convert these from and to-nodes to their resp. longitude and latitude. If these values are inside a specific area around the long. and lat. values of the new request, it could be interesting to first consider the vehicle that is already assigned to this new passenger. This could probably help and reduce calculation times as less calculations have to be considered, while also increasing the probability passengers are combined.

- Only release a new taxi to the available taxi list if their is no taxi found in the current list of available taxis. If a taxi has dropped off his last passenger: make him drive back to a centralized location but remove him from the available taxi list. This way the amount of drivers present inside the simulation software could be reduced when they are not needed. This would reduce iteration time during the initial phase of listing taxis based on distance.

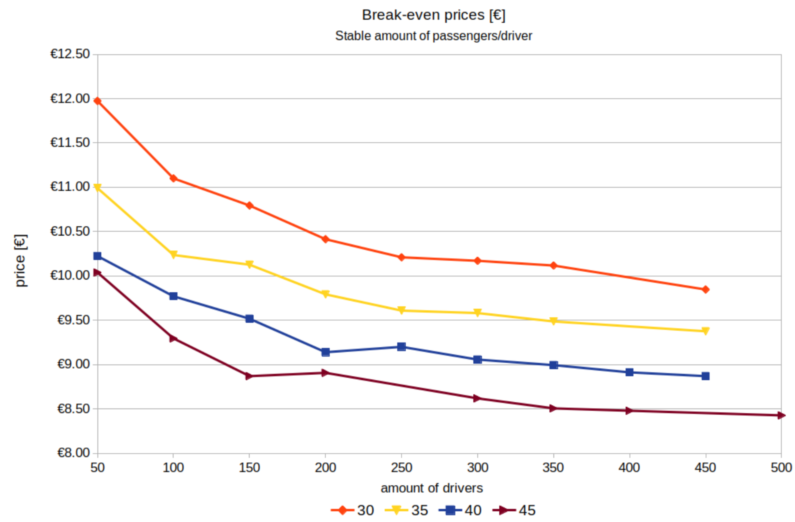


Figure 5.3.1: Break-even price for a fixed amount of passengers per vehicle

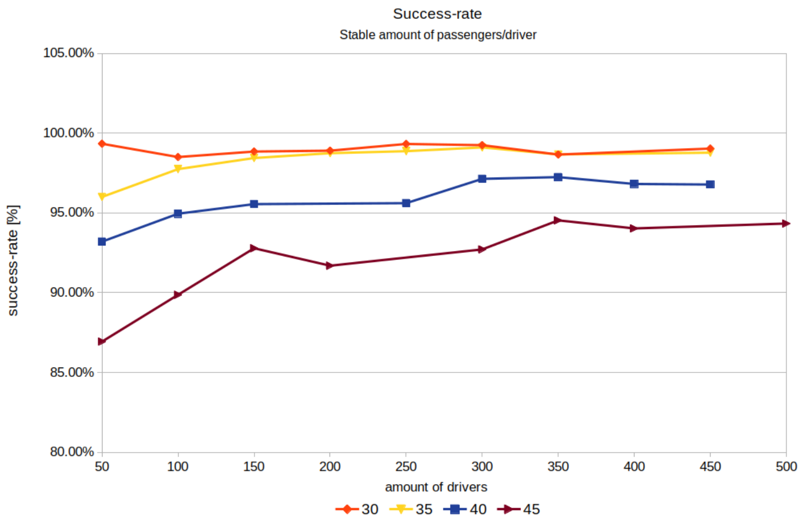


Figure 5.3.2: success-rates for a fixed amount of passengers per vehicle

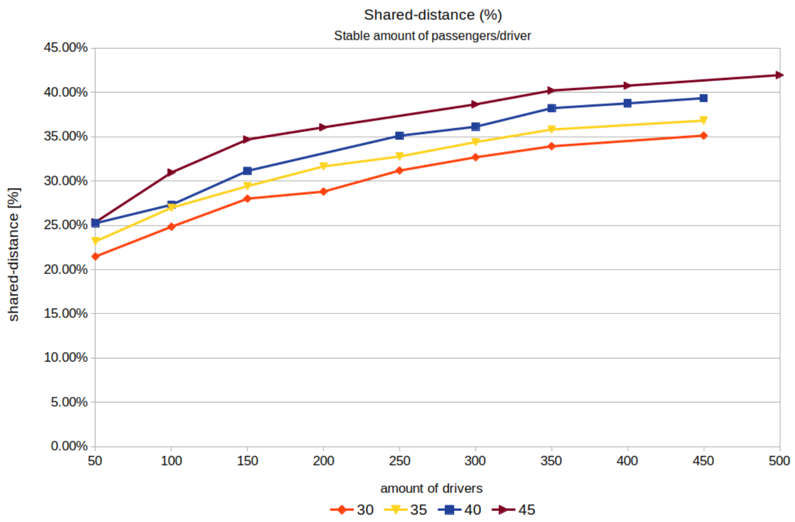


Figure 5.3.3: shared distance for a fixed amount of passengers per vehicle

Chapter 6

Economic Feasibility Analysis of DRT-services in Ghent

6.1 Acceptable trip-demand levels in Ghent

While predicting the actual trip demand in Ghent is impossible, three scenarios are taken into consideration to be discussed when validating the feasibility of a DRT service in Ghent: an optimistic, a pessimistic and a realistic scenario.

For the pessimistic scenario, lets assume the estimation as done by Kutsuplus. They estimated the total amount of trips to be around 2 million a year in 2018, averaging to about 5000 trips a day. Comparing the population level of both Ghent (259000) and Helsinki (620000) the demand level in Ghent is considered to be about 44% of Kutsuplus demand levels. Therefore the pessimistic scenario considers demand levels of around 2000 trips a day.

For a realistic and optimistic estimation, lets start with the an overview on mobility, made by the city of Ghent in 2019: "Mobiliteit in cijfers" [59]. Around 33% of the population say they use a bicycle as their primary means of transportation, 10% uses public transportation in form of bus and tram and around 40% uses a car (passenger/driver), 1% a motorcycle. It is estimated that each person in Ghent makes 2.3 trips a day and given the fact that there are 229925 people of age 10 and up in Ghent, this combines to around 525047 trips a day ([60]). Taking into account the different shares for the different transportation means, and the and the total amount of daily trips, it is estimated that in Ghent there are every day around 210018 car trips, 52504 trips by bus or tram and 173265 bicycle trips.

In the literature study it was already shown that around 48% of car owners would consider giving up use of their personal car if autonomous mobility solutions were available. This would result in a very optimistic total of around 100000 trips a day. To be on the safer side it is assumed that 5% of car trips would be switched to DRP in our realistic scenario, and 10% in our optimistic scenario. This gives 5000 trip/per day for our realistic scenario, and 10000 trips in our optimistic scenario. (assuming that we do not take away passengers from traditional bus/tram transport). Later, this section will discuss break-even prices under these scenarios, and compare them to the price of car ownership. If the DRT-service would be a cost effective alternative at these levels of demand, it seems that the transition to the estimated 100000 trips a day could be a realistic expectation.

If the service would be publicly owned (and trips subsidized), the DRT-service could also become an extension and replacement for current fixed bus routes, meaning some share of the 52504 trips would become DRPT-trips. To estimate this share two ideas are considered. First, DRPT would probably only become a more affordable alternative for trips that start or finish in rural areas. Secondly, for these rural trips, the DRT would probably only be important during times at which convenient busses are considered "overkill" and drive around with a low amount of passengers on board. Around $80km^2$ or about $\pm 50\%$ of the simulated area is considered city-center, an area enclosed by the outer-ring road. If number of bus tram trips would be 75% urban and 25% rural, around 6500 trips can be considered rural. Assuming that it only makes sense to replace traditional busses by a DRPT service between 21:00 and 06:00. Considering the demand distribution as used by the simulator 4.3.6 it can be concluded that around 20% of trips take place during these hours. This would represent 1300 trips. This is the number that will be used in the realistic scenario. In the optimistic approach this will be doubled to 2600 daily trips. In contrast, it is harder to predict if passengers traveling by bus and tram would change their transportation mean to a more comfortable DRT-service given it was provided for by a private company (because of the expected higher price). Therefore the 1300 daily trips are now considered optimistic and half of this (650 trips) to be a more realistic amount.

