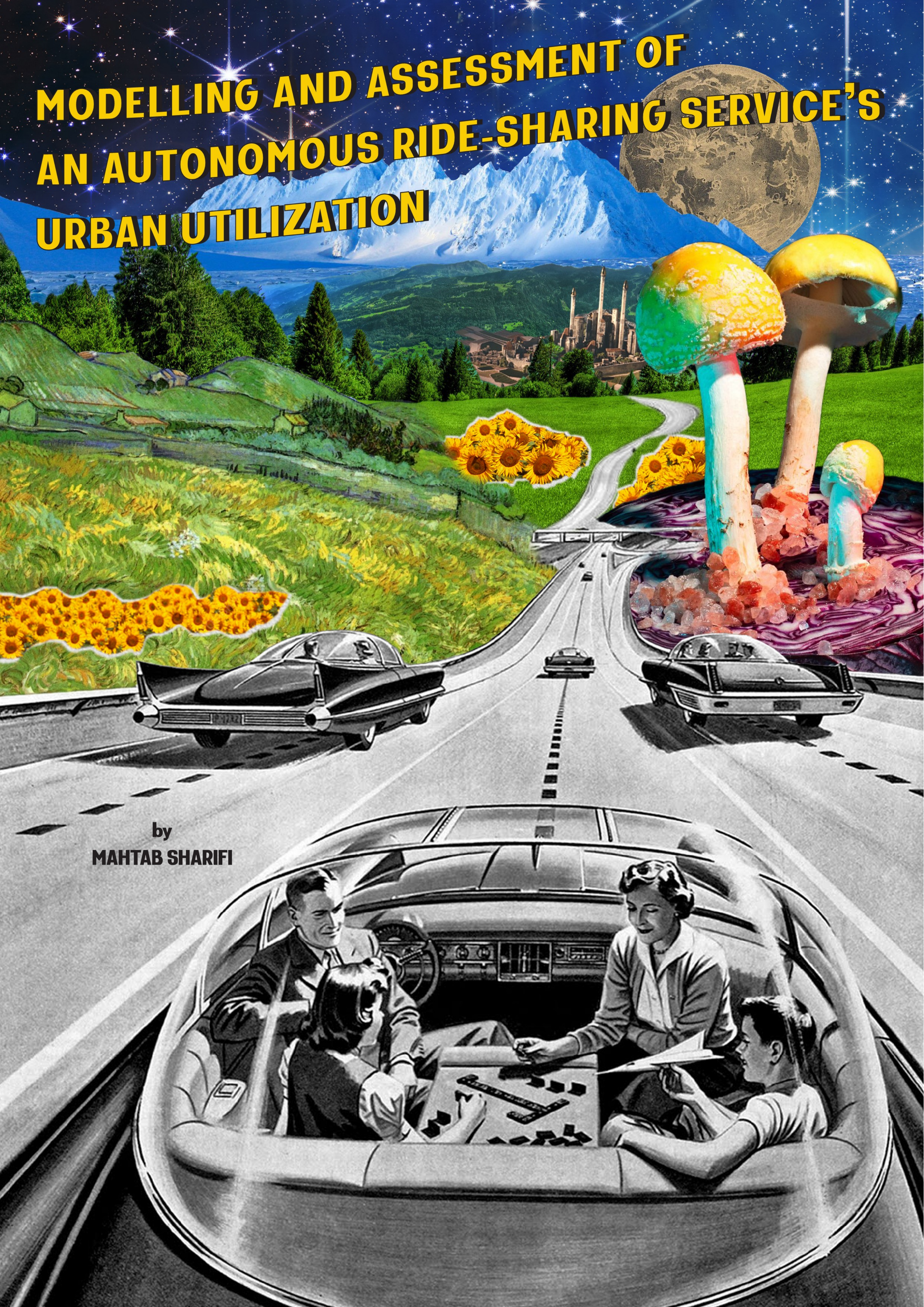
MODELLING AND ASSESSMENT OF AN AUTONOMOUS RIDE-SHARING SERVICE'S URBAN UTILIZATION



by

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MODELLING AND ASSESSMENT OF AN AUTONOMOUS RIDE-SHARING SERVICE'S URBAN UTILIZATION

CASE STUDY - ROTTERDAM

THESIS
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Master of science
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PREFACE

I, Mahtab Sharifi, hereby declare that the thesis presented in this document is solely and entirely my work and where other sources or information have been used it is explicitly indicated in the body of the text and bibliography. I also confirm that this research does not contain outcome of work performed in collaboration with or by others except when summarised in the Statement of Contributions.

This thesis, designing and testing an assessment methodology for an AV ride-sharing service's impact on CO_2 emission, was carried out within the Infrastructure and Environmental Governance specialisation track and at the department of Engineering Systems and Services of Delft University of Technology, under the supervision of Dr Annema, Dr van Daalen, and doctoral student Ms Führer.

Before or at the time of the submission of this document, no other substantially similar work has been submitted or concurrently carried out as part of a degree at TU Delft or any other institution of note except as specified in the text and references. This dissertation, including footnotes, tables, and figures but excluding bibliography, appendices, and supporting code, does not exceed 30,000 words.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to my supervising committee, Dr Annema, Dr van Daalen, and Ms Führer, whose patience and kindness was undoubtedly a great source of support. Their sharp advice, pointed critique, and expertise kept me focused on the core of my research and guided me towards the concrete outcome now laid on these pages. They were consistently within an arm's reach for consultation and provided their assistance with continuous encouragement that made the completion of this project possible.

Although the life of a graduate student, especially during the thesis phase and the inauspicious presence of global crises of various kinds, is often a solitary one, it is by no means accomplished only by the efforts of one person. I was held deeply in the warm and loving embrace of my parents, my sister, my aunt, my partner, and my wonderful friends. They held me as I fought, struggled, cried, doubted, cried, slowly chipped away at what seemed like an impossible mountain centimetre by centimetre, and cried some more. They were there from the start, and I cannot express enough how marvellous and beautiful it is that they are here with me at the end of this journey at last. I am grateful to them always and hope they understand how precious they are to me. To love and be loved by them is a delightful privilege.

"To be truly visionary we have to root our imagination in our concrete reality while simultaneously imagining possibilities beyond that reality"

– Bell Hooks.

ABSTRACT

Increasing demand for passenger services in densely populated urban environments, are currently covered overwhelmingly by private vehicles. Their impact on CO_2 emission, present a serious obstacle to the reduction objectives, in the Netherlands alone the target of 45% by 2030, for limiting the global warming to 1.5°C degrees. Autonomous Vehicles (AV) and Ride-Sharing services are believed to be offering a crucial technological and perception shifts to reducing emission. In this work, a methodology for assessing the impact of a large-scale AV fleet ride-sharing system to replace the one-two passenger vehicle traffic using Rotterdam as the case study is designed and proposed.

The approach includes three stages: 1. Building and finetuning a traffic model using publicly available data 2. Designing and implementing a trip merging component, in the form of two distinct heuristic greedy algorithms and a variation of the second one, using Python programming language. 3. Evaluating the impact of each merging scenario on the network in SUMO.

The system's influence and results are driven from the deployment of the ride-sharing service on the 2016 traffic model. The decrease in total number of trips, vehicle kilometres travels, and subsequent improvements in traffic flow resulted in 39% reduction in CO_2 emission with the third algorithm. This result not only establishes the extent of AV ride-sharing service's potential for emission reduction and traffic quality improvement. This adaptable methodology also operates as a proof of concept for a preliminary step for policy makers when considering implementing such service in any urban setting. Two of the major elements not included in this research are multimodal travel, like combination with public transport, and changes in demand for each mode choice based on traveller's behaviour. These elements thus remain open for future consideration.

SUMMARY

Introduction

Although the growth rate of greenhouse gas emissions has lowered between 2010-2019, globally institutions continue to warn against the rising levels of these gases as a direct result of human activities across all major sectors with an ever-increasing portion of that share belonging to urban areas. Amongst greenhouse gases, CO_2 takes significantly longer, centuries, to leave the atmosphere while this lifetime is around 15 years for the other types. This makes a compelling case for focusing efforts in decreasing the production of this gas. (IPCC, 2022; UNFCCC. Conference of the Parties, 2015)

In the Netherlands, the delta city of Rotterdam is in a double bind. It is both a vulnerable target for climate change related calamities like flooding and counting its port activity, one of the biggest contributors of CO_2 emission with 20% share of national total production. So, the city of Rotterdam presents itself as an interesting choice for investigating climate change mitigating policy measures in the mobility sector and is the study case for proof of concept in this research. (Rotterdam Climate Alliance, 2020)

In private driven transportation, there are a variety of technologically innovative areas of exploration, two of the most prominent of these technologies in academic and transport research are autonomous vehicles (AV) and ride-sharing transit models. So, an on-demand ride-sharing service using AV could be a green MaaS solution to replace the one-two passenger private owned vehicle fleet. (Greenblatt & Shaheen, 2015)

The core of this proposal hinges on being able to merge the trips currently being completed using private vehicles, into new shared ones, subsequently decreasing the total number of vehicles on the road and improving traffic. This research attempts to answer that very question by designing, developing, and implementing a methodical

empirical approach for building an AV ride-sharing service and assessing its impact on reduction of CO_2 emissions, using the City of Rotterdam as the case study. Thus, the research question is *"How private vehicle trips in an urban area could be merged within a ride-sharing autonomous vehicle service and what would be the service's impact on the CO_2 emission?"*

Proposed On-demand AV Ride-Sharing Service

In the conceptualised system, a user files a request for a ride typically through an online platform, website and/or smartphone application, in-advance of their desired departure time. The requests, demand, from users are fed to the merging component of the response system, developed by the author for this thesis, and if a shared trip is possible between two passengers, as in their scheduled trips overlap fully or in some parts, an AV unit will be assigned to the trip. It would pick up the passengers at their predetermined origin, access point, within an acceptable window of their specified departure time. So, in the current taxi service market, it is closes to Uber-pool in the way it's intended to operate.

