A look into the effectivity of autonomous mobility on-demand

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Abstract

This article presents a solution and a tool to better understand efficiency of autonomous vehicles in transit services. Because of the thriving industry of autonomous cars and buses, this has been done to help make public transport more effective.

Since more and more autonomous vehicles roam the streets, and the society sees a change in how transport is regarded, this article bridges the gap of lack of knowledge about efficient transport. With the help of MATSim-MaaS, an on-demand simulator, this question was answered.

Based on Rajgopal’s presented method Operations research, simulations were done and results were given to evaluate the efficiency of two on-demand services, which led to a proposition regarding which of the two services were the most optimal out of the perspective of operational efficiency. By using the method and the creation of a tool, an answer could be proposed to the question of how long the distance should be between stops.

The method operations research was evaluated with the simulator MATSim-MaaS as it produced data on efficiency parameters such as average driven distance per vehicle, average waiting time and the total time spent walking.
Table of contents

Abstract................................................................................................................................. 2
1. Introduction......................................................................................................................... 4
   1.1 Research Questions......................................................................................................... 5
2. Related works and gaps found in the literature................................................................. 7
3. Method................................................................................................................................. 10
4. Technical Background....................................................................................................... 13
5. Results............................................................................................................................... 17
   5.1 RQ1................................................................................................................................ 17
   5.2 RQ2................................................................................................................................ 21
6. Discussion........................................................................................................................... 22
   6.1 Analysis......................................................................................................................... 22
   6.2 Factors found................................................................................................................. 23
   6.3 Future Works.................................................................................................................. 23
7. Conclusion........................................................................................................................ 24
8. Reference list....................................................................................................................... 25
1. Introduction
In 2023, as of writing this thesis, the technology for autonomous vehicles have been booming and advancing further every month. In recent years, Tesla has been developing their self-driving technology, which can be used by the customers of the cars, states Tesla on their website [1]. By the use of sensors, the car can scan the surroundings around itself. Others have also made strides in the possibility of self-driving vehicles, with one of them being Waymo, according to their own website waymo.com [2]. By looking at the timeline and how far the progress of autonomous vehicles have gone, it is only a matter of time before most cars are autonomous.

An autonomous vehicle, or AV, is a vehicle that can drive by itself. It does not need a driver controlling it. Many cars sold today are semi-autonomous. An example of a semi-autonomous feature is adaptive cruise control, where the car can keep speed but also a distance from a vehicle in front of the car. The car accelerates and decelerates to keep the distance. There is also a feature called lane pilot, where the car notices the lane and stays in it according to the magazine Car and driver [3] and Volvo Cars [4]. Some cars have taken a step further, having a full autopilot mode, like Tesla’s cars. The scope of this paper is to research public autonomous vehicles rather than private AVs.

Autonomous cars and buses, have become more common on roads. A possibility behind self-driving vehicles is that they can be used for picking up and dropping off customers. A vehicle in this service would work as a taxi, without the need for a driver. A service for when the customer is picked up at e.g. their home and dropped off at their wanted destination is called door-to-door. Another service is the stop-to-stop service. The stop-to-stop service works more closely like a bus, with stops along the road where customers can hop on or off the vehicle. Instead of the customer going door to door, they walk from their origin point to a stop, go in a vehicle to the closest stop to their destination and then walk the last bit to their destination point. A possible extension to both services is what is called ride-sharing. Ride-sharing is a service where many customers can share one vehicle, either door-to-door or stop-to-stop. Although stop-to-stop service shares similarities to bus services, the difference between stop-to-stop and bus services is that stop-to-stop can be on-demand. Whereas a normal bus will go the same route, even if no clients are riding it, the on-demand vehicle will drive and pick up customers only if the ride is requested.

The reasons behind using autonomous vehicles can be because of better safety, larger capacity and better comfort while also being more energy preserving. As much as 88% of traffic collisions on the road are caused by human error, according to The Guardian [5]. A computer handles the driving in self-driving vehicles. The computer can react and handle situations much faster than a human could. Because an AV lacks a driver, more travellers can fit in the vehicle.