If publicly owned, the DRPT-service would probably not target to take away market share from bicycle transport, as this would only result in a negative environmental impact. Sadly, lots of DRT-services are currently mostly gaining extra customers by offering cyclists a more affordable alternative which also offers higher levels of comfort ([37]). This is increasing congestion levels and pollution inside city-centers. Luckily, if compared to its North-American counterparts, Ghent is rather cycling friendly and it seems hard to assume that the share of cyclists changing to DRT would become substantial. Therefore a realistic estimation for DRPT-services would be that only 1% of the 173265 bicycle trips would become DRPT trips, resulting in 1700 trips. This will be the number used in the realistic scenario. In the optimistic

scenario, the number is set to zero, given that avoiding cannibalization of bicycle transport is a positive outcome for the city.
If not publicly owned, the service would of course love to see its user-base grow by persuading cyclists to use their service. While they would probable like to be perceived as environmental friendly by taking out private cars from city centers, in reality it could also be walking and cycling kilometers that are now replaced by car travel. To estimate the share of bicycle transport they would take, focus will be on how much cyclists are wiling to pay for this more luxurious transportation service. Overall this effect will be considered minimal as Ghent is cycling friendly and lots of the cyclists here are students, a customer segment that typically has less money to spend and is often less convinced by an increased comfort. Estimations on the amount of trips are set to be between 1% (realistic) and 2% (optimistic) of cycling trips (1700 and 3500 trips)

Combining all of these estimations and differences between publicly and privately owned DRT-services the following (rounded) daily trip levels are considered:

	Pessimistic	Realistic	Optimistic
privately-owned DRT-service	2000	7500	15000
DRPT-service	2000	8000	12500

Table 6.1.1: estimations on daily DRT-trips

A side not on the legislation on taxi services in Ghent: In Ghent the current legislation (2019) states that only 220 taxis are allowed to operate in the city, of which 20 have to be electric. Currently (2019) there are 160 taxis and 14 e-taxis driving around. If DRT-service would be considered as a regular taxi service, this would mean only 46 vehicles (of which 6 fully electric) can be introduced. It is assumed that this regulation will not be applicable for DRT, or if applicable, that the DRT service will cooperate with the existing taxi services to switch them also to DRT services.

6.2 Introduction on different type of services

Different options exists for a DRT-provider to come into service. One such option already discussed in section 5.2 is a completely newly introduced DRT-service with its own vehicles and drivers. This section will shortly introduce different type of operators and discuss how pricing would by affected by each of the options.

6.2.1 Newly introduced taxi ride-sharing service

This type of operator was already discussed in sections 3.1 and 3.2. In this case the PV is calculated for a stable situation, meaning for a constant amount of passengers during a period of ten years. The PV calculation will include the acquisition costs (for example for the necessary cars and IT equipment), yet it will not take into consideration the startup capital required to survive the early (growth) years. It comes to no surprise that this provider would face the greatest risk when starting up his business. This risk was also an incentive to consider other options available that could help reducing the early risks.

6.2.2 Coalition between traditional existing taxi services and a DRT-software provider

Another option for the DRT-provider could be to co-operate with an existing taxi operator to introduce a ride-sharing scheme to its customers. By doing so most of the acquisition costs could be reduced because the operational taxi service already has a vehicle fleet and drivers at his disposal. While the active user base of the taxi service would probably still be insufficient to operate cost-efficiently (in Ghent 70% of people never use a taxi and 18% only once or twice a year) heavy promotion and accepting early losses could help scaling the service.

In this scenario, 2 different business cases are build: one for the provider of the taxi trips, and one for the DRT-software provider. To determine the price costumers would have to pay, two slightly different models are build for the taxi operator. One in which the taxi company fully pays for the development of the DRT-software and one in which he shares some of his profits with the software developer. For both models the excising cost model (3.2) is slightly adjusted. The amount of vehicles and parking space that has to be bought is lowered by the amount already present and all administrative start up costs are eliminated. For the first business model the development cost (€ 150000) remains. For the second business model the development cost is completely eliminated and the price customers pay is increased by a margin to pay the DRT-software provider. Of course other schemes of cooperation would exist, yet these two models will already provide some insight in the possibility of such a partnership.

6.2.3 Operating with a PHV business scheme

It could also be a possibility for the DRT-provider to offer ride-sharing to customers based on a PHV business scheme. In this case, it will not be necessary to invest in a vehicle fleet (excluding marketing to find potential drivers). Next, PHV-drivers earn less compared to licensed taxi drivers at around € 10 per hour ([61], [62]) but this low-wage value is highly disputed and it can be expected that these wages will increase in the near future. Therefore a wage of around €15/hour will be considered for this calculation. It is difficult to estimate licensing and insurance costs as in Belgium the current ruling is not yet fully defined and changes from state to state ([62]). Often drivers have to pay for their own licensing and vehicle insurance. This can give the PHV-provider higher profit margins. The impact of eliminating licensing and insurance will be discussed in the next section.

6.2.4 DRPT-service

Costs for DRPT-services will be mostly be set equal to those found for privately owned DRT-services. The only change would be licensing costs, start-up costs (administrative start-up costs), taxes and the company contribution, values all set to zero. The amount of daily trips will also slightly change compared to its privately owned counterpart (table 6.1.1). Interesting to consider for DRPT-services are the so called positive externalities: KPI other than pricing that could create benefits for the service area. Such positivities can include the amount of shared-kilometers (less-pollution), reduction in congestion (less vehicles), less accidents.... By offering the decision makers these positivities they could be more inclined to take positive actions to help and subsidize the service. While these positivities are not converted to an equivalent money value in this project, they are still interesting enough to consider. Notice that the privately owned service could also use such positivities to gain more customers.

6.3 Pricing levels for the different type of services

This section will introduce and compare pricings found for the different types of providers. This will allow to make a validation of the feasibility. Notice that pricing levels are calculated for services operating for a 10 years life-span, in which all vehicles will be replaced after 5 years of use.

6.3.1 Simulation results

While costs could be different for the discussed DRT-providers, they all use the same input variables in the simulation testbed (except for the number of trips between public and privately owned).

The estimated daily amount of trips as given in table 6.1.1 are each simulated for 5 days. By averaging over this period it is possible to average out to generous demand. This effect is considered to be small but it will still make the results more stable. To determine the minimal amount of vehicles needed to provide a sufficient service, the success-rate (%) is set to be minimal 95% and an iteration is done to find an acceptable fleet-size. All results can be found in tables 6.3.1 - 6.3.5. (S.rate: success-rate, Tot.dist: total distance, Srd.Dist:

shared distance, Dist.p.pas: distance per passenger, Avg.prod: average vehicle productivity (passengers per hour), Avg.occ: average occupancy)

55 drivers	**S.Rate (%)**	**Tot.Dist (km)**	**Srd.Dist (%)**	**Dist.p.Pas (km)**	**Avg. prod**	**Avg. Occ**	**Hours Driven**
Day 1	95.55	18353	21.80	9.60	2.18	1.14	1035
Day 2	94.65	18010	23.69	9.52	2.25	1.15	1039
Day 3	95.80	18391	22.61	9.60	2.15	1.14	1030
Day 4	96.35	18515	22.65	9.60	2.23	1.14	1053
Day 5	96.65	18831	23.19	9.73	2.18	1.15	1042
CI(97.5%)	95.80 ±0.78	18420 ±297	22.79 ±0.01	9.61 ±0.08	2.12 ±0.04	1.15 ±0.008	1039 ±8.7