The demand pool targeted for this work is users with known schedules registering requests to the service with enough time in advance for the merging component to match them with another. These users make up the bulk of peak hour traffic volume, those in their morning and evening commute to/from work. In this work the focus is on reducing such single-occupant trips by private vehicles, so that through reducing vehicle kilometres travelled (VKT) and traffic, the CO_2 emission might drop significantly as well.

Developed Methodology

To assess the impact of an AV ride-sharing service on an urban environment, this work has built a traffic model and simulated the service adoption scenarios using that model on Simulation of Urban Mobility software package or SUMO. The model was developed for a private vehicle traffic flow of trips throughout the day, acting as potential demand that could be merged into shared trips with the proposed service. Making up the network in a "before service deployment state" or "baseline model", modelled after Rotterdam traffic data in 2016. This demand was then filtered through the merging component of the ride-sharing service, where the trips with potential "gain" where paired using three different algorithms. The difference in terms of system performance, the VKT, total and average time lost when using shared-ride as opposed to own vehicle, and CO_2 emission levels are used as comparative evaluation variables for the three scenarios.

Trip Merging Scenarios

The central differencing element of the service, and the core contribution of this research, is the different approaches to finding the best pairings and merging them into shared trips. This assignment comes with a potential loss for the passengers since they might experience a longer trip in comparison to their original intended departure time due to detours and added access/egress times for the joining passengers. Three different heuristic merging greedy algorithms are written making up the three ride-sharing service implementation scenarios:

> **Baseline Model:** Rotterdam's road network and private vehicle traffic in an average day in 2016, "as is" state.
> **Scenario 1**: Algorithm 1, sorting the trips based on the departure time and selecting the best pairing candidate with highest overlap gain (first come, first served)
> **Scenario 2**: Algorithm 2, sorting the trips based on trips length so longest trips are paired first with their best match with best gain
> **Scenario 3**: Algorithm 2 without blocking, same approach to matching trips but the shared trips are broken down to their three legs to simulate the available space for access/egress without interfering with ongoing traffic during the scheduled intermediate stops

All three of the ride-sharing scenarios are implemented on the network and their simulation output compared with the baseline benchmark.

Results and Conclusion

When studying the scenario's outcome against the baseline, the first variable to compare is the total lost time metric:

Total Time Lost = SUMO output waitingTime + timeLoss

Based on total time lost, algorithm 2 is performing best, with its highest total lost time at average of 4 minutes per trip.

Moving to the main interest which is the ride-sharing service's impact on CO_2 emissions, the algorithm 2 without blocking steals the crown with a notable 39% of reduction from the baseline levels. The second and first algorithms stand in 32% and 28% respectively. This reduction in emission production is the aggregate result of fewer vehicles on the road, less VKT compared to baseline total, and faster smoother flow of traffic. Algorithm 1 reduced VKT from baseline by 21.3% and algorithm 2 by 24.9%.

In conclusion, the methodology developed as a policy-making tool, could contribute towards assessment of the vision for an AV technology-based ride-sharing service on the CO_2 emission levels of an urban area. Three merging component blueprints were designed and simulated to assess what kind of approach would yield the most reduction while maintaining service quality. This method offers a series of customisable problem-solving tactics for lack of observed count data for private vehicle behaviour, network construction, synthetic traffic flow production, and finally a time saving near optimal merging component for the ride-sharing system.

The result of this process not only confirms the potential of such a service in bringing a network in alignment with its goals for climate change mitigation, but the operationalised methodology could act as a preliminary tool for transport authorities and a jumping board for further research. The next step is to incorporate this type of service with the current PT services and study the modal shift from and to public transport if AV ride-sharing were to be used as the solution to access PT hubs.

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ABBREVIATIONS

GHG: Greenhouse Gas

AV: Autonomous Vehicles

MaaS: Mobility as a Service

TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution

VKT: Vehicle-Kilometre Travelled

OD: Origin-Destination

NDC: Nationally Determined Contributions

IPCC: Intergovernmental Panel on Climate Change

SAE: Society of Automotive Engineers

FSD: Full Self-Driving

ISO: International Organization for Standardization

PT: Public Transport

1 INTRODUCTION

The Paris Agreement objectives declared a clear need for withholding the increase in global mean temperature well below 2°C with regards to the pre-industrial levels and to limit the warming to 1.5°C (UNFCCC. Conference of the Parties, 2015). However, in nearly all countries, including the Netherlands, emission levels projected for 2030 do not meet national mitigation pledges submitted under this agreement as part of the Nationally Determined Contributions[1]. According to the Netherlands' Environmental Agency report this country would not be able to accomplish its portion of the Paris targets, essentially to be at or near carbon neutral by 2050, through its current policies (van Vuuren et al., 2017).

The latest report by the Intergovernmental Panel on Climate Change[2] paints an even more urgent picture of our climate future. According to this newly published document, although the growth rate has somewhat slowed but we reached the highest recorded levels of average annual greenhouse gas emissions in human history from 2010 to 2019. The IPCC agency once again calls for brisk climate action across all sectors to limit warming to 1.5°C and suggests to cut emissions in every sector by 43% before 2030 or miss the very small window of opportunity for returning to pre-industrial temperature levels by the end of the century (IPCC, 2022). We are locked in a now or never scenario.

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[1] NDCs

[2] IPCC

"We are at a crossroads. The decisions we make now can secure a liveable future. We have the tools and know-how required to limit warming," — by Hoesung Lee, IPCC chair, April 2022.

The introduction of the national Climate Law in the Netherlands by the coalition of parties in 2019, was a potentially crucial step to attempt to reach the self-imposed national reduction target of 49% by 2030[3]. The ambitious targets set up by the Climate Law require long-term planning in different sectors. Amongst these different sectors, transport accounts for a quarter of the Dutch CO_2 emission. So, apart from the crucial task of searching for alternative sustainable fuel sources, for example electricity[4], other aspects of mobility too must be aligned with emission conscious solutions. Of these aspects, the push towards increased use of public transport and the bicycle is a staple of national attitudes towards sustainable solutions, whereas CO_2 reduction through shared mobility for transporting passengers is still a less explored but promising avenue. These shared services have the potential to reduce daily vehicular traffic's impact on the environment. (EZK, 2019a)

Urban areas with their ever-growing concentration of car traffic, could be prime choices for efforts to reduce CO_2 emission. Efforts realised by way of seeking alternatives to enhance the passenger mobility services, combine traveller's modal choices, and incorporate technological innovations. One of the hot-topic strategies is ride-sharing[5] or merging separate travellers with identical or spatially similar origins and/or destinations into shared trips (Chan & Shaheen, 2012).

Since a privately owned vehicle is typically used only 50 to 60 minutes per day all the while occupying valuable urban real state, 15% to 30% in extreme cases of land-use, looking to utilise this dead time is another element that could be explored to optimise motor vehicle fleet (Igliński & Babiak, 2017). Autonomous Vehicles[6] and automated driving are amongst the technological possibilities that could drastically

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[3] The Netherlands supports a target of 55% reduction of emissions in Europe by 2030

[4] It is of note that in this example the source of said electricity should also be included in any net emission calculations, otherwise the issue is simply shifted to another part of the system.

[5] This use of this term here should not be conflated with sharing the same vehicle amongst multiple travellers for short time use in separate trips

[6] AV

change the current mobility services (Scheltes, 2015), infrastructure, and have a significant impact on the climate and the environment (Milakis, Arem, & Wee, 2017). One of the potential changes that AV could bring is reducing the number of traditional vehicles by an estimated factor of 11, which could also result in smoother traffic flow, higher freeway capacity, and lower the demand for parking space (Fagnant & Kockelman, 2014).

So, offering a ride-sharing service using autonomous vehicles could potentially reduce the number of private vehicles, lower congestion levels result in a substantial decrease in the CO_2 emission. It is presently unclear how much of the trip demands from private car owners could be combined into common trips and what would be the extent of this potential change specifically on the CO2 reduction.

1.1 PROBLEM DEFINITION

The research on the implementation of AV has largely been limited to technological development of partial and highly automated driving in both software and hardware, close-distance manoeuvres, crash reduction, fuel efficiency, and human factor (Gandia et al., 2019).

Efforts have also been directed towards the environmental, social, and financial implications of AV along with few comparative studies into the potential positive and negative impacts of major implementation scenarios, citing travel behaviour, possible increase in car trip demand due to reduction of travel and parking costs, and improved accessibility as some of the major points of debate over the benefits of AVs (Milakis et al., 2017; Ross & Guhathakurta, 2017). These uncertainties and knowledge gaps warrant continued research to discover the extent of this technology's efficacy, especially the long-term net effect of AV on CO_2 emission.

On the ride-sharing front, while privately owned services such as Uber Pool and Lyft Line, have been relatively successful in their business models, they often take passengers on considerable detours which results in longer trip durations, aka increased travel time for the passenger which not only lessens the attractiveness of such a service in comparison to owning a private vehicle but could perhaps negate the positive impacts on CO_2 emission by maintaining the same amount of kilometres travels and subsequent fuel consumption (Daganzo, Ouyang, & Yang, 2020).