Self-driving vehicles still have a long way to go though. In 2018, a pedestrian was killed by being hit by a self-driving car by Uber, even though a safety driver was in the driver’s seat when the accident happened, according to BBC News [6]. Since more self-driving vehicles have populated the roads, as of April 2023, when autonomous buses rolled into traffic in Scotland, Edinburgh [5] and many more places have seen self-driving buses it is very important that the safety measures work. In the urban area of
Stockholm, two projects of self-driving buses has launched. The first project launched in January of 2018, states [7] and the other one launched later that year in October, reports SVT [8]. In 2021 according to Vti, the city of Linköping launched a project of self driving buses [9], and two years later, in 2023, Trelleborg municipality followed on the same path, according to Trelleborg’s municipality website [10]. Since the buses have not been in traffic for long, it is still too early to conclude how safe the systems are and how much better riding one is compared to a normal bus. It is still mandatory for a driver to be able to manoeuvre the vehicle, should there be a malfunction of the system. Issues can occur, and occurred when SVT was riding a bus in Kista in Stockholm, where a driver had to solve multiple problems [8]. SVT reports that it is still a long way until self-driving buses drive as fast as normal traffic, as the buses in Kista operates at a maximum of 15 km per hour [8].

The issue of who's responsible for traffic accidents by AVs as happened with Uber, has surfaced but will not be looked into in this paper. Instead, the scope of the research in this paper is to find out which service, stop-to-stop or door-to-door, is the better one, when efficiency is the factor being studied.

The thesis will compare two transportation services. These are door-to-door and stop-to-stop. To find the result, to know which one service is better than the other, data of the operational efficiency, like waiting time was needed. Operational efficiency means such metrics as average driven distance per vehicle, waiting time, walking time and travelling time. Through a simulator, the data was fetched, to later on be analysed for results. The simulator of choice is MATSim-MaaS [11]. Firstly it needed to be decided what the optimal stop-to-stop service was, since the efficiency of that system may differ on where stops are distributed. Since no tool for distributing stops that cooperated with MATSim existed, such a tool had to be created in Java. The created tool could be rerun with a different interval between stops. The tool created, worked together with MATSim-MaaS and produced an XML-file of transit stops that could be read by MATSim-MaaS. The most efficient stop-to-stop simulation was then compared to the door-to-door service simulation to decide which of the two were the most efficient. The goal of the thesis is to find an answer to the best distance between transit stops, and also finding out if stop-to-stop is better or worse than door-to-door. As the findings are targeted towards AVs, the results cannot be fully applicable towards manually manoeuvred vehicles. Since not many autonomous buses exists in cities as of 2023, an argument could be made that a change in transit traffic to the proposed more efficient transit services found in the article could be made now, and later on a smaller adjustment towards AVs will be made to take full advantage of the findings. The study’s target groups are therefore ride-sharing companies and companies who provide bus services, who want to design public transport and want to find out where to put stops along the roads for better connectivity and efficiency out of a standpoint of operational efficiency.

1.1 Research Questions

This thesis looks at the two previously presented services closer, to gather knowledge about which is the most beneficial out of an efficiency standpoint. The research questions have therefore been chosen to examine what type of autonomous mobility on-
demand service is the most efficient, but also asking the question of which distance between stops prove to be the most beneficial.

The research questions that will be answered in this paper are:

**RQ1**: What is the optimal distance between stops when efficiency is the main goal in a stop-to-stop based transport system?

**RQ2**: What is the difference in efficiency between door-to-door service and stop-to-stop service when examining autonomous mobility-on-demand?

To answer the second question, the first research question shall be answered first, so that the most optimal stop-to-stop simulation can be compared to the door-to-door simulation.

To answer both of the research questions, there is a need to put stops on a road network to run stop-to-stop simulations. In the creation process, a tool will be made for the purpose of distributing stops. This tool, will be programmed in Java. Additional reasons why Java is chosen follows in section 3. In the text that follows, the programmed tool is referred to as “the tool”. This tool was made with the consideration of reusability in future studies which needs stops along a road network.
2. Related works and gaps found in the literature

The article *Simulating the Impact of Shared Mobility on Demand: a Study of Future Transportation Systems in Gothenburg, Sweden* by Fabian Lorig, Jan A. Persson and Astrid Michielsen conducted a simulation [12]. In their article, they used Gothenburg as the city and area to examine. Lorig, Persson and Michielsen examined the difference in various parameters such as vehicle kilometres, the amount of kilometres travelled by a vehicle, to conclude the efficiency of autonomous mobility on-demand. They compared that data to data of private car usage. The study found that just 17% of the cars in Gothenburg, were needed for shared mobility where everyone could ride and get to destinations by car, as of 2022.