Table 6.3.1: results for 55 drivers and 2000 passengers

185 drivers	**S.Rate (%)**	**Tot.Dist (km)**	**Srd.Dist (%)**	**Dist.p.Pas (km)**	**Avg. prod**	**Avg. Occ**	**Hours Driven**
Day 1	96.74	65200	34.24	8.99	2.59	1.23	3355
Day 2	96.47	65474	34.02	9.05	2.66	1.24	3315
Day 3	95.98	64953	32.89	9.02	2.64	1.23	3344
Day 4	95.35	65348	33.49	9.14	2.61	1.24	3346
Day 5	96.84	65149	33.42	8.97	2.62	1.23	3431
CI(97.5%)	96.28 ±0.62	65225 ±199	33.61 ±0.53	9.03 ±0.07	2.62 ±0.03	1.23 ±0.01	3358 ±43.5

Table 6.3.2: results for 185 drivers and 7500 passengers

195 drivers	S.Rate (%)	Tot.Dist (km)	Srd.Dist (%)	Dist.p.Pas (km)	Avg. prod	Avg. Occ	Hours Driven
Day 1	95.30	64779	34.02	8.50	2.59	1.25	3652
Day 2	96.26	65134	34.05	8.46	2.66	1.25	3618
Day 3	95.51	64787	33.28	8.48	2.62	1.23	3651
Day 4	95.63	64810	32.86	8.47	2.61	1.23	3656
Day 5	96.84	65149	33.42	8.41	2.62	1.23	3672
CI(97.5%)	95.91 ±0.63	64932 ±168	33.53 ±0.45	8.46 ±0.03	2.62 ±0.02	1.24 ±0.008	3650 ±17

Table 6.3.3: results for 195 drivers and 8000 passengers

300 drivers	S.Rate (%)	Tot.Dist (km)	Srd.Dist (%)	Dist.p.Pas (km)	Avg. prod	Avg. Occ	Hours Driven
Day 1	96.00	98212	37.62	8.19	2.70	1.27	5553
Day 2	95.72	99546	38.25	8.32	2.75	1.27	5555
Day 3	95.63	98972	37.15	8.28	2.76	1.27	5580
Day 4	96.14	99246	37.93	8.26	2.71	1.27	5550
Day 5	95.73	99048	36.84	8.28	2.71	1.26	5556
CI(97.5%)	95.84 ±0.22	99005 ±497	37.56 ±0.57	8.26 ±0.05	2.725 ±0.03	1.26 ±0.005	5558 ±12

Table 6.3.4: results for 300 drivers and 12500 passengers

375 drivers	S.Rate (%)	Tot.Dist (km)	Srd.Dist (%)	Dist.p.Pas (km)	Avg. prod	Avg. Occ	Hours Driven
Day 1	97.16	120299	37.73	8.26	2.72	1.27	6872
Day 2	97.11	119240	38.20	8.19	2.75	1.27	6803
Day 3	96.60	120479	38.45	8.31	2.77	1.27	6821
Day 4	97.31	121542	37.18	8.33	2.75	1.27	6904
Day 5	96.96	121056	38.30	8.32	2.78	1.27	6881
CI(97.5%)	97.0. ±0.27	120523 ±497	37.97 ±0.52	8.28 ±0.06	2.75 ±0.02	1.27 ±0.004	6856 ±43

Table 6.3.5: results for 375 drivers and 15000 passengers

6.3.2 Pricing levels found for newly introduced taxi ride-sharing service

In table 6.3.6 we see the different price levels that a completely new introduced DRT service should demand from its passenger if there were no profit margin. As can be see in the table, prices drop significantly between the first 2 lines, but not anymore for the other lines. This can be explained by looking at the number of passengers per taxi driver. In the first line, there are 36,4 passengers per taxi driver, while in the other scenarios the passengers/taxi driver stay stable at around 41. It can also be said that the difference between the scenarios is quite minimal and that the service is not made much more viable by taking advantage of the optimistic demand levels. The most acceptable scenario, both for demand under the condition of a private service and a DRPT service, provides a price of around €9.10. For a privatized service (and 7500 trips per day) figure 6.3.1 shows the present value of all costs (sum of the discounted values of the different costs for the next 10 years) and how they are distributed. In the search for cost reduction it can already be concluded that the wages for the taxi drivers have the greatest impact. This also explains the success of the PHV models, were salaries for taxi drivers are lower. Figure 6.3.2 shows a pie chart for the same operator in which driver wages are now excluded. From this figure it can now be concluded that, after wages for divers, the purchase of the vehicles and their use (maintenance and fuel) are dominant factors. To see what the impact of some variables would be, a sensitivity analysis is performed. Figures 6.3.3 and 6.3.4 show the most important factors in order of influence: driver wages, purchase price of vehicles, fuel price and or fuel efficiency, maintenance costs and the insurance of the vehicles. Notice that other influences (purchase of parking space, lifespan of the vehicles and insurance of all workers) are also considered, yet their impact on pricing is minimal (if occurring separately).

Scenario	Avg-price (€)	CI (97.5%)
2000	10.66	0.08
7500	9.01	0.09
8000	9.14	0.06
12500	8.89	0.04
15000	9	0.05

Table 6.3.6: pricing as found for a new DRT-service.

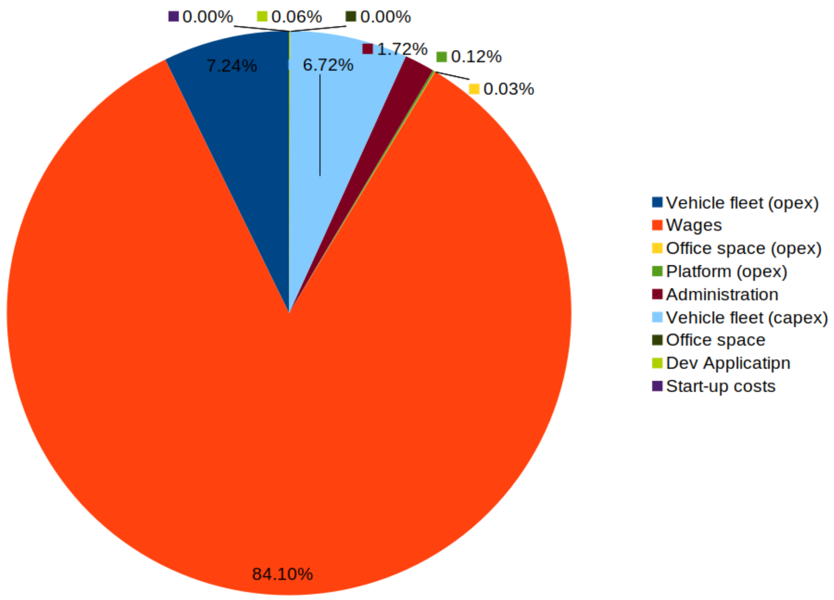


Figure 6.3.1: Pie chart on the PV for a DRT-service (185drivers, 7500trips)

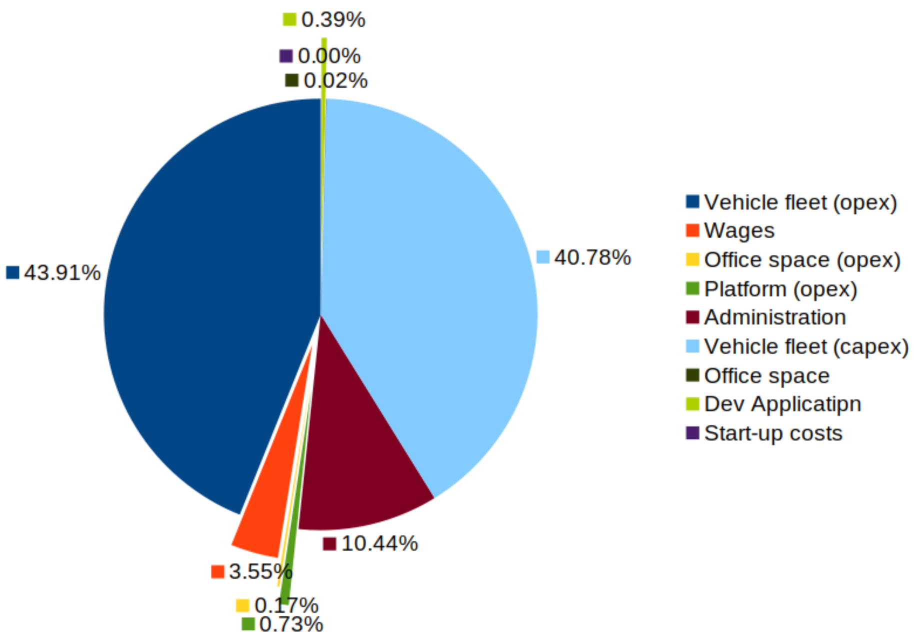


Figure 6.3.2: Pie chart on the PV for a DRT-service (185drivers, 7500trips) without driver wages