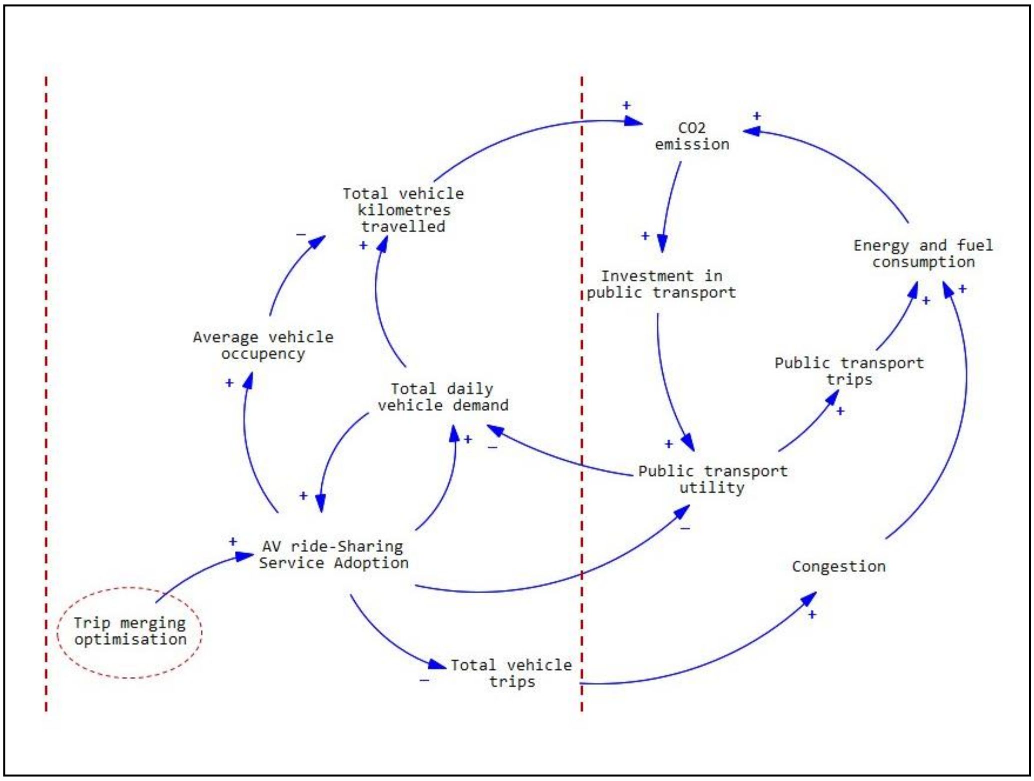

Figure 1. 1. Causality diagram of transit associated emission

The Figure 1. 1 showcases a conceptual outline of the major causal relationships between transit, public and private vehicular, and CO_2 emission in an urban traffic system. As marked by the dash lines, the goal here is to explore the impact of ride-sharing autonomous vehicle service in reducing fleet size, improving congestion, and the subsequent effect on CO_2 emission by simulating said service on a case study city, in this instance Rotterdam, and analysing the output performance characteristics. The focus is specifically directed to the trip merging component of the proposed service. The potential interaction with other modes, specifically public transport in terms of traveller's interest in switching modes, potential competition syphoning of those who are currently using PT to the ride-sharing service, and the influence on daily car demand is left out of this work's scope. The next section delves deeper into what remains wanting in the present research collection which has become the focus of this work's contribution.

1.2 RESEARCH GAP

Urban transportation networks today go toe to toe with the increasingly more demanding challenges stemming from population growth, densely inhabited urban environments, and public transport services inability to keep up with the accelerating demand which also affects the quality of the service offered by these modes which subsequently drives travellers toward private car dependency (Bulkeley, 2010; Currie, 2018).

With the introduction of new alternatives, like car-sharing and ride-sharing gaining rapid momentum, and new technologies such as AV or electric vehicles opening an avenue to more flexible and greener solutions, the transportation landscape is subject to fundamental changes. These changes represent a great challenge for urban and transportation planning, and as such have become an attractive field of study. Calderóna and Miller in their comprehensive study of the modelling of emerging mobility paradigms (Calderón & Miller, 2020) suggest that these services differ from their more conventional transport modelling counterparts, in that the frameworks established for their examination lack consensus and tend to be inconsistent in their use of terminology. They also argue for separation between the mobility service and its user/consumer interaction "MaaS" framework since the mobility service itself can operate independently from it (Hancock, Nourbakhsh, & Stewart, 2019).

The majority of literature focuses on AV, forgoing the human driver element as an agent notably except for Nahmias Biran, Oke, Kumar, Lima Azevedo, & Ben-Akiva who have included and modelled driver's behaviour. Since this work attempts to test the validity of adding a ride-sharing component for reducing CO_2, and considers the

AVs availability as a given, the driver behaviour is not relevant or represented in simulations. Another issue is that most of the research limits the approximation to real-life conditions by way of isolating different mobility services and therefore casting doubt on the soundness of the predicted environmental benefits. The goal of this research is to determine suitable trip merging algorithms, evaluate their impact on the network, and select which one should be be pursued for further exploration in the next stages of the service deployment. Thus, by breaking down the systems complexities to phases that can be more easily tackled while remaining flexible enough that more agents and constraints could be added to the model in later stages, the issue of separation from real-world conditions is hopefully systemically bypassed.

In this approach, the inclusion of competition or cooperation with existing transport services, and the human incentives at play are not ignored but temporarily set aside in favour of finetuning the initial new service proposal before injecting more nuance to the system. In a time-sensitive assessment of a new proposal such as this, it seems critical to first determine what it means for the service to perform “well” as opposed to pursuing its impact on the other parts of the network while it is operating sub optimally. Furthermore, the methodology proposed here is not localised, but adjustable to the characteristics of the choice study area.

Examining how many trips could practically be combined in a realistic day long demand pattern, and how that would affect the system output variables is a robust choice of a thread to pull on in attempting to understand this tangled yarn.

1.3 RESEARCH QUESTIONS

This work sets out to develop a simulated model of adopting a shared autonomous vehicle as a mode choice response to trips completed by privately owned and operated vehicles. The challenge is to determine which trips during the day within the case study urban area and the constructed demand model, could be combined and then use the generated scenarios to determine and compare the potential effect on CO_2 emission. Taking all these factors into consideration, we arrive at the following main research question:

"HOW PRIVATE VEHICLE TRIPS IN AN URBAN AREA COULD BE MERGED WITHIN A RIDE-SHARING AUTONOMOUS VEHICLE SERVICE AND WHAT WOULD BE THE SERVICE'S IMPACT ON THE CO_2 EMISSION?"

To answer this research question, the following sub questions have been defined:

- What are the characteristics of the selected urban road network?
- What is the baseline daily vehicle demand?
- What criteria are used to determine potential trip merging candidates?
- How can the best merged candidate in terms of "gain" be selected amongst the potential suitable pairs?
- How does combing the trips affects the traffic attributes? Travel time? Total kilometres travelled?
- How do car-sharing scenarios affect the CO2 emission in comparison to the baseline simulation?

1.4 SCOPE

This thesis is concerned with an AV ride-sharing's potential to be utilised as a CO_2 reduction measure in Rotterdam. So, these vehicles are assumed to be one and the same as the privately owned cars representing trips in the model. Therefore, two car trips could be merged into one with the assumption that no passenger would be the driver of the resulting shared trip. Since the passengers themselves are not included as an autonomous entity in the model, the pairing is limited to two cars/trips at once. This way there is no need to track the number of passengers per vehicle or possibly risk having more than five passengers in one shared ride.

Ride-sharing itself is defined as an on-demand service where multiple travellers use the same vehicle for the same or similar trip, it should be noted that since not all origins and destinations are identical, some passengers might reach their destination before others or be picked after.

Following the principles of using modelling as a tool for informed policy-making and governance in cases of high uncertainty, the main idea is to employ this repeatable and adequately reliable analytical method of simulation on similar questions with limited amount of observed data and come to a dependable answer. Thus, the same methodology could be applied to other case studies and incorporate new technologies as they become viable.

1.5 LIMITATIONS

As there is no definitive solution to finding the optimum merged trip combinations, two heuristic main algorithms with varying logics are developed for merging the trips in the model. The focus of this research is on the impact of the ride-sharing on the CO2 emission reduction and whether it could be a viable path for climate change mitigation, therefore while solid effort has been put in optimising the code and select the best merging options, finding optimal choices in a system itself is a complex mathematical question and an ever-evolving discipline. The lack of observable data adds another level of difficulty to this as well.

In simulating the traffic flow for this research there is no variation in driver behaviour included, meaning we are working with homogenous traffic[7] where vehicles follow the lane discipline. This approach is also generally consistent with on-road vehicle behaviour in the Netherlands, where there is not a great deal of different types of vehicular interaction like presence of three-wheelers, or bicycles which generally have separate lanes from passenger car traffic and follow traffic signals. In Rotterdam, the electric trams run on dedicated tracks which utilise the same urban streets as passenger vehicles, but they were not included in this traffic model.

This work is meant to assess, with some confidence, the potential of ride-sharing services using autonomous vehicles for reducing CO_2 emission in transport sector, using a real-world city infrastructure and characteristics for the hypothetical implementation. While the author has attempted to approximate the reality of the current traffic conditions, using limited publicly available data, this work alone cannot support an application of such service, therefore further research and data collection must be performed.

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[7] Or HOM as opposed to Heterogeneous traffic or HET flow type which is used for modeling traffic flow with significant variation in available vehicle types and driver behavior.

1.6 REPORT STRUCTURE

This work consists of seven chapters and corresponding sub chapters. Chapter two is the background, a detailed look at the history and important facets of ride-sharing services, technological prognosis of autonomous vehicles, and climate mitigation approaches involving private passenger cars, followed by the third chapter, methodology. Chapter four delves into the selected case study for the implementation of the proposed service, the city of Rotterdam, and the baseline traffic model constructed using its road network. This chapter also features the characteristics and primary results of the baseline simulations, which is considered the “as is” state.