Another paper, *On-demand Ride-sharing Services with Meeting Points* by Sevket Gökay, Andreas Heuvels, and Karl-Heinz Krempels, examines and introduces "meeting points" as they have called them [13]. The meeting points consists of combining pick-up and drop-off to get spots of high vehicle density. By doing this, the authors reduced the cost of possible vehicle detours. The study used New York City as the base for the algorithm, and fetched their data of trips from New York City.

*Demand responsive - vs. conventional public transportation: A MATSim study about the rural town of Colditz, Germany* is an article that studied responsive opposed to public transport using MATSim [14]. The authors of the article, Kathrin Viergutz and Clemens Schmidt chose to study the town of Colditz in Germany as other articles have not studied rural areas before. In their estimations, door-to-door service is more beneficial as it allows for reducing vehicle kilometres and impacting the environment in a favourable way, as opposed to stop-to-stop service.

The article *Rebalancing and fleet sizing of mobility-on-demand networks with combined simulation, optimization and queueing network analysis* by P. Bazan, A. Djanatliev, M. Pruckner, R. German, and C. Lauer conducted an experiment to find the optimal fleet size of vehicles to be able to handle the customers using the system without rejecting too many trips [15]. They used a simulation and created a queueing system to handle the requests, that was implemented into the simulation. They found that for their experiment and scenario, a fleet size of 7700 vehicles would have been optimal to be able to serve all of the city’s population as opposed to everyone owning a private car. For the authors to get this number, they had to take into account how many customers should be able to be rejected.

The article, *Forecasting Transit Walk Accessibility Regression Model Alternative to Buffer Method* by Fang Zhao, Lee-Fang Chow, Min-Tang Li, Ike Ubaka, and Albert Gan explained a solution to the issue of forecasting transit traffic relative to walkability in a certain area [16]. The solution was made using three different steps. The first one was to solve the estimation of the city’s population and in what areas the population resided. By using tax data of a certain area and by that extrapolating the information of how many bedrooms existed in each house, it could be estimated that each person had one bedroom. That data was then plotted on a map to know which areas were highly dense and which were sparse. The second issue needed solving was that of barriers, either man-made or natural, such as lakes. The third issue that needed solving was how long people would be prone to walk to take public transport. When all of
these issues were solved, a forecasting solution could be made. The article stated that the maximum walking distance to get to a transit stop is 0.25 miles, or about 400 metres.

*On-demand ridesharing with optimized pick-up and drop-off walking location* by Andres Fielbaum, Xiaoshan and Javier Alonso-Mora meant to find out in what regard ride-sharing would be possible where the users must walk to so-called pick-up and drop-off (PUDOs) locations [17]. The article found that by walking to PUDOs instead of the vehicle driving to each client's house and picking up and dropping them off, would reduce rejections by a big margin and increase efficiency in travel. The solution was found using mathematical formulas and then tested with two networks in a simulator. These networks were a toy network and a network of Manhattan. In their estimations, prompting the customer to walk a small distance, increases the efficiency of the system as a whole, lowering both the rejection rates and the amount of hours travelled in vehicles. It shall be said that Fielbaum, Bai and Alonso-Mora stated that the relationship between public transit and the simulator, in this case SMoD, is worth investigating further.

The paper *Methodological Distribution of Virtual Stops for Ridepooling* by Dennis Harmann, Sefa Yilmaz-Niewerth and Christina Jacob aimed to find where to place virtual stops to increase the efficiency of the transit system [18]. Virtual stops are transit stops that are visible on a mobile phone. The possible places to distribute stops were in intersections, where streetlamps were placed, and in a grid formation. These were then checked on several criteria to determine if the position of a stop was good for the environment around it. The criteria were if the transit stop blocked parking spaces, delivery and loading zones, bicycle lanes, private properties, or if the stops were placed at dead ends. The study found out that from the perspective of the provider, the use of intersections as transit stop points is the best. Contrary to that, at streetlamps were better placements of stops from the users’ perspective, since the light contributed to the safety of the user.