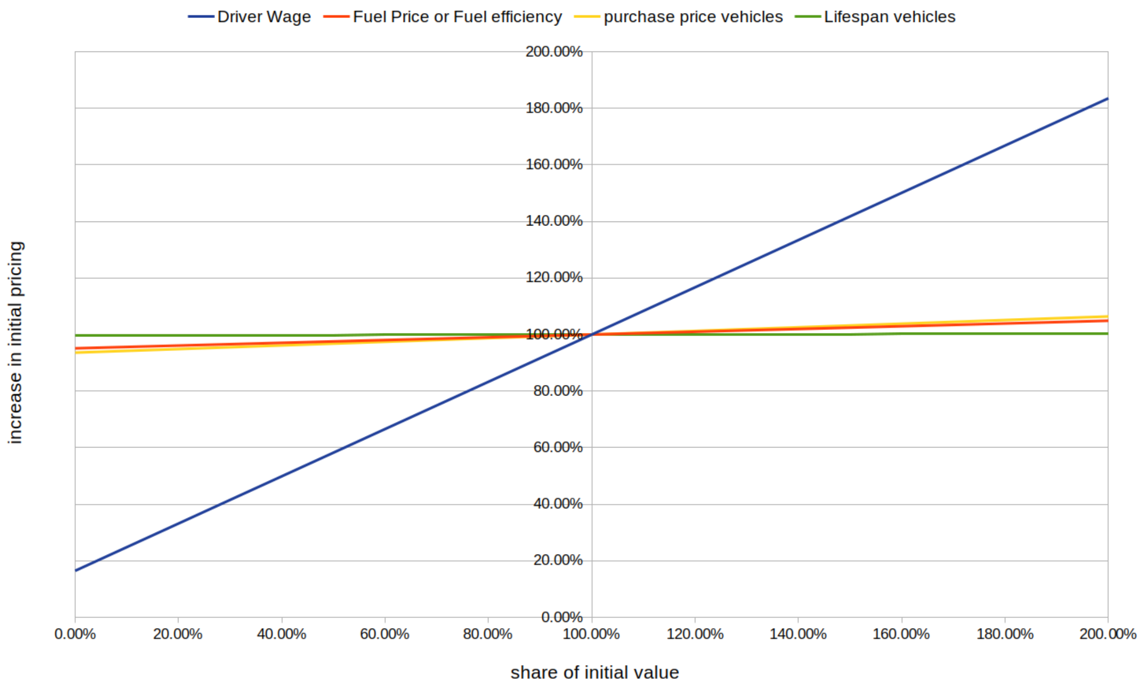


Figure 6.3.3: Sensitivity analysis on the pricing for a DRT-service (185drivers, 7500trips) including driver wages

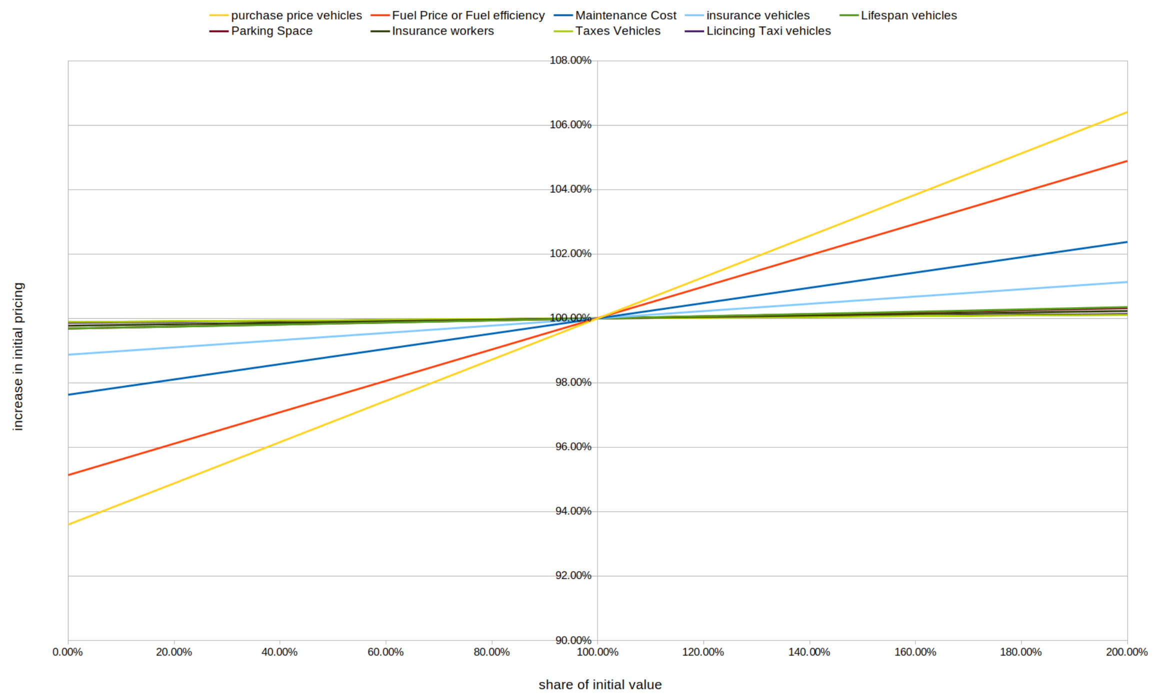


Figure 6.3.4: Sensitivity analysis on the pricing for a DRT-service (185drivers, 7500trips) without driver wages

6.3.3 Pricing levels for a coalition between operational taxi services and a DRT-software provider

The existing cost-model is slightly altered to mimic such a coalition. In the first setting the development cost will remain the same, as if the service payed for the development of the DRT-software. In the second case the development cost will be set to zero, but the taxi-service will now share his revenue with a software provider.

The most obvious coalition partner in Ghent would be V-tax . It is currently the biggest taxi provider operating in the city with a total of 130 vehicles. For the pessimistic setting, in which 55 vehicles are active, no vehicles would have to be purchased. For all other scenarios the required amount of new vehicles is set to be the simulated service fleet minus the 130 vehicles currently owned (same logic applied to parking space). The startup cost is also removed. Table 6.3.7 shows the different pricing levels for each of the tested scenarios in which the development is payed fully by the taxi operator. In the second scenario, the revenue will be shared with the software developer to pay for the software development. Reducing the development cost to zero, reduces the break-even price by 0.07% or € 0.006 (for 8000trips). If the developer would share 0.08% of the revenues , the passengers would see an increased price of €0.01 per trip. This will by no mean change the viability of the service.

Scenario	Avg-price (€)	CI (97.5%)
2000	9.96	0.08
7500	8.78	0.07
8000	8.76	0.1
12500	8.63	0.03
15000	8.8	0.05

Table 6.3.7: pricing as found for a coalition between operational taxi service and DRT-provider: development cost included

6.3.4 Pricing levels for a PHV-operator

Calculating break-even prices for a PHV-operator could be interesting. In previous examples it was shown that the highest cost influencing variables were driver wages, the acquisition price for vehicles, maintenance and insuring vehicles. These costs are all reduced by operating in a PHV-scheme in which drivers now earn less, pay for their own vehicle, vehicle insurance and licence. The fuel cost will still remain fixed at the current price as it will be considered that the PHV-operator pays back drivers their fuel usage.