Chapter five proposes two different algorithms, and a variation on the second, for merging the daily trips and their different approaches to the question of selecting best candidates for pairing. Chapter six compares the output of the simulation scenarios and the baseline, and discusses the implications of important resulting variables, along with a brief look at the financial and political complexities regarding commissioning such a service. Lastly, the conclusions and closing notes are drawn in chapter seven.

2 BACKGROUND

As briefly discussed in the introduction, our cities continue to grow significantly and with them so does the demand for accessible and affordable transit. The pressure for sustainable urbanisation is rising, making the transport sector one of the high priority areas for development. In road transport, private vehicles play a major role in generating emission through various means, such as congestion as well as the regular carbon emissions produced by each vehicle (Çolak, Lima, & González, 2016; Viet, 2019).

Naturally, the elements involved in pursuing more sustainable solutions to this issue are complex and have been subjects of academic fascination for prior decades. In this chapter, the author will summarise some of the leading ideas and supporting literature pertaining to governmental intervention in emission reduction, the city of Rotterdam's[8] climate initiatives and ambitions, ride-sharing and car-sharing services, the rise of autonomous vehicles as potential technological response to traffic flow issues created by human error.

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[8] The case study in this thesis

2.1 GREENHOUSE GASES AND CLIMATE CHANGE

The theory of "greenhouse effect", emerged at the turn of the 20th century. The phrase highlighted that the planet's temperature was subject to change based on the levels of greenhouse gases particularly carbon dioxide. In 1856 Eunice Newton Foote, a painter and dabbling scientist, showed CO_2 capacity for retaining heat through series of experiments with glass tubes containing the gas and air separately which were then exposed to sunlight and their temperatures recorded. Though, she then correctly went on to speculate that if the atmosphere contained more CO_2 it would make the planet warmer, it wasn't until the 1960s that the theory started to be taken seriously (MacCracken, 2004).

The scientific community by and large reached consensus over the observable upward trend in global temperatures by the end of the 1970s and concluded that these warming effects where in fact due to release of greenhouse gas emissions into the atmosphere by human industrial activities (MacCracken, 2004). This oil companies and their beneficiaries response however, was to discredit the empirical evidence and instead fabricate a false image of insufficient scientific understanding and climate change denialism (Moser, 2010).

B. Franta, PhD candidate in history from the Stanford University, details in his article the on-going archival research by him and other scholars to bring fort the sizeable involvement of major coal, oil, and gas companies in derailing and stalling efforts to change our trajectory towards climate catastrophe. A wide cast of characters make appearances as early as 1959, namely Edward Teller[9] during a symposium attracting both scientific and industry heads and other notable instances in 1965 for Frank Ikard the American Petroleum Institute's president speaking at the group's annual gathering, mentioning in no uncertain terms and recorded in the transcripts of

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[9] The Hungarian-American theoretical physicist known for his work on the creation of hydrogen bomb

speeches their knowledge of carbon dioxide's influence on the climate and time sensitivity of the issue (Bonneuil, Choquet, & Franta, 2021; Franta, 2021).

Despite knowing the extent of the problem since the 60s, the oil and gas industry continues to relentlessly pursue profit maximisation. In 2009, after the failure of Copenhagen's Climate Change Conference, Shell openly announced their plan to join the frensy of other oil and gas giants' in extracting from arctic reserves that have recently become accessible due to the rising temperatures melting the icecaps (Buxton & Hayes, 2015; Shell, 2008). Knowing full well that in order for us to be able to retain fifty percent chance of limiting the increase in global temperatures to 1.5 °C by 2050, two-thirds of the current fossil fuel reserves must remain untouched (IEA, 2012; Welsby, Price, Pye, & Ekins, 2021). So, the continuation of climate change denial, as a corporate backed and profit driven mass marketing strategy and impeding necessary mitigative measures only ever benefits fossil-fuelled capitalist interests.

The ecological sphere is not where the reach of oil, gas, and coal end, but extraction, distribution, and consumption of energy is deeply connected to political power. Cara Daggett argues that this reliance has not only historically given rise to authoritarianism both in regions rich with fossil fuel resources and the prospective consumers of the products in developed countries but has created intimate cultural dependencies on fossil fuel. In her work specifically, connecting the very notion of achieving "The American Dream" to that consumption, oriented around amongst other things, owning, and operating private cars. Concluding that an attachment has been formed to fossil fuel as a lifestyle, which seeks to not only ignore but actively deny climate change and the signifiers of green movement in favour of maintaining the socio-political-economic hierarchies (Daggett, 2018).

Then it perhaps follows, that if we are to maintain or create a course towards a liveable future, we should address the attitudes and desires behind the love for oil. Our issues stem from systemic failures and to address them we must turn our eyes to systemic solutions too, including demanding from and becoming part of mitigating initiatives of global and local institutions. Corporate and political power that is used to fuel crisis can also be leveraged to combat climate change and focus on its impacts. Although a global issue, local policies favouring collective solutions like ride-sharing as later proposed in this work, could be a wholly effective avenue in managing climate change. And a closer look at the Dutch climate challenges and mitigation policies so far, reveal quite an untapped well of potential for just that.

2.1.1 The Netherlands

"Elfstedentocht" or the "Eleven Cities Tour" is a well-known and beloved event amongst the ice skating fans and public alike here in the Netherlands. This ice-skating marathon established in January 1909 and spanning eleven cities wide held in Friesland, requires very specific and temperature reliant conditions to take place, namely that the thickness of ice should be at least 15 cm along the entire 200 km long route. For that level of ice density, the temperature should drop down to around -10 °C during the winter months (Koninklijke Vereniging de Friesche Elf Steden, 2022), or more specifically if the mean temperature of the coldest consecutive 15-day period in the winter is lower than −4.2 ºC based on the readings by the Royal Dutch Meteorological Institute stationed in De Bilt, the ice would be thick enough to hold the event[10]. As such the study of the probability of the recurrence of this event is in the context of a changing climate is of national interest. Unfortunately, but predictably, that chance has decreased not only for the Elfstedentocht but any outdoor ice-skating activity due to warming effects on the climate. The probability of favourable weather for 15 cm thick ice has decreased from 20% in the early 1900's to about 8% now, and is projected to drop even lower to 1% or 2% if the global warming surpasses the 1.5 °C by 2050 (Van Oldenborgh, Visser, Brandsma, & de Vries, 2019; Visser, 2005).

The Netherlands has theoretically aligned itself with the Paris Climate Agreement, to limit the global temperature rise to 1.5 °C compared to pre-industrial level, and that increase is directly defined by accumulated CO_2 emission (IPCC, 2014; UNFCCC.

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[10] Apart from the ice density, there are other indicators such as snowfall and wind that could influence the event.

Conference of the Parties, 2015). This means that the Netherlands needs an emission cut of 45% by 2030 in order to remain under the 1.5 °C target, and more than 100% by 2050. However, the reduction trend observed between 1990 to 2015, shows a decline of only 11% for the overall levels of greenhouse gas emissions, while the CO_2 emission rates remaining rather stable with a slight declining trend between 2010 and 2015 (van Vuuren et al., 2017).

That is to say, if the Netherlands is to achieve its national and international climate targets, there needs to be more effective policies in place which also put a specific focus on the reduction of CO_2 emission as the most important culprit. The Climate Act, drawn in 2019, provides a long-term outline of steps necessary to reach the reduction targets by 2030 and 2050 respectively. Included in this vision, is the Integrated Knowledge and Innovation Agenda[11] detailing the required changes in each area. Listed in the mobility sector is the focus on reducing car usage by changing the ways we think about transport of goods and passengers and the implementation of alternative modes of transport (EZK, 2019b).

Amidst the global and national plans for mitigation, there also seems to be a rising trend in locally conceived and enacted policies by municipal governments to reduce emissions. But these developing small scale efforts require further research to determine their impact and effectiveness as a key factor in climate governance (Bulkeley, 2010). In this instance, the city of Rotterdam is a rather intriguing choice for further examination.

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[11] IKIA

2.1.2 Rotterdam, an alluring case study

As the climate trend in the Netherlands points to upcoming higher temperatures in summer, milder winters along with increased rainfall, and more likeliness of extreme conditions, a delta city like Rotterdam seems ever more vulnerable. Situated in the Rhine and Meuse delta, with significant parts of the city below sea level, the rising water levels puts the area in danger of flooding. The changes in climate have already manifested these risks during recorded periods of severe rainfall in the form of flooding along the docks in the older outer-dike sections of the city, streets, and basements (Rotterdam Climate Initiative, 2013). Meanwhile, Rotterdam itself is also a big contributor to greenhouse gas including CO_2 emission. As the Europe's largest port, it also ranks first in terms of port[12] related pollution with 13.7 million tons of CO_2 emitted in 2018, almost twice the amount of the second runner up in the ranking, Antwerp (Transport & Environment campaign group, 2022).

The city's port activities and high industry presence also marks Rotterdam at a greater CO_2 emission rate per capita than the national levels, emphasizing the important role of dense urban areas, specifically those acting as transport hubs, in the overall emission impact (Hoornweg, Sugar, & Gómez, 2011). Rotterdam, including the port, industry and the inner-city area, is responsible for around 20% of the national CO_2 emission (Rotterdam Climate Alliance, 2020). The mobility sector's contributions amount to a quarter of the air pollution and one third of that CO_2 emission share, not to mention the noise and overall negative impact of congestion and dense traffic on quality of life. Within the mobility sector itself cars are responsible for around half of the CO_2 footprint (Rotterdam, 2019).