*Agent-based simulation of city-wide autonomous ride-pooling and the impact on traffic noise* by Felix Zwick, Nico Kuehnel, Rolf Moeckel and Kay W. Axhausen proposed an experiment in the simulator MATSim to compare stop-to-stop with door-to-door service [19]. The information sought after was efficiency and noise pollution. In the study, the authors used already existing transit stops that were gathered with OpenStreetMap. Zwick et al. assumed the network of stops was already optimized. By also taking electric vehicles into account, Zwick et al. showed that by changing to electric ride-pooling vehicles, it reduced noise by a big margin, almost 5 dBA on average. From the results, it can be seen that overall, the waiting time in the city core was higher in the simulation of door-to-door service than that in the stop-to-stop service simulation. The waiting time in the stop-to-stop simulation was also less than that of most of the places in the door-to-door simulation.

The article *The role of shared autonomous vehicle systems in delivering smart urban mobility: A systematic review of the literature* by Fahimeh Golbabaei, Tan Yigitcanlar and Jonathan Bunker made a literature study to determine if shared autonomous vehicles were worth investing in [20]. The paper concluded that an implementation of
SAVs, shared autonomous vehicles, as they are called in the article, would help in many aspects, including environmentally and economically. Because the SAVs never being stationary, more parking spaces are free. In the literature study, the authors found that traffic congestions became fewer. On the economic aspect, the authors stated that the cost of a trip in an SAV would be much less, not having to pay the wage of a taxi driver.

There is to my knowledge not many studies researching the difference in efficiency between the two different modes of transportation, while also researching the optimal distance between stops. There are as stated above, other research on the efficiency of a system of autonomous vehicles and mobility on demand as in [12], [13], [14]. The article [16] is especially interesting, as it brings up the maximum distance people are prone to walk to get to a stop. The metrics that those articles have taken into account have been noted, and some are also looked at in this paper. The articles [14],[16], [19], [20] bring up the social and ecological perspective of efficiency, instead of the efficiency of the vehicles that this paper is based on. The article [15] created a fleet of vehicles and a road network, which will not be necessary for this type of research as both the vehicle fleet and the road network are pre-made and exist in MATSim. This paper looked at the efficiency metrics of average driven distance per vehicle, and waiting and walking time, rather than other social aspects as those were more difficult to quantify in the method chosen for this article.

The article by Fielbaum et al. [17] states that by using a stop-to-stop service and enabling the customers to walk, the efficiency of the service improved tremendously. A short walking distance helped with lowering the amount of hours travelled with vehicles, and also lowering the rejection rates. Though the paper stated that walking to a stop helps in the efficiency of the system, it also stated that walking is more uncomfortable than waiting in the comfort of a building at your origin.

These articles brought up the benefits and disadvantages of AVs. Social and economic aspects greatly benefited from an implementation of AVs in cities, by helping lowering the noise according to [19], spending less time in traffic and trips costing less. The last point is directly correlated to taxi service as of today, since the reason for the lower trip fares is because there does not need to be a driver to be paid [20]. The study by Viergutz and Schmidt [14] found that door-to-door was more beneficial both according to efficiency and environmentally, when compared to stop-to-stop. The article by Lorig et al. [12] stated that just 17% of the total of Gothenburg’s vehicles would reach a satisfying goal of handling each customer, if converted to shared vehicles.

Though, as stated before, autonomous vehicles cannot be trustworthy as of yet, since traffic accidents have happened, which have in some cases led to death, reported by BBC News [6]. A safety driver has to be able to take control of the vehicle and manoeuvre it. This is a clear disadvantage as the vehicle cannot be driverless, therefore not meeting the lower trip fare [20] as of yet.
3. Method
The research method that is chosen for this article is Operations Research, presented by Jayant Rajgopal [21] (OR) done on MATSim, where observations are taken to determine the most efficient transportation service for RQ2, while also solving the question about the optimal distance for stops for RQ1. Operations research is the method of using technologies to find a solution to a problem.

Another possible research method that was not chosen was experiments, presented in Briony J. Oates article [22], where real people would need to be gathered and real vehicles would also be needed to perform it. That was something that would cost more, both in time and money. A case study could have been a good option, where studying the estimated efficiency of the transport services by letting the people who partook in the case study fill out a survey [22].

A reason why OR was chosen and neither experiments nor case studies, was because of prior knowledge of autonomous mobility on demand simulators and OR existed at Malmö University, that could help in the process of writing the paper.

To examine RQ1, setting up several simulation experiments was needed in which the distance between stops was altered for each run. The language to program in was decided to be Java, since the author of this article have knowledge in the language, and MATSim-MaaS was written in Java. The efficiency metrics that will be measured are the cost of trips for the people using the system such as the waiting and walking time together with the time of travelling, and the average driven distance per vehicle.