Results presented in table 6.3.8 are promising. In a realistic scenario a PHV-provider working with ride-sharing could ask a price of around €5.5 per passenger. If the cost would be time-dependent (per hour), it would even go as low as €3.5 during peak hours.

To validate these results a comparison is made to the current Uber-pricing in Belgium ([63]). Uber is asking its customers a fixed €1 + €0.2/min + €1.1/km. The average trip in our simulation was 9.62km and direct travel would take around 19 minutes (Uber is currently not sharing rides). This means that an Uber would cost around €15.4. Online search into the price for UberPool (ride-sharing variant) shows the price is usually between 20% and 50% cheaper than regular Uber ([64]). This means the trip in Brussel would cost between €12.32 and €7.7 depending on the time and availability of ride-sharing. The results as found in this simulation are somewhat cheaper, yet there is no profit margin taken into acount. Next, there is currently little data available on the amount of daily trips in Brussels. An article by "De Tijd" states that Uber had served around 100000 different users in 2017 ([65]). Estimation on the daily amount of trips is quite difficult considering this statement, but 2000 daily trips would probably be somewhat an overstatement. Other sources online also show pricings in the same range: €5 (short trip New-York,[66]) €3.76 (starting price short trip, [67]). It can be concluded that the current simulation model and cost model generate a pricing that could be considered somewhat generous, but are in the correct price range.

Scenario	Avg-price (€)	CI (97.5%)
2000	6.07	0.05
7500	5.14	0.04
8000	5.11	0.04
12500	4.96	0.02
15000	5.02	0.03

Table 6.3.8: pricing as found for PHV DRT-provider

6.3.5 Pricing levels for a DRPT-service

For a publicly owned service the taxing, licensing, start-up costs (included in existing public provider) and company contribution is set to zero. One could also argue that they could see a lower fuel-price (not taxed), lower rent (eg in buildings already owned by current public providers) and a reduction in the development costs (the service could be included in excising software). In this simulation however, these costs are not reduced. But it is clear that this offers possibilities for a further reduction in break-even price.

Table 6.3.9 shows how similar pricing for DRPT is compared to DRT (table 6.3.6). The price difference is to small to say DRPT is more viable. In a next section the positive externalities will be included when validating the viability of DRPT.

Scenario	Avg-price (€)	CI (97.5%)
2000	10.63	0.08
7500	9.12	0.09
8000	8.99	0.06
12500	8.87	0.04
15000	8.98	0.05

Table 6.3.9: pricing as found for DRPT-provider

6.3.6 Some interesting future possibilities

This subsection will shortly discuss two interesting future possibilities that could provide opportunities to the DRT-services in the current state. These are self-driving vehicles, also called

Automated Vehicles (AV) and Electric Vehicles (EV). Next some other possibilities will be given, examples to improve the DRT-software. These options are to complex to be analyzed in this paper, yet they should still be considered if viability of a DRT-service is the main discussion.

While Electric vehicles are more expensive to buy, the reductions in fuel (€4/100km, [68]) and maintenance cost (75% of conventional vehicles, [69]) will, after a minimum number of kilometers driven outweigh the increased purchase price. Increasing the purchase price to 1.5 times the price of a standard diesel Sedan (based on Tesla model Y), reducing the fuel and maintenance cost results in an average break even price of €9.16 for the 8000 trips a day setting, which is somewhat higher then the €9.14 as found for conventional vehicles. This shows that the current price difference between a comfortable EV and the short (5yr) life-span of the vehicle is outweighing the current price reduction in usage. In the future it is expected that the price for EV will continue to fall and if they become equally as expensive as their conventional counterparts pricing could drop to €8.86. But, one should also consider that the charging of EV takes considerably more time compared to refueling, this would result in a higher need for vehicles, so drivers can change their vehicle when charging. Overall it can be concluded EV would not drastically change the cost model and pricing levels of DRT-services.

It stays hard to predict if Automatic Vehicles (AV) will ever exist and how much they would cost [70], yet its impact on DRT-services would be enormous. For this setting all driver wages are eliminated and the purchase price doubled. For a service operating with 8000 daily trips, the price would make a staggering drop from €9.14 to €1.98. This can also be predicted from figure 6.3.3, in which a 100% reduction in driver wages would reduce the price to only 17% of its original price. This comes to show that if AV ever became reality it could drastically change the way we commute, probably eliminating the need for private car ownership

Other opportunities also exist. Yet these are currently not considered considering the scope of this project. Nevertheless, they are shortly discussed to show that pricing could be reduced by changing existing policies.

- Door-to-door service: The current DRT-provider offers its users a door-to-door service. If passengers were given a cheaper alternative travel option in which they are required to walk a short-distance, it is expected that cost savings would be found. It would become easier to establish ride-sharing as walking would decrease the driving time between passengers. This would probably result in less distance driven to achieve the same success-rate and would reduce the amount of vehicles and drivers needed and as a result lower the break-even price.

- Combine static and dynamic demand: Discussed in policy 5.2.3 was the option to improve upon the DRT-software. By allowing a combination of both static and dynamic demand it would become possible for passengers to make reservations in advance. Static linear algorithms could be used with heuristics to reduce the total distance or maximize the amount of ride sharing. Next, the current DRT-algorithm could be used to inject dynamic demand. It is expected that this would result in a more efficient algorithm and as a result reduce costs.
- Improve upon discussed policies: All policies that were discussed in section 5.2 should be taken into consideration. Variable pricing and limiting the service between 5h00-24h were shown to be possibilities to reduce costs. These, and all other policies (eg centering to a more efficient location) are still open for changes. They where introduced to search for a viable provider, but are not proven to be optimal policies.

6.4 Viability of DRT in Ghent

After presenting the different DRT-services and their simulated pricing, the next step would be to validate their feasibility and, as a result, the viability of the whole idea of DRT in Ghent. First some competitors to DRT are given. Their pricing will be compared to pricing found for each of the different DRT-services. Based on this comparison it should become clear if their exists an opportunity for DRT-services to operate in the city.

6.4.1 Comparing DRT to its competitors

6.4.1.1 Private car ownership

The main competitor for DRT-services is private car ownership. Jani-Pekka Jokinen ([6]) estimates that ownership of a car has a fixed cost of around €13.5 per day. This includes its purchase and payment plan. Next, he also estimates a variable cost of around €0.09 per km. For this simulation the average travel distance for each trip was 9.62km. Considering the average of 2.3 daily trips per person the price for car-ownership would be €15.5/day or €6.7 per trip. Other then PHV-services no DRT-service would be able to compete with this price.

In the previous comparison it was considered that the car owner would use his car daily. If not, the fixed €13.5/day would probably be reduced because of various reasons (lower insurance, longer life expectancy), yet their would still exists a fixed daily cost. For people who do not need to travel by car each day, all DRT-services could now become worthy alternatives.

To give one such example as proof: let us consider a car owner who only uses his car every other day. He chooses to own the same sedan as used in the cost model (€36250) and insures it with a full omnium (€900). The average expected life-time of a car is 12years, considering his low usage this will be extended to 15years. The daily worth (2% yearly interest, 15% discount rate) results in €7.44/day. Traveling the expected $2.3 * 9.62 = 22.13km$ every other day would result in a total price of €16.9. Per trip: €7.4, a value close in reach for every possible DRT-provider. This is of course without any profit margin taken into account, but even then it would seem that DRT could be a valuable alternative.

In addition to the difference in cost price, both options also have their own additional advantages. These are difficult to convert to monetary value and highly differ from person to person. The biggest advantage for car-ownership is the enormous freedom it provides. If somebody often makes different trips from day to day it seems difficult that DRT would give him an affordable alternative. But if, for example, someone lives and works in Ghent and often cycles, yet is still looking for an alternative that can transport him comfortably from time to time at a reasonable price, DRT could be become such an alternative. In addition, it is also possible to point out a number of other advantages that exist when you don't have to drive yourself. For example, one could use the travel time to be busy with other things, such as preparing for the working day or answering mails. Of course there are other alternatives in this case, these will be discussed next.