It is no wonder then, that Rotterdam finds itself in a particularly unique and precarious position in its transition towards ambitions goals of reducing its carbon dioxide emission by half in 2025 compared to 1990 within the Rotterdam municipal borders. Current measures are not enough to reach these targets, so more investment

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[12] This calculation also includes at berth operation emissions for example loading, unloading or refueling in ports.

in effective policy measures in the mobility sector seem to be one of the key factors to align this city with the Paris climate targets and push towards sharper and faster decline in emission levels. Future forms of pollution conscious transportation systems could be built based on not just advances in vehicle/traffic control technologies, but also careful craft of robust urban networks replacing the much-criticised private vehicle fleets (Gemeente Rotterdam, 2020; Rotterdam Climate Initiative, 2013; Rotterdam, 2019). One of the most prominent and cited technological advances in this sphere is the coveted autonomous vehicle.

2.2 AUTONOMOUS VEHICLES

The term "Autonomous Vehicle" itself, can and is at times used to refer to different levels of automation and addressing connected but distinct aspects of mobility systems, both in colloquial mediums and some scientific work. What one routinely thinks of when hearing the term autonomous vehicle is an automated car, capable of navigating traffic without the presence of a human driver. A scenario where the human component has been replaced fully with a system that does not require regular input from a "driver" but can perform the task independently. However, technically there are different levels to the automation and the term "automatic" which is sometimes used as interchangeable does not automatically mean self-driving (Ionita, 2017).

The first large scale public encounter with the idea of AVs dates back to the General Motor's[13] Futurama exhibit at the New York's World's Fair in 1939, offering a vision of cars that would drive themselves. This initial version of the idea was presented as an automated highway that interacted with the vehicles through alternating electric currents to maintain course and distance between vehicles. But even earlier, in 1925, a radio-controlled car was steered through the streets of Manhattan, using radio signals, by an inventor called Francis Houdina. However, this

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[13] GM

demonstration did not create much confidence in the idea since the connection was lost twice and the ride ended with car crashing into another vehicle (M. Markus, J. Gerdes, B. Lenz, 2016; Tomorrow's World Today's, 2021).

The AV concept has since continued to attract investment and efforts from both public and private sector and has moved away from radio or electromagnetic signals and strives to eliminate external guidance entirely. Continued work on the subject and the variety of technological achievements necessitated a standardised reference to readily classify and understand the stage at which each project operates. As such, the Society of Automotive Engineers or SAE (SAE International, 2021) in partnership with the ISO[14], has categorised the automation into six levels starting from Level 0 *"no automation"* to level 5 *"full automation"*. These levels compare engagement of three main components, the human driver, the automation system, and the vehicle system[15], at a given moment during a sustained Dynamic Driving Task[16]. The complete list of levels is as following:

- Level 0: As mentioned the "no driving automation" level meaning it does not have vehicle control or AV features.

- Level 1: Or "Driver Assistance" where some assistance is provided to the driver for control of simple functions such as Adaptive Cruise Control and Parking Assistance. In the first example the driver remains in control of the steering while the speed is managed by automated system and in the latter steering is automated while the driver has control of the pedals.

- Level 2: "Partial Driving Automation" in which the automatic system can take full control of the vehicle including acceleration, braking, and steering,

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[14] International Organization for Standardization

[15] In this classification the vehicle is seen as separate from the automation system even though in reality they share hardware and software components.

[16] Including the operational (i.e., steering, braking, accelerating, and observing both the vehicle and motorway) along with tactical (i.e., responding to incidents, changing lanes, turning) facets of driving.

however the presence of a driver as a monitoring agent is necessary for intervention in case of failure.

- Level 3: “Conditional Driving Automation” moves away from previous levels where the observation of the environment by a driver in crucial by a significant leap. Here the automated system can control two or more simultaneous functions including keeping to a lane without requiring the drive’s active engagement with the road. Emergency braking is another example of such system.

- Level 4: “High Driving Automation”, if the previous level is nicknamed as “eyes off”, this level is “minds off” improving and expanding on the functions from the previous model and can self-drive while the driver is not in the driving seat, sleeping, or browsing social media.

- Level 5: “Full Driving Automation” perhaps the level most people imagine when AVs are discussed, where there is functionally no need for human driver intervention and the automated system fully controls the vehicle.

As one might imagine, the progress in automation from level 3 onward is very resource intensive and its commercial availability timeline is difficult to anticipate.

2.2.1 Current Technological State

In general terms, an autonomous system relies on a series of sensors to map out and navigate its environment, a combination of machine learning, laser projectors, cameras, radar, and ultrasonic sensors are what most companies and research teams are building their systems upon. Currently, the only available autonomous technologies fall under the first three levels (0-2) and need involvement of a human driver or operator to some capacity, especially with regards to on-road obstruction and avoiding collision with other vehicles, cyclists, and pedestrians.

Some of the major contributors and competitors in this field are Uber, Tesla, BMW, Honda, Toyota, and other smaller companies such as Stellantis, and Polestar. Unfortunately, Uber is responsible for the first pedestrian death by a "self-driving" Volvo, sighting a combination of "technical and human errors" as the cause of the fatal accident. Uber has sold its self-driving-car division, Advanced Technologies Group, to a start-up called Aurora that is funded by Amazon, calling the deal a "technology partnership" (Kollewe, 2020). Tesla is already commercially offering what they call the Autopilot system on all their models, which cannot drive themselves. Their beta "Full Self-Driving" or FSD feature fits the California Department of Motor Vehicles' Level 2 definition[17]. BMW is due to start rolling out its 7 Series full-size sedan with level 3 automation, in the second half of 2022. Here too, scepticism is abounded, especially from the EU legislators suggesting this might be a similar situation with Tesla, where a level 2 assistance system is being marketed as a Level 3[18].

In fact, at the beginning of this year, January 2022, the biggest lobbying group for the AV sector in Washington, with members like Waymo, Ford, Aurora, Lyft, and Volvo, announced that they are abandoning the term "self-driving" altogether. The group cited their desire for boosting consumer trust as a reason for pushing against the conflation of AVs and driver-assist systems[19].

So, is the prognosis for the AV rather grim? The author does not necessarily think so. The dream and research behind "self-driving" vehicle is an ambitious intersection of robotics, electronics, software engineering, communications, and artificial intelligence. Not only technologically a challenge but determining the impact of a technology that is yet to be operational is no "binging your favourite show while your steering wheel less car drives you to work". The safety is a major issue to iron out, no doubt requiring tens of thousands of hours of test driving and simulation, plus there is the matter of legal and ethical questions to maul over. There are optimistic

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[17] The system cannot respond to situations such as adversarial vehicles in the driving path, construction zones, emergency vehicles, static objects, uncharted paths, and neither can it reliably recognise them and notify the driver, so not autonomous - https://www.tesla.com/support/autopilot

[18] https://www.forbes.com/wheels/features/bmw-7-series-level-3-autonomy/

[19] https://www.theverge.com/2022/1/26/22901349/self-driving-coaltion-rebrand-autonomous-vehicle-industry-tesla

projections suggesting we may reach level 5 by 2030, with 75% of light-duty vehicle sales belonging to AVs by 2035. Some think all vehicles could be automated by 2030, others cautiously talk of reaching level 4 in 2030-40s or at least within twenty first century, and of course those who think road transport might move to an entirely different direction and we voluntarily shift our resources elsewhere (Greenblatt & Shaheen, 2015). Regardless of the “when” question, the “how” and “what” of the AVs potential impact on pollution and specifically CO_2 emission are very much on the table.

2.2.2 AVs in on-demand shared systems

The AV could theoretically provide an alternative to owning, storage, and maintenance of a personal vehicle, and operate as an on-demand form of mobility for some users. Considering current pricing trends for semi-automated vehicles of level 2 and projected sales of autonomous technology development for the next decades, purchasing AVs seems to be quite expensive for individuals. Subscription in a trip based shared service, mimicking existing subsidised public transport models, instead of taking on the costs of insurance, registration, fuel, parking, and other fees could conceivably be much more affordable for the users, while simultaneously offering the comfort and convenience of door to door travel by one mode without transfer (Childress, Nichols, Charlton, & Coe, 2015).

Car and ride sharing services like Lyft and Uber have already been part of mobility sphere for some time now, more on these services on section 2.3, but AVs could bring new opportunities to the scene. They could pick up the users at their specified origin and deliver them to their point of destination without any addition to the traveller’s trip time, refuel or in case of electric AVs recharge without intervention, save on operational costs for the provider, transport authority, and subsequently traveller especially in terms of driving labour, reduce energy consumption per kilometre and congestion by more efficient driving, and increase vehicle utilisation. Though, the long-term effect of this type of service on demand as a whole and its relationship to other public transport modes or to for example cycling and walking share as the first/last mile mode choice is a matter of uncertainty (Greenblatt & Shaheen, 2015; Offer, 2015).

The main idea here is that considering the current state and trajectory of CO_2 and other GHG emissions' catastrophic impact on our environment and subsequently quality of life, organising our cities and expanding road/parking spaces around the notion of four to six capacity vehicles occupied by single passengers for a fraction of their designed utility is no longer justified. The public transport was and continues to be the most notably efficient and sustainable answer to the environmental, spatial, and social conundrums caused partially by the one passenger per vehicle mode (Watkins, 2018). Van der Bijl et al. in their framework (van Oort, van der Bijl, & Verhoof, 2017) for assessment of public transport options, suggest a five prong approach to quantify the value of a mode: the *Effectiveness* of mobility, *Economy*, *Efficient* use of urban spatial capacity and potential for development, *Equity*, and sustainable for the *Environment*. All of which can be engaged with, when assessing the automated service's capabilities for being used in a MaaS context. So, it is within this consideration of the people, planet, and profit that AV innovations have the greatest potential for becoming part of the answer by taking on the trips now done by single passenger private vehicles.