RQ2's question needed a comparison between the door-to-door service, where vehicles pick up agents at their origin, and the stop-to-stop service which was examined in RQ1. To answer RQ2 a simulation was run, with the configuration to enable door-to-door service. The result of that simulation was then compared to the result of the most optimal stop-to-stop simulation run.

MATSim-MaaS has some files that are needed to be able to run simulations. One of these is a road network, which contains part of roads, called links that has a number of parameters. These parameters are the length of a link, x- and y-coordinates of the starting and stopping point and the speed of which vehicles can drive on the road. A histogram was made of the links' lengths to measure what ranges of spacing between stops was needed. The histogram in Figure 3.1 shows these ranges and the number of links per range. Based on the histogram, suitable ranges was identified and with each simulation run, the spacing between stops increments 100 metres. The increment stopped at 800 metres to get 8 different results. These results were then studied to determine the best spacing between stops. The acceptable length to a stop from a house is 400 metres, according to Trafikverket [23] and Zhao et al. [16]. This is hugely correlated to the research being made in this paper, as walking distance is covered, which is a big factor when measuring the social efficiency of the stop-to-stop service. The upper limit was therefore set to 800 metres between stops, since then there are only 400 metres at most to the nearest stop if the traveller is located in the middle between them.
Figure 3.1: A histogram was made to better show the links lengths in the scenario. It can be seen through this that most of the links have a length between 0-699 metres. There are only 62 links with a greater length than 899 metres.

The area of research that was chosen was Mielec. Mielec is a small city in southeastern Poland. The MATSim-MaaS [11] had already a configuration of the road network and agent plans for Mielec that was used in this study. Why a specific scenario was not created was because of the place of study was not crucial, but the distribution of stops was. In the Mielec configuration, a scenario of plans for each agent's activities existed, along with a vehicle fleet consisting of 10 vehicles. The scenario consisted of 388 agents travelling in the simulation.

Since the study was made in a smaller town, the results that are to be found are only validated to be applicable to a town of similar size. If the services are wanted to be in a bigger town, there may need to be adjustments because of the change in town size that do not fit the service found out to be the optimal in this paper.

The framework of operations research consists of:
1) Orientation
2) Problem definition
3) Data collection
4) Model Formulation
While all parts of the framework can be used to get a result, mostly just the fourth, fifth and sixth points are emphasised in academics, but for ease of the reader, all points are addressed below [21].

1) Orientation: The orientation is that the problem shall be solved with technical knowledge where a solution shall be programmed in Java.
2) Problem definition: The problem is that no research exists of comparing door-to-door and stop-to-stop services with the goal being to examine and find a result on which is the most optimal out of the standpoint of operational efficiency. Along with this problem, there also exists no tool to distribute stops at a certain interval, which is why to solve the problem, such a tool would have to be created.
3) Data collection: The data collected is the scenario, a toy scenario, that is open to anyone to download and use with MATSim-MaaS.
4) Model formulation: To be able to gather data and reach a result to analyse, the simulator MATSim-MaaS was of help.
5) Model solution: The model solution is the data collected. All of these files are explained in detail in section 4.
6) Validation and Output Analysis: The scenario’s outputs files will be evaluated and the results will be analysed.
7) Implementation and monitoring: The solution proposed in this paper will not be applicable to an implementation as that would require real vehicles and people.
4. Technical Background

This part acts as a summary of the technical background, bridging the gap of uncertainty between the results and MATSim-MaaS.

From an agent’s perspective, a travelling person’s perspective, the simulation looks like this: The traveller has a plan to go somewhere. It announces that plan to the system, and requests a ride to the destination. The waiting starts when the ride is requested and ends when the agent is picked up by the vehicle. The simulation places the vehicle in a queue of a route that is the most optimal to go and then picks up the agent.

The simulation can take in XML-files as input parameters. They are described more in depth later in the section.

- The necessary data for the experiment being done in this paper, are a road network file, a stop file, and a file containing the agents’ schedules. The stop file contained a coordinate to each stop that exists. A file with the specification of the vehicles was also necessary.

- To know which files the simulator use, it needs a settings file. In the settings file, all of the other files are written out as parameters.

- If the simulator shall run a scenario with stops along the links, the simulator requires a file containing the location of the stops, and a parameter explaining where to find the stop file. This parameter need to be in the settings file.