To conclude this comparison: while in the current state DRT-seems a bit more expensive for car owners, there are still lots of opportunities to further reduce DRT-costs (6.3.6). It doesn't seem unthinkable, since the current price difference is already quite small, that a strong alternative to car ownership would be achieved this way.

6.4.1.2 Public Transportation

The cheapest possible option to use public transportation in Ghent would be to purchase a yearly subscription to the service. In Flanders this will cost €334 if you are between 25 and 64 years old ([16]). Considering the average amount of daily trips (2.3), each trip would cost €0.4, regardless of the distance. The most expensive option available is €2.5 (single-trip fare payed to the driver).

This price seems hard to beat for DRT-services, yet more then often public transportation requires the customer walking and waiting. Also, public transport is heavily subsidized, so the above mentioned price will not reflect the real cost. As discussed in section 5.2.2, the average speed of public transportation could be set to about 15km/h in Ghent. This speed would include the time passengers spend waiting, walking and switching busses. The maximum allowance (for travel time increase versus a direct trip) for the DRT-services was set to 100%, this meant the passenger could receive trip proposals for all possible speed equivalents between 15km/h and 30km/h for his direct route. More intuitively: if the passenger would be "lucky" and no ride-sharing takes place, his equivalent travel time would be direct travel at the average speed of 30km/h. In contrast, when the passenger is combined with other passengers in such a way that he sees his own travel time increase by the maximum allowed additional travel time, his direct travel equivalence would be a car that is driving at an average speed of 15km/h. For the DRT-service operating with a daily demand of 8000 trips the average relative increase of travel time is 21.39%. Meaning the average equivalence of travel speed is 24.7km/h. It was already calculated in sect. 5.2.2 that the equivalence money value of time for each minute was worth between €0.1 and €0.2. If the user would travel the average 9.62km 2.3 times a day he would save around 36 minutes if he chooses DRT. This increases the relative travel cost per trip for public transportation to somewhere between €4 and €7.6. This price is a lot closer to the price DRT asks. The difference between the two options is therefore a question of how much value each user attaches to his time and how long and often he travels.

This example has shown that public transportation would not necessarily be a much better alternative than DRT. And so it can also be said that the competitiveness between public transport and DRT exists. If real costs for public transport (without subsidies) would be charged to customers, DRT will be a much more interesting option, certainly in rural areas (as proven by the operation by "bel-bus" in these areas). It can certainly also be mentioned that the added value of comfortable transport and a door-to-door service can be worth the small extra charge for DRT.

6.4.2 Car-sharing

Another competing solution to non-car owners that need transport would be to participate in a car-sharing service. There are different options available in Ghent, of which the most famous one would be Cambio ([71]). In case of Cambio pricing levels vary based on customers need. Taking a look at the average user, who travels between 50 and 300 km per month: he would pay a monthly subscription fee of €8 + €1.75/h + €0.25/km. If a user is considered to travel 300km a month, over a total of 300/9.62 = 31 trips using Cambio would cost him $8 + 0.25 * 300 + 1.75 * 10(30km/h) =$ €100 per month, resulting in a trip cost of €3.2. In the current calculation, it is considered that the duration of the car rental is exactly the travel time to travel 300km. In reality he would have to park his Cambio car at one of the allowed parking spots, otherwise the hourly wage will continue until he returns the vehicle. Next, by using Cambio the user also has to be lucky that their is such a Cambio parking close by, otherwise he would have to include some walking distance. For each hour spend with the vehicle not being parked at a Cambio spot, he increases the trip cost with €1.75. €9.01 - €3.2 = €5.8, resulting in a maximum parking time of 3h30. If parking rate in Ghent is taken into consideration the difference in pricing between DRT and car-sharing could start favoring DRT. Low availability of cambio cars in rural areas is also a disadvantage.

6.4.3 Taxi-services

In Ghent, the average price for a taxi is between €1.6-2.3/km plus a base fee of around €9 (including the first 3km). For the a trip of 9.62km the customer would pay ±€22.4. It is clear that DRT-services would be a worthy alternative if customers accept the possible ride-sharing and its increased travel time.

6.5 Conclusion on viability

The first section of this chapter (6.1) estimated a daily demand of trips DRT could possibly reach. This estimation was done without any pricing in mind. Now, after simulating each of the different estimations, calculating a base price for each of the different providers and comparing DRT to other transportation means, these estimated demand levels should be reconsidered.

It can actually be said with hindsight that the presupposed trip numbers would be achievable. Since it has just been shown that DRT can be a strong alternative for most comparable transportation options when reaching the realistic 7500/8000 daily trips. So it also seems that once these numbers have been reached, for example through massive marketing, the service is viable on its own, without huge additional subsidies or investments from external parties. Of course, there is the problem of getting sufficient investors and budget at the beginning to achieve this scale, and this has been seen as one of the reasons why other similar services were discontinued. It can be said that if this budget was there and the service could experience rapid growth, there would be viability.

6.6 Case study on cooperation with taxi service

This section will discuss the opportunity that exists for an existing taxi services to boost their output (handled passengers) and therefore revenues when using a ride-sharing scheme. A comparison will be made for V-tax (current biggest taxi-service in Ghent) in which both a non ride-sharing and ride-sharing simulation is considerd.
For this setting a comparison is made between a taxi service with and without ride-sharing where the number of taxis is set equal. Vtax currently has 130 vehicles available in Ghent and

for this level different daily demand inputs are simulated. The cost difference between the 2 situation is mainly the development (and operational) cost for the software. Development cost for software will be zero for Taxi and €150000 for the DRT-services. The operational costs (platform cost)for conventional services is set to to €500, and €4000 for DRT-services. Also omitted is the purchase cost of the vehicles. Figure 6.6.1 shows the comparison between DRT and a traditional taxi service for success-rate and (break-even) price. What has to be noted is the relative low cost for the conventional taxi service. This is notably less then the price found in reality (9.62km = ±€22.4), and notably less then the initial pricing found when using the simulator to simulate a taxi-service in section 3.2. Two reasons can be given for this. First, in the initial simulation (sect.3.2) the simulation software was used without any smart policies in place. The first available taxi (not sorting based on distance) was assigned to the passenger. Next he was set to a "busy"-state and could not be used in the dispatching unit until he dropped of his passenger and was again set to "free". Therefore the dispatching algorithm could not estimate which taxis would be driving closest to the new request. Now, in this experiment, even though the maximum capacity of the vehicles is set to one, there is still some smart algorithm sorting taxis based on the distance to the new request. This also shows that conventional taxi services can really save costs by using such an easy to implement algorithm. The second reason would be the non-existence of available data on the amount of daily trips and an overstatement to assume there are 3000 daily trips or more. Even if it is said that there are 130 taxis driving for the service, there is nowhere described how many daily users are served. After contacting V-tax they said, on average, around 900 and 1300 passengers use their services daily. If these number of daily demand are simulated inside the testbed more realistic pricing levels are found. Figure 6.6.2 shows how prices an success-rate compare for services operating with a more realistic daily number of trips. These prices are much more in range of real pricing levels.

These numbers lead to an important consideration: It seems there are far too many taxis for the current demand in gent. This can be explained by two facts. Firstly: taxi-services are probably not using smart dispatching systems to increase their efficiency. This is mainly explained by the fact their are far to many businesses operating with only one or two vehicles. The total amount of taxi vehicles in Ghent is maximized at 220, yet there up to 74 businesses. Vtax has 75% of the market share, resulting in the other 73 businesses operating with on average 1.25 taxis each. These companies do not have the budget, nor the possibility to increase their efficiency. Taxi businesses are currently fighting to increase their own individual profits and are in not working together to use the 160+ vehicles in such a way that the total amount of passengers per taxi could be maximised. If such a central-dispatching agent would exist in Ghent, and all taxi companies would except to be included in this service, it can

can only be assumed that the total efficiency would rise, decreasing pricing and attract much more passengers to use a taxi-service. This would result in higher total profits for the whole market and would help increase profits for the smaller businesses. Of course this cooperation is blocked by the search to only maximize your own profits.