2.3 RIDE-SHARING

Ride-sharing is a subset of on-demand mobility, where the user/traveller can hail a vehicle through an application, typically done online, some time before their trip. There are a variety of types of services offered under the umbrella of on-demand mobility and the terminology used to describe them is not always standard and the different forms are not easily interchangeable. The service could be divided into two general groups: *Car-sharing* which is the parallel share of one or multiple private vehicles. This division could mean carpooling, usually involving friends or colleagues who share their vehicle space with each other in a rotation, or mean time sharing of one vehicle usually owned by the service provider; *Ride-sharing* or sometimes referred to as shared taxis, where users with overlapping or approximate origins and destinations join the same vehicle taking a route that passes through all their OD points, so not everyone would remain for the entirety of the route (Viegas, Martinez, Crist, & Masterson, 2016).

There is also a distinction made based on where the vehicle is placed before and after the trip. In a "*Static"* system the vehicle is picked up from a specific location and has to be returned there, whereas in a *"Dynamic"* system it could be dropped off at a different location than pick up. The former can also be referred to as "Round Trip" and the latter as "One Way" or "Free Floating" (Chan & Shaheen, 2012). The free-floating ride-sharing services are flexible and do not require the user to take on the renting expenses during their activity time but providing the users with sufficient fleet size to avoid unavailability is one of the issues. This type could also be offered on a station-based practice, in which case the vehicle must be returned to a station but not where the vehicle was picked up at. There are several dynamic ride-sharing services already in use, such as the evolving car-pooling features within Uber and Lyft, ostensibly making them an extensions of taxi-services. (Dorenbos, 2018)

Ride-sharing raises important questions with regards to its impact on congestion, VKT, and competition with existing public transit systems. Considering that shared trips seem to make up a rather small portion of all trips, one of the more interesting forms of ride-sharing is with advanced requests. This means that the ride requests are registered prior to the time when a vehicle must be sent out, so an algorithm matches the requests and determines the trip route. In their investigation of the evolution of ride-sharing mobility, Ma, Koutsopoulos, and Zheng suggest that shared trips are selected and evaluated based on user willingness to join the pool and tolerable time window variations while the VKT ranks the highest in its importance for performance estimation (Ma, Koutsopoulos, Zheng, & Board, 2019).

3 METHODOLOGY

As has been discussed, the objective here is to determine how much offering a ride-sharing alternative to the single-passenger private vehicle trips, would affect the aggregated CO_2 emission. In this assessment, the existence of fully automated AVs is a given, and the selected urban area for study is the city of Rotterdam. To evaluate this autonomous ride-sharing service, a methodical process is followed to build a network representing the real road network of the choice case study. Then, a traffic model is constructed, and different trip merging algorithms are simulated on the network. Lastly, the simulation's output variables are analysed to ascertain the service's effect. The methods selected for each section are elaborated upon further in this chapter.

The process followed in this research, is design and calibration of the road network, producing trip demands and time distribution patterns based on publicly available data, building of the case study current status scenario as the base line, implementation of the shared service through combining suitable trips, and analysing the relevant output variables. It is worth to mention that the method is not case dependent and can be replicated on smaller or larger road networks and further comprehension could be built by including the complexities of combined modal choice and traveller behaviours to reflect more and more a realistic traffic profile.

In the second chapter, the academic literary context on climate change and CO_2 emission in the transport sector and specifically in the Netherlands was laid out. In the national context the status of Rotterdam as a notable contributor of GHG emissions and a promising candidate for mitigation policies was also explored and therefore selected to be a case study in this work.

The Figure 3. 1 shows the conceptual structure of the autonomous ride-sharing service proposed here. The users connect to the user interface online and enter their scheduled trip information, departure/arrival, origin, and destination. The registered demand is processed by the merging component. The merging algorithm then pairs suitable trips, and the results are communicated back to the users.

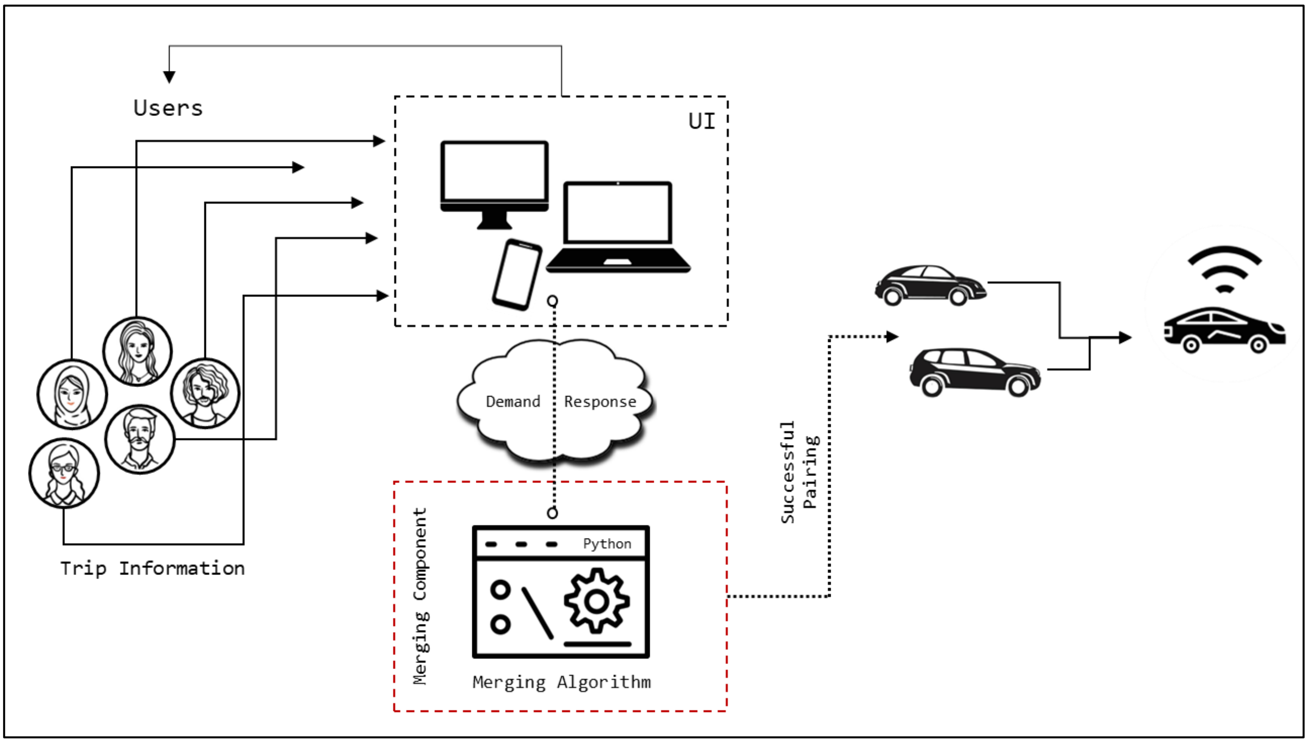

Figure 3. 1. Proposed autonomous ride-sharing service[20]

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[20] The graphic was created using icons from "https://www.vecteezy.com/free-vector" under the creative commons by attribution 4.0 license.

The merging algorithm's variations programmed are the unique contributions of this author. After the merging component is made, the next part of this research is to test the effectiveness of the ride-sharing service, on the private vehicle fleet operating in Rotterdam.

To carry out that test, the author has turned to a simulation platform to impose the changes on constructed traffic flow behaviour on the road network of Rotterdam. A model, replicating the real road network conditions, could render reliable estimates and be used as a tool for decision-making when it comes to ranking and selection of climate change mitigation measures. So, by way of modelling the traffic, feeding a certain quantity and flow of traffic into the network, performance of said network could be evaluated using indicators such as aggregated kilometres travelled, lane usage, and GHG emissions.

Furthermore, traffic flow simulation is divided into three types of models: *Microscopic*, *Macroscopic*, and a combination of both which is the *Mesoscopic* model (Ullah et al., 2021). The type applicable to this research is the Microscopic Model which considers both vehicle and driver as individual agents and operates based on each vehicle's microscopic properties like position and speed, that are important for determining the volume of vehicles passing through and the time interval they were in each lane to arrive at an estimation of CO_2 output. The model used here should also be continuous so that the traffic could be constructed for an entire day including different activity-based trips during peak and off-peak hours and their continuous effects on the network recorded. Taking these specifications into account the software selected for modelling this project is **Simulation of Urban Mobility** or abbreviated to **SUMO**.

3.1 SUMO

SUMO (SUMO, 2021) is an open source microscopic traffic simulation software package, and suitable for modelling large networks. As mentioned above it is continuous in terms of spatial properties of the agents, and the simulation status changes in every simulation step[21]. In the preliminary step to build the network, the selected geographical area was exported from Open Street Map (OSM, 2021) to SUMO. Apart from topology, and the complete network in the selected area, the OSM extracted file also includes metadata on for example additional dedicated lanes which can be edited out for simplifying the network, land-use data, speed limits, default traffic light pattern that also needs to be adjusted based on the dynamic system in use.

SUMO is not the only modelling and simulation software available for studying traffic flow in road networks, in the commercial circles other noteworthy tools are OmniTRANS and VISUM that have wide use and are both macroscopic in scale. In fact, OmniTRANS is the most popular traffic modelling software in the Netherlands, and the Rotterdam Traffic Model ("RVMK") is modelled in OmniTRANS 6.0.26. Along with SUMO, MATsim and OpenTrafficSim are the top open-source simulation programs.