The road network file consisted of nodes and links. Links are roads, containing information on speed limit, length, and the number of lanes on the road. Nodes are the pieces connecting the links together. Each node have an x- and a y-coordinate. Each link has two connecting nodes, from and to the link. Figure 4.1 shows a map of the town Mielec, fetched through OpenStreetMap. There were in total 388 agents that travelled, with 10 vehicles serving their requests.
Figure 4.1: A map of Mielec showing the roads. The road network is dense in the city centre and then become more sparse as the roads go out from the centre.

The simulator had a configuration file. This configuration file contained settings concerning which mode of transport the simulation should run with, the maximum waiting time and others such as the fare for the ride. There were also settings on rebalancing strategies, but the only setting that were changed was mode of transport, and making sure the same vehicle fleet was used for both door-to-door and stop-to-stop.

The agents file contains the link that they go from and to in a day. It also contains the time when the trip will be completed. No agent travels more than once. The stop file contained a stop id, and x- and y-coordinates, along with which link it is connected to. Each stop facility contains a boolean value if it is blocking the road, but that is set to false for simplicity. Figure 4.2 shows how an agent’s plan look like in the file.
Figure 4.2: A code example of an agent’s plan going from road link 123 to road link 373. It completes an activity at 06:53:13 and then requests a ride from a vehicle.

To create the stop file, the tool was created and it used many methods for distributing stops in the stops file that MATSim-MaaS [11] needs. The method createTransits() in the created program file take input parameters of the spacing of the stops, the network file, and the file where the stops shall be outputted.

Each agent has one trip in the simulation. An activity before hand has an end time and then a vehicle and ride is being requested. The agent walks to the nearest stop or waits at the origin point, depending on the type of service. If a vehicle is available, the vehicle drives to the agent and picks them up [24]. In the stop-to-stop service, if a passenger is riding a vehicle, the vehicle has a planned route to get to the destination. If other passengers request a ride on the same or nearly the same route as the passenger already riding the vehicle, the vehicle can pick the other passengers up. Otherwise a different vehicle will pick them up [24].

Below follows a list of the libraries that were used in the creation process of the program, and what their use cases are:

- NetworkUtils: The NetworkUtils library helped get the links from the network file to an ArrayList that could be traversed, with the method readNetwork(). Another crucial use case was the getNearestLink() which took in the network file and x- and y-coordinates as the parameters, so that it could map the coordinates given to the nearest link and thus place a stop there. This was done on a grid on both the x- and y-coordinates.

- CoordUtils: The CoordUtils library was helpful to calculate the Euclidean distance between stops, to measure the approximate length between them, and to make sure the spacing of the stops was true to the algorithm. This function was also used to find out if the coordinate reference system had coordinates corresponding to metres.
• NetworkSummary: NetworkSummary was useful to get the minimum coordinate of the network so that the grid system went from the smallest coordinate on both x and y, to the biggest.

The tool appends a stop to a stop file through a nested for loop. The outer loop is created by looping through the x coordinates, from smallest to biggest, adding the spacing in each new iteration. The inner loop does the same with the y coordinates. In the nested loop, a coordinate of a stop is extracted, while also checking the list if that coordinate as a stop already exists. If it does not, it is inserted into the transits XML file.
5. Results

5.1 RQ1

This section presents the results, which are gathered in Table 5.1.1. Below the table follows three graphs over the data presented in the table. The graphs were made to easier plot trends in the data.

Overall, the amount of time spent travelling, stayed on average the same, differentiating only a maximum of 2 hours. The time spent travelling in hours lied between 38-40 hours, and did not increase or decrease in the number of metres between stops, but instead fluctuated up and down and can therefore be said to not correlate to the different distance between stops.

By looking at the results presented in the Table 5.1.1 and the three Figures 5.1.2, 5.1.3 and 5.1.4, it can be stated that the optimal distance between stops is 300 metres, since the performance of waiting time was the best. It also had good average driven distance per vehicle and a low amount of time spent walking. The only one that had better average driven distance was the distance between stops 600 and 800 metres. 300 metres was chosen as the most optimal, since the 600 and 800 metres simulation runs had much higher walking times, which decreased the social efficiency by a big margin.