The second fact would by that because so many services are combating each other, it seems the only way to increase profits is to increase your scale (vehicle-fleet size). Ghent is also using fixed taxi rates. Probably to defend the smaller taxi-services. V-tax is probably making much more profits compared to other services because it has a big fleet size and is able to attract more passengers by being the first service you find on google and the service most seen driving around in the street. Next, by having such a fleet-size V-tax is probably also using smart-algorithms to steer its fleet (for high size fleet the development cost would now be more then worth it). Resulting in more passengers traveled per taxi compared to other services. By fixing the price for taxis in Ghent, V-tax is not able to lower its price compared to other services which would probably result in monopolizing the market. But is still able to increase the fleet-size

All this combined can only explain why current players are so afraid for a new competitor such as Uber ([72]). This Service does not only reduce costs by having lower driver wages, it also takes advantage of its huge scale to have an efficiently routing. In Ghent it seems the only viable alternative to players such like Uber would be to combine all current taxi-providers and compete Uber by maximizing the total efficiency of the available taxi fleet.

To come back to the initial question of this section, would it be profitable for existing services to implement DRT-software? Both figure 6.6.1 and 6.6.2 show that pricing levels are reduced by an average of 10% just by allowing ride-sharing. Again, the simulated taxi service is already using smart algorithms to steer its fleet. While the gained 10% in pricing seems rather low, it could still be sufficient to gain more customers. By allowing for ride-sharing the success-rate is also more stable when demand increases. Allowing for a lower price for the current demand levels and the fact that ride-sharing is more future proof could help scale the service without the need to purchase extra vehicles in the short future.

To conclude on this section. Implementing DRT-software could most definitely reduce costs by increasing the service efficiency. For large players such as V-tax this would reduce costs by an average of 15%. If this average initial gain is used to offer customers lower pricing (and if this would be allowed in Ghent). Customers on average would see their price drop with a substantial 15%. But again, it seems that the current pricing for a taxi in Ghent is artificially held at a much higher price to protect small businesses, who are not able to use smart technologies like reservation apps/site for customers and a control mechanism to steer the vehicle fleet. It seems that the city would need to make huge efforts to combine the current vehicle fleet available and make taxi services work together, otherwise it seems that players like Uber are going to rip apart the current taxi market.

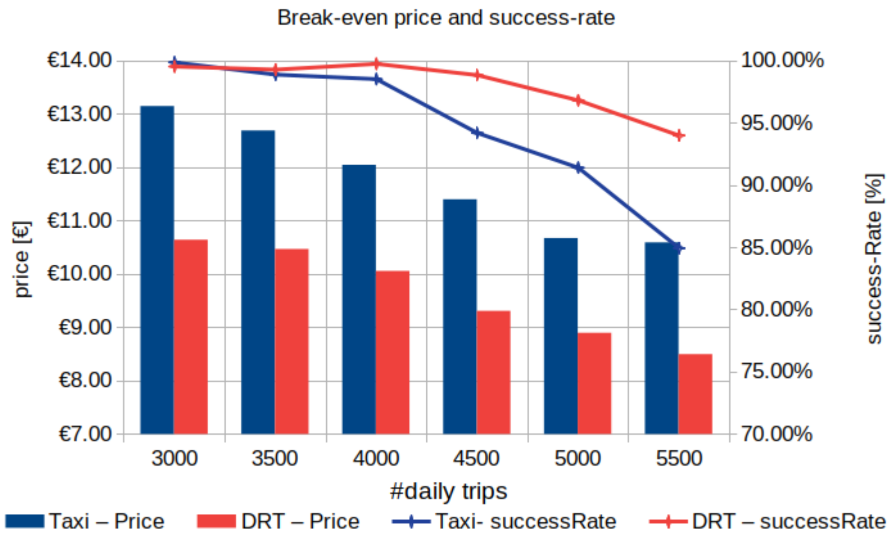


Figure 6.6.1: Comparison Taxi and DRT with high levels of demand

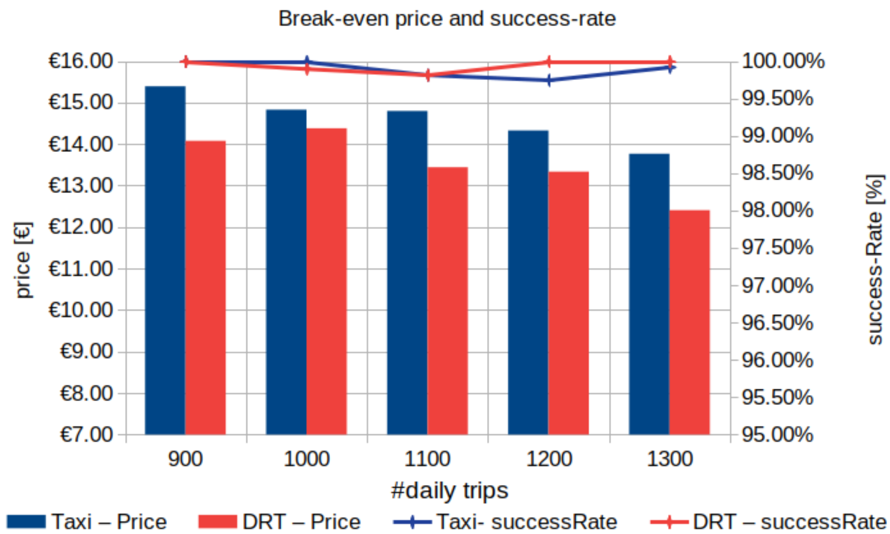


Figure 6.6.2: Comparison Taxi and DRT with realistic levels of demand

6.7 Can DRT help reduce congestion and pollution?

In this small section the focus will be on the positive externalities that can be found when using DRT, these could then help the decision-makers to justify a subsidy for the service.
The first question decision makers should consider when validating DRT-services is the savings in emissions. An important KPI that should be considered for this question is the distance per passenger. On average the trip length was found to be 9.62km. If the total distance all taxis cover (with and without) passengers is less then the total distance passengers would travel without ride-sharing, one can conclude that the service is effectively reducing both congestion and pollution (if all these passengers would take a car, and not their bike). The average distance per passenger for 8000 daily trips was found to be 8.46km. This means 67680km was "saved" by offering ride-sharing. Overall this would reduce the total distance by 12%. If each vehicle had the same 118.75g CO2/100km this would reduce CO2 emissions with around 80kg each day. About 30 ton a year. These results are minimal, considering the average family has a yearly emission of 20ton CO2. Next to CO2 savings directly linked to the total distance driven, other savings also exist. If a user decides not to purchase a new car because of the DRT-service, it can also say that there would be much less production emissions. It is of course highly difficult to make any assumptions on this based on the simulation results. Overall the environmental impact purely based on shared-distance on the more realistic scale (8000daily trips) is considered minimal.

Next to a savings in total distance, it should also be considered that for this amount of passengers, only 195 vehicles are driving around. During peak-hours it is estimated around 600 passengers are traveling, this would reduce the total amount of vehicles driving around with ±400. Sadly this amount seems rather limited. An other impact would be the fact that 8000 passengers are now not in need of parking space, this is probably more beneficial for the decision maker. There are currently around 45800 parking spaces above ground. Reducing this amount with 8000 cars would be almost a 20% reduction.

Based on the current state of the DRT-algorithm and the amount of trips that are considered realistic, it seems hard to convince decision makers to opt for DRT based solemnly on the environmental impact of the service. An interesting other subject for further investigation should be how much money could, if even, be saved by introducing DRT-services as an alternative to fixed-bus routes that have limited to no passengers on-board.

Chapter 7

Conclusions

The concept of DRT services has been around for some time and is getting more and more attention in the search for an alternative to car ownership. There are many examples of services that exist or have existed. But many of these have difficulties to become viable. The main difficulty for these services is to obtain sufficient starting capital to survive the initial growth phase. This effect is described in several other studies and the need for scale to become viable is often mentioned. While many other papers focus more on the technical issues surrounding DRT, it seemed interesting for this thesis to focus more on the financial side of the story. This could help to show how important the scalability effect is and to what extent DRT can be considered viable in a Flemish region.