The multimodal interaction is outside of this research's scope, but it was important that it'd be possible to be included in the model at a later stage. In that regard, the general academic consensus seems to be that though MATsim offers a more realistic public transport supply, it operates at a higher abstraction level. So, SUMO allows for a more detailed look into the pedestrian crossings, ride and park locations, and bus stops' involvement with the road traffic. (Diallo, Lozenguez, Doniec, & Mandiau, 2021; Ullah et al., 2021)

In SUMO, there are at times some issues with the traffic flow at intersections, where vehicles temporarily remain stationary, subsequently creating artificial traffic

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[21] 1 second by default

jam. But the source of these problems can be resolved manually by working through the extensive warnings and error feedback lists of early simulation iterations. So, considering the author's requirements for this research namely dynamic detailed control over construction of traffic flow model, availability of multimodal choice integration in later stages, open source, compatibility with varying programming languages, integrated visual platform, moderate learning curve, and prior familiarity with the tool, SUMO was deemed an established and robust software option for this project.

When the model is calibrated, the assumptions and specific changes made on the case study will be discussed in more details in the chapter 4, the prominent four-step modelling method (Ortúzar & Willumsen, 2011) is followed, namely that after dividing the area into different zones, determining the attractive elements of each zone using the socio-economic metadata for example offices/retail shops/parks etc, in that zone, these four steps are followed:

1. Trip Generation, 2. Trip Distribution, 3. Modal Split, which is not relevant in this research, since the trips are done by only one kind of transportation mode, a gasoline powered Euro norm 4 type passenger car using the HBEFA4.1[22] standard for its emission output. Here, it should also be noted that each vehicle moves individually and operates based on the Krauss car-following model (Krauss, Wagner, & Gawron, 1997) which determines that each vehicle is bound by the one ahead of it and limited in acceleration or braking to maintaining a strict safe distance therefore adapting and calculating the "safe" velocity at each simulation step to the behaviour of the leading vehicle. And lastly 4. Route Assignment.

After the base model has run and stabilised, three scenarios with different ride-sharing algorithms are tested on the network and the outputs are compared and discussed.

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[22] The Handbook Emission Factors for Road Transport (HBEFA) an agency supported by European Research Center of the European Commission which provides fuel/energy consumption and CO_2 emission factors for all current vehicle classes.

3.2 DATA COLLECTION

It was initially thought that the author could use the same data set provided by the City of Rotterdam to Anne van der Veen for his master thesis[23], however the data was not disaggregated to individual trips and therefore not suitable for this project. On a high note, the traffic model construction process used here can be replicated with a need for "on-line" real-time data but can be based on entirely publicly available information and is sufficiently formative for the purpose of assessing the effectiveness of ride-sharing as a policy.

To model the traffic flow, the attractiveness or weight of each zone must be determined. The Institute of Transportation Engineers (ITE) 9th edition data base provides estimations for the number of trips to and from a certain location based on its land-use category and correlated unit of measurement. For example, number of trips to a hospital are determined by its bed capacity, and to a train station based on its parking capacity. The land-use categories and number of certain elements, like schools, shops, or restaurants, for Rotterdam are extracted from OSM and cross referenced with ITE's data base to determine their related total number of trips. The items, like park, school, museum, in each zone are then aggregated to calculate that zone's total weight (attraction) so the frequency of passenger trips from home-to-activity are calculated for each zone as a function of land-use. This weight is then reversed for activity-to-home trips.

Knowing the total number of trips for an average day in Rotterdam from municipality documents (Gemeente Rotterdam, 2020), and the typical travel distribution patterns on peak and off-peak hours (Weijermars, 2007), the trips are distributed throughout the day from origin to destination zones. After which the route for each individual trip is designated, based on the dynamic routing shortest travel time. This travel time is measured during the simulation run based on vehicle maximum speed controlled by road speed limits, traffic conditions, and dynamic route

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[23] "Applying Fairness to Planning Practice: Operationalising Equitable Transport Planning for the City of Rotterdam", 2017, Delft.

assignment. After the end of run time, the duration of each trip is documented in the trip output file along with unscheduled stops making up the "waiting time" or functionally the delay suffered per trip. This allows the observation of overhead travel time that have occurred due to congestion at parts of the network and use this as a comparative metrics for the ride-sharing scenarios.

At the end of the simulation, the CO_2 emission is determined for all the edges based on the number of passing vehicles during the 24-hour run time and is aggregated per zone and for the entire network. Figure 3. 2 visualises the entirety of the developed methodology described in this chapter.

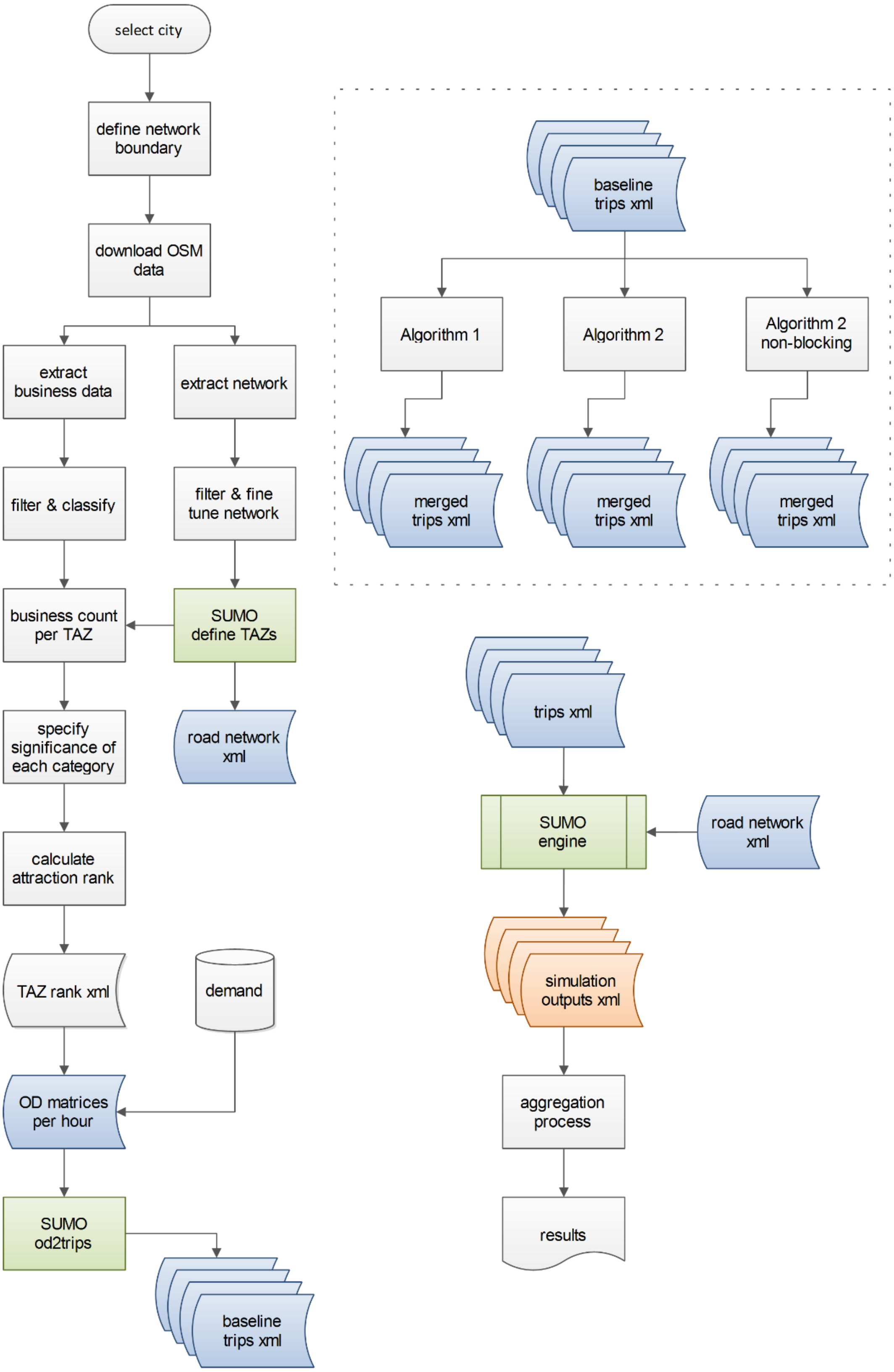

Figure 3. 2. Methodology in pictures.

4 CONSTRUCTING THE MODEL

As previously mentioned, the case study selected for this research to determine the effect of a ride-sharing service on its private vehicle traffic, is Rotterdam. This chapter will follow the outlined approach to implementation of this service, starting from the selection of the geographical area, extraction, and construction of the road network along with the necessary changes that were made to prepare the network to be used effectively in SUMO. Then the traffic pattern for the network is created, and the results of this simulation run considered “as is” state and will be used as the “before” service implementation or the baseline model.

4.1 ROTTERDAM

The city of Rotterdam is in the province of South-Holland, with 655,468 inhabitants as of July 2022, and 629,606 inhabitants in 2016 (StatLine, 2022). The 2016 census is used since the available distribution of the number of rides per day per modality including cars, bikes, and OV, in Rotterdam in absolute numbers applied in the traffic model is from 2016. Rotterdam is the second largest city in the Netherlands, after Amsterdam, and one of the centres of southern Randstad conurbation encompassing fifteen other municipalities such as Capelle a/d IJssel, Nieuwerkerk aan de IJssel, Krimpen a/d IJssel, Schiedam, and others extended eastward to form the Metropolitan Region of Rotterdam-Den Haag.

4.1.1 Study Area Boundary

Figure 4. 1 shows the administrative topographical map of the city of Rotterdam which does not include the southern Randstad conurbation in its entirety.