The table’s columns consists of data points that MATSim-MaaS outputted. These are:

- Average wait time per ride (s) – This is the average wait time per ride.
- Average travelling time per ride (s) – This is the average travelling time per ride.
- Average driven distance per vehicle (m) – This data point is the average driven distance per vehicle. A lower number is better since that means the vehicle is driving less to do the same amount of work.
- Total wait time (h) – The total amount of time waiting by all agents combined per simulation.
- Total walking time (h) – The total amount of time spent walking by all agents combined to and from stop points per simulation.
- Total travelling time (h) – The amount of time spent travelling by all agents combined in the vehicles per simulation.
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<th>Average travelling time per ride (s)</th>
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</table>

Table 5.1.1: Results of the different simulation runs based on the distances between stops.

Figure 5.1.2: Results of the walking time, waiting time and travelling time. On the x-axis is the simulation runs’ stop spacing or distance between stops.

From Figure 5.1.2 it can be seen that by extending the distance between stops, the only thing that changes by a big margin is the walking time. The waiting and
travelling time stays roughly the same. The travelling time differed ± 2 hours in between the spacing between stops and the waiting time ± 4 hours.

![Figure 5.1.3: Results portraying the average waiting time and travelling time against the different stop spacing on simulation runs.](image)

From Figure 5.1.3 it can be seen that the average waiting time per ride does depend on the distance between stops, It can though be stated that it is by a smaller margin. Since the average travelling time per ride does not differ more than 13 seconds from the lowest to highest, this metric will be disregarded in the analysis.
Figure 5.1.4: The average distance driven per vehicle plotted against the different stop spacing.

Figure 5.1.4 shows that by changing the distance between stops, the average driven distance per vehicle changes with it. As with Figure 5.1.3, it is not known why the distance per vehicle ascends on 700 metres stop spacing. The amount of metres driven per distance differs only a small amount when the distance between stops are changed.
5.2 RQ2

To find an answer to the second research question, the two services explained in this paper, stop-to-stop and door-to-door service, were compared to see which fared the best out of a perspective of operational efficiency.

The door-to-door service simulation had the same scenario as the stop-to-stop based simulations run above, with the difference being that it could not use stops to pick up and drop customers off. Because the scenario was the same, the data for 300 metres between stops could be reused. The results can be seen in Table 5.2.1.

<table>
<thead>
<tr>
<th>Type of service</th>
<th>Average waiting per ride time (s)</th>
<th>Average travelling time per ride (s)</th>
<th>Average driven distance per vehicle (m)</th>
<th>Total wait time (h)</th>
<th>Total walking time(h)</th>
<th>Total travelling time(h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door-to-door</td>
<td>280</td>
<td>386</td>
<td>211286</td>
<td>29</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Stop-to-stop</td>
<td>250</td>
<td>388</td>
<td>197084</td>
<td>26</td>
<td>78</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 5.2.1: The results comparing door-to-door service to stop-to-stop service. The distance between the stops in the test is 300 m.

As can be seen from table 5.2.1, the improvements for waiting time and the average driven distance per vehicle comes with the cost of making the users walk to the stops. The time spent walking can be seen as a decrease in the service quality, but that is not something that was looked into deeper in this thesis.

Since the average travelling time per ride does not differ more than 2 seconds from between the services, this metric will be disregarded in the analysis.
6. Discussion

6.1 Analysis

In this section, the results are discussed in detail. As the data outputted by the simulations are many, a decision was taken on what to prioritise. The focus of this paper has been to firstly, compare the two service door-to-door and stop-to-stop to see which one fared the best, while also delivering a tool to estimate the optimal distance between stops. The tool was created using Java, and the output was used in MATSim-MaaS, an on-demand mobility simulator. A thought was that by creating this tool using Java, it can easily be reused with a similar simulator, by just changing the distance parameter in the file.

This thought was applied in the creation process, and the developed tool can be reused by others in different projects and with different road networks. These road networks do not have to be a smaller road network like the one used in this paper. Instead it should in theory work on cities of a greater size as well. It shall be mentioned though, that the output file of the tool is tailored towards MATSim-MaaS and has not been looked into how it would work in other simulators.

According to [13], [17], [19], using a stop-to-stop service would increase the operational efficiency of the system. While [13], [17] showed that having many detours in the system, decreases the efficiency of the vehicle, [19] brought up the lower amount of waiting time in stop-to-stop service compared to door-to-door service. These points of data can also be seen in section 5.1 as it shows that by walking a short distance, and by that minimising detours of vehicles, the metres driven per vehicle decreased, showing a greater operational efficiency but also that the stop-to-stop has lower waiting time. Both Zhao et al. [16] and Trafikverket [23] showed that people were not prone to walk any more than 400 metres, something that can also be examined in the results above, as the operational efficiency does take a toll because of the amount of hours spent walking.