The first step of this research was to collect different options to simulate DRT, but soon it appeared that it was interesting to use the software provided for by Michal Certicky, Michal Jakob, and Radek Píbil ([54]). In general it was chosen because it was described as easy to use for testing DART algorithms. Unfortunately this turned out to be more complicated than expected, but after some time, a dynamic model could be developed that can be used to simulate ride-sharing in a fairly effective way. New transportation requests are combined with requests already assigned while still respecting all requested arrival times. But in order to allow ride-sharing, passengers had to accept that their effective transportation time could be slightly longer than a direct journey.

The next step was to create a dynamic cost model. All cost factors that are relevant for a DRT service located in Flanders were determined. By conducting extensive research into existing similar services, such as taxi companies active in Flanders and DRT services abroad, appropriate values could be assigned to each of the different cost elements. For a lifespan of 10 years, all fixed and variable costs were put into a discounted cash flow model using a 15% discount and 2% inflation rate. By using both the dynamic cost model and the simulation software, different types of DRT-services could be validated. This was done by implementing the simulation results inside the cost model. The cost model would then generate the future costs and calculate a PV for the service. With this, a daily worth and hourly worth were determined, these could then be used to provide a break-even price per customer.

After this way of working was tested for a real-life DRT operator (Kutsuplus), and the results were found to be in a very plausible range, it was decided to test a number of policies of which we expected they would increase operational cost efficiency and reliability of a DRT service. From these tests a number of conclusions were drawn:

- Impact of centering taxis: It is recommended for DRT services to have a central point to which empty taxis return when they dropped off last passenger. It can also be concluded that this point needs to be chosen so that it is centrally located compared to the so-called "hot-spots", places where the probability for new requests is greater.
- Impact of extra allowed travel time: In order to allow ride-sharing, passengers must accept that their trips take somewhat longer than a direct route. In order to limit this extra time, it was decided to limit the extra travel time to a percentage of the direct travel time. After testing different percentages, it appeared that the maximum acceptable scenario (100%) in general did not have a large impact on most trips and the average increase of travel time was found to be about 20%. When looking at the monetary value of the extra added travel time, it can also be stated that the extra efficiency found by increasing this allowance has a greater impact than the travel time added. And in general this allowance should be set as high as practically acceptable. .
- Impact of an increase in the allowed reservation time-window: From this research question it could be concluded fairly quickly that the service performed better when passengers could not book long time in advance. This is for the most part due to the unpredictability of future location of taxis. As a result, taxis were assigned to passengers while in retrospect there would have been better options available. Of course, there are also extensions that could be added to the simulation model that would help solve these inefficiencies. For example, request that have already been accepted by the service could be re-released (and re-calculated) to look for a better alternative.
- Impact of a flattened demand-curve: This policy tested the impact of a flattened demand curve without effectively looking at what impact certain cost models would have on demand. It can be concluded that the impact is positive for services that are overloaded because they can now transport the otherwise rejected passengers at less busy times, while ride-sharing is often still taking place. For lower loaded services, the opposite is

noted. There is now less ride-sharing during peak hours because there are less ride-sharing possibilities.

- Is a night service economically interesting: The break-even price found for services operating only at day were on average 2.3% lower then those found for the same services operating 24/7. As a result, it can be concluded that it would not have a major impact on the viability of the service, under the condition that wages are equal during day or night.
- Impact of an increased vehicle capacity and vehicle type: From a large number of simulations it can be stated that no enormous improvements are found when the capacity of vehicles is increased. Simulations show that only in a very small number of situations more than 2, let alone 4 passengers shared-rides. However, this could change when each request could represent more than one passenger, which was not yet the case in these experiments. It is also pointed out that more savings can be found if a more fuel-efficient vehicle is used, even if it is more expensive to purchase.

After these policies were tested, we looked at the effect of scalability on the service. In this section it was clear that the effect of scalability of DRT-services, based on the implemented algorithm, should not be overestimated. It became clear that for a fixed amount of passengers per vehicle, the success-rate of the service with increasing scale converged to a less then 100% success-rates. This achieved success-rate also dropped with increasing pas/vehicle ratio. As a result it seemed impossible to ever achieve the acceptable 95% rate for services operating with 40pas/vehicle. The prices follow the same curve, in which they seem to converge to a stable minimum. This result is unfortunately not what was had hoped for and it is hard to validate the scalability effect on DRT-services based solemnly on this experiment. However, it can be stated that the scale on which was tested here is still not significant. This is due to a relatively inefficient algorithm combined with extremely high demand. There are still lot of opportunities here that could help reduce calculation time. And these are shortly discussed in section 5.3

The last chapter then covered the viability of DRT-services in Ghent. First daily demand was estimated. This was done for a pessimistic, optimistic and most probable scenario. These also differentiated between private companies and publicly owned companies. The estimates were: 2000, 7500/8000 (the lower number for private-owned company) and 15000/12500 trips a day. These demands were simulated and used as input for the cost model considering a multiple of different type of providers: A newly introduced DRT-service, a cooperation between an existing taxi service and DRT-provider, a PHV-type operator and a DRPT-service. Differences between these different types are mainly in the purchase price of the vehicles, in the hourly wages of the drivers and in the number of daily trips. As break-even price for the most realistic scenario we found respectively €9.01, €8.76, €5.14 and €9.12. It was also easy to conclude that the most influential parameters on pricing were (in order of magnitude): wage drivers, vehicle purchase price, fuel efficiency and/or fuel prices, maintenance costs and insurance for the vehicles.

After this, all DRT providers were compared with car ownership, public transportation, car sharing and existing taxi companies in Ghent. From this it could be concluded that DRT can certainly offer a good (cost efficient) alternative to these services. The differences between DRT and existing alternatives were never unacceptable large, this made it possible to always find an option for different users where they might want to choose DRT as opposed to other existing options. Because of this it seems likely DRT-services could become economically viable at the estimated demand levels, the only disadvantage that remains is the fact that this scale has to be reached with sufficient starting capital to survive the first years of growth.

To finish this thesis a case study was done on the cooperation between an existing taxi-service and a DRT-software provider. For v-tax, the biggest player in Ghent, introducing ride-sharing could probably save them up to 15% per trip. But the biggest conclusion is that taxi-services, as they operate today, are doomed to fail in the face of new transportation systems such as Uber. This is mainly explained by the fact that the market is divided over a whole array of small players who do not work together efficiently in any way. As a result, there are simply too many taxis in Ghent that would be needed to meet current demand. The city tries to protect these small businesses by setting a fixed price and this makes it plausible that the biggest players, such as v-tax, can earn a lot more profits. In general, a collaboration of all players and the use of a central dispatcher could reduce the total number of vehicles needed and increase the efficiency of the service, which would generate higher profits for the entire taxi market. Unfortunately, it seems very unthinkable that these players will work together, and players who do use more efficient DRT algorithms on a larger, rapidly available fleet, like Uber, are probably going to be the winners.

The last section also covered some extra positive externalities that could be considered by decision-makers. It was concluded that on the current realistic estimation of daily trips the total environmental impact was limited. The CO2 savings by sharing rides was only found to be 30 ton a year. Next on the question if DRT could help reduce congestion levels, it seemed that during peak hour only 400 vehicles less were driving around compared to car-travel.

It is clear that a lot of additional research is possible on this subject, which can unfortunately not be included in the scope of this paper. While a positive indication for economic viability could be established, the question remains whether DRT could also have an ecologically positive impact, as this would need significantly more ride-sharing to take place. So I would certainly recommend further research on a whole spectrum of issues. First of all, my suggestion to my colleagues in computer science would be to further improve the simulation software. Secondly, to my friends in environmental sciences and psychological sciences, I would suggest to you examine what impact this service would have on the decision whether or not to buy a car. In addition, I ask any interested reader to continue looking for innovative policies for DRT service. Also, while I have able to some extend to provide answer to the scalability impact, it seems that further improvements on time-efficiency of the software, or more computational power and time will be needed to simulate higher numbers of demand.

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