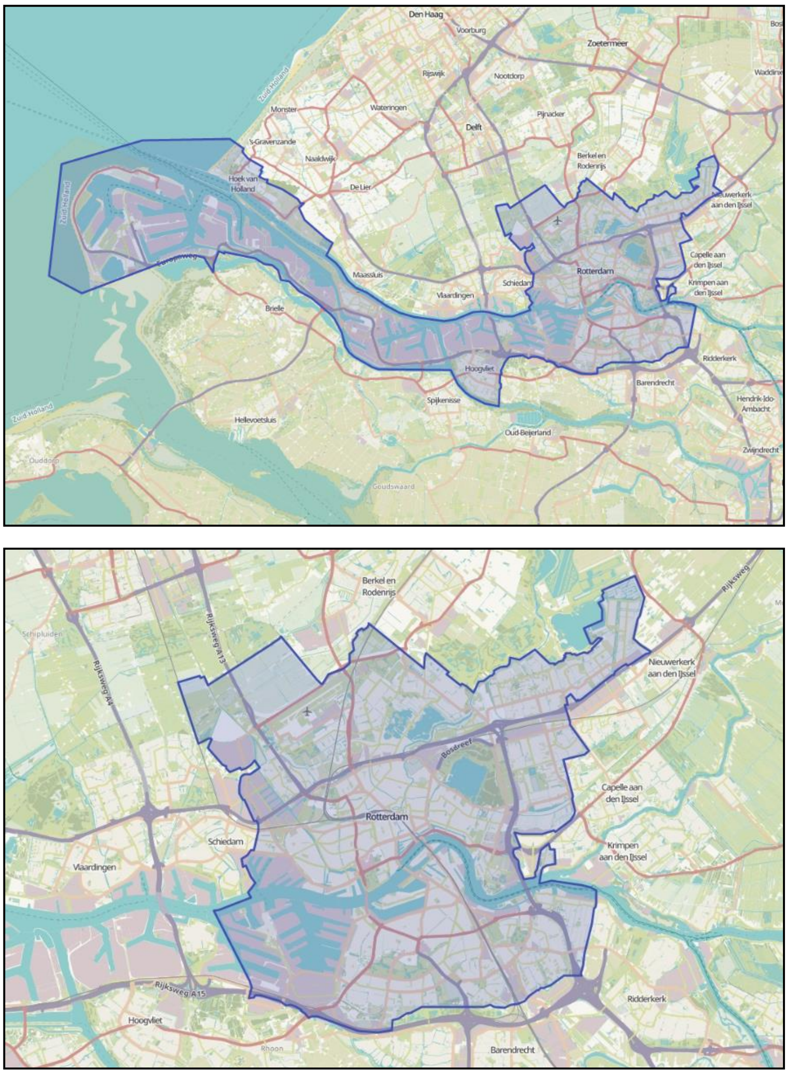

Figure 4. 1. Rotterdam Municipal Boundary with and without the port of Rotterdam[24]

The port of Rotterdam is also omitted from the simulation, as the focus is outside of the industrial and port section of this urban area. As seen in Figure 4. 1, the sizable road network is encapsulated by the “Rotterdamse Ruit”, or Ring of Rotterdam formed

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[24] Sourced from Gemeente Rotterdam, created by Githob

by the highways A4 in the west, A16 in the east, A20 in the north, and the A15 in the south. The other notable topological feature is the Maas River, crossable by car via four bridges Erasmusbrug, Willemsbrug, De Hef and Van Brienenoordbrug and two tunnels the Maastunnel and the Benelux on the A4. The city centre is also accessible by car, but since January 2016 Low Emission Zones were implemented to reduce soot particles in the area between A20, Kralingse Zoom, Vierhavensstraat, and Maas, with fines having gone in effect from April 2016. There is also a zero-emission zone for trucks and vans on 's-Gravendijkwal, and this street is only open to electric vehicles[25].

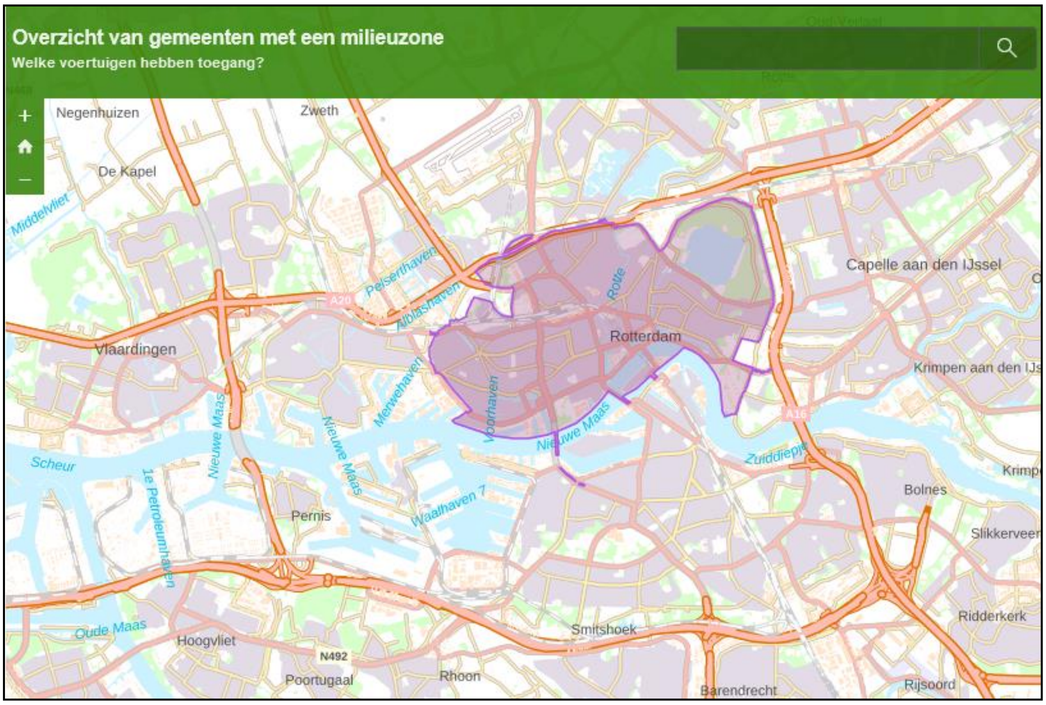

Figure 4. 2. City centre low emission zone

The inhabitants and travellers also benefit from an extensive public transport network of buses, tram, and subway system, connecting the city centre and suburban areas. This subnetwork is connected to the railway system through Rotterdam central train station, Blaak, Alexander, and Schiedam stations. The subway line E can also take passengers from Slinge stop, though central station, and all the way to Den Haag central station in 23 stops. The A, B, C, D, and E lines all intersect at Beurs stop. Since

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[25] https://www.milieuzones.nl/locaties-milieuzones

the focus here is on the road network trips, the public transport interactions with the traffic will not be discussed further.

The municipal border presents a strict division on street level between what constitutes as “Rotterdam” and what does not. However, traffic in reality moves freely and frequently on and marginally outside of this border to connect the points of interests that do in fact fall inside the boundary. To not intentionally shape the route configurations in a way that lengthens shorter distance trips along the border, this boundary was extended to include plausible routs at the margins (see Appendix 9.1.1).

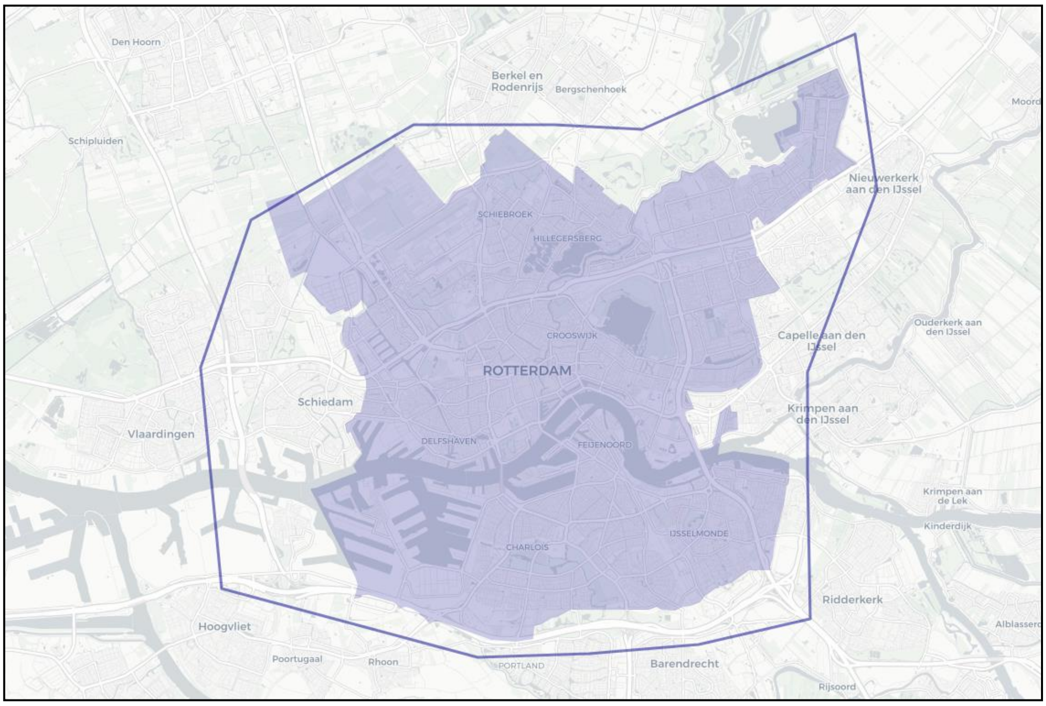