The article by Harmann et al. [18] brings up during their discussion that the experiments showed an increase in efficiency of ride-pooling with virtual stops, compared to door-to-door service. The increase in efficiency is something that can also be seen in the simulations’ result in section 5. Door-to-door had an average driven distance per vehicle of 211286 m while stop-to-stop’s amount was 197084 m. The difference between those were 14200 m. While the average driven distance per vehicle differed in the favour of stop-to-stop service, there was no walking time for door-to-door as the vehicle drove to the user’s origin point. As can be seen in table 5.2.1, the waiting time differentiate 3 hours between the services, which decreases the social efficiency of door-to-door service. Since this paper’s focus has been to answer the question of the operational efficiency, it is deducted that stop-to-stop service with a distance per stop of 300 metres is favourable to the alternative door-to-door service.
6.2 Factors found

As brought up in section 2, the study by Viergutz and Schmidt. [14], showed the reverse of the description above. This may be the result of a few factors that can be interesting to the reader. What Viergutz and Schmidt found in the article was that by using door-to-door service the result had a lower number of vehicle kilometres.

The simulations showed a big difference in walking time, but a very small or no difference in waiting and travelling time. This occurrence may be because the simulations were running on a small scenario. The links’ lengths were not large, nor was the number of vehicles or agents either. If the simulations were run on a bigger scenario, it could be tested to verify if the demand issue, in terms of a small scenario, is a faulting factor.

MATSim-MaaS limited the possibility of placing stops at precise locations. With a method in the Java library NetworksUtils, presented above, it was possible to get a link’s starting coordinates. Although this method helped, it placed a stop at the beginning of each link. This meant that on a longer link than the stop spacing was found, only one stop point would be distributed, meaning lesser stop points was placed than was desired. This raises the question about verification of how correct stop distribution is in this implementation.

Taking into account the method presented above, it is no wonder why 300 meter as a distance between stops was the most favourable. In the histogram Figure 4.1, it can be seen that the majority of the links’ distances lies between 300-399 metres. This span is approximately 25% of all links. A thought is that by developing the tool further, so that it does not only place stops on links that are greater than 300 metres, a better result for the most optimal stop spacing may be found.

Since this paper focuses on operational efficiency, the social, economical and ecological aspects have been neglected. It should be said that even though the stated mode of transport as stop-to-stop service is better out of an efficiency standpoint, the trade-offs may be huge on other aspects. A can be seen in Table 5.2.1, the walking time for door-to-door was 0 hours, which, out of a social perspective, is great, since people prefer to wait at origin point, without having to walk to a stop, as was stated by Fielbaum et al. [17].

6.3 Future Works

As was described in subsection 6.1, there were issues and factors that were not accounted for in this paper. These issues may be interesting to research further, especially the demand issue with such a small scenario, along with running a better tool for distributing stops on the road network so that it will place the stop approximately at more precise locations.
7. Conclusion

The purpose with this study was to find the optimal distance between stops, and compare stop-to-stop service to another service called door-to-door. This was done to see which performed best in the given scenario and with the help of MATSim-MaaS.

In conclusion the problem of finding the optimal distance between stops was solved with an approach of creating a tool to solve the issue. The question was answered with the scientific method Operations Research. By looking at the results in section 5, it can be seen that results were found to answer the research questions.

An answer to RQ1 is given since the results showed that 300 metres is the optimal distance to have between stops, because of the lower number of metres driven by the average shared vehicle. In the simulation the number of hours spent walking to the nearest stop was also quite low. The operational efficiency is the main focus of this article. As can be seen in the discussion, people are not prone to walk more than 400 metres, which is why 800 metres is disregarded and excluded as a fitting result, even though that simulation had less driven kilometres than the 300 metres stop spacing. Instead, 300 metres as a stop spacing is found to be the optimal solution to RQ1.

The answer to RQ2 is given by the table above, which with the help of the discussion can be interpreted to state that the stop-to-stop service is favourable when being compared to the door-to-door service. The stop-to-stop service simulation was ran with the most optimal distance between stops as was declared before to be 300 metres.
9. Reference list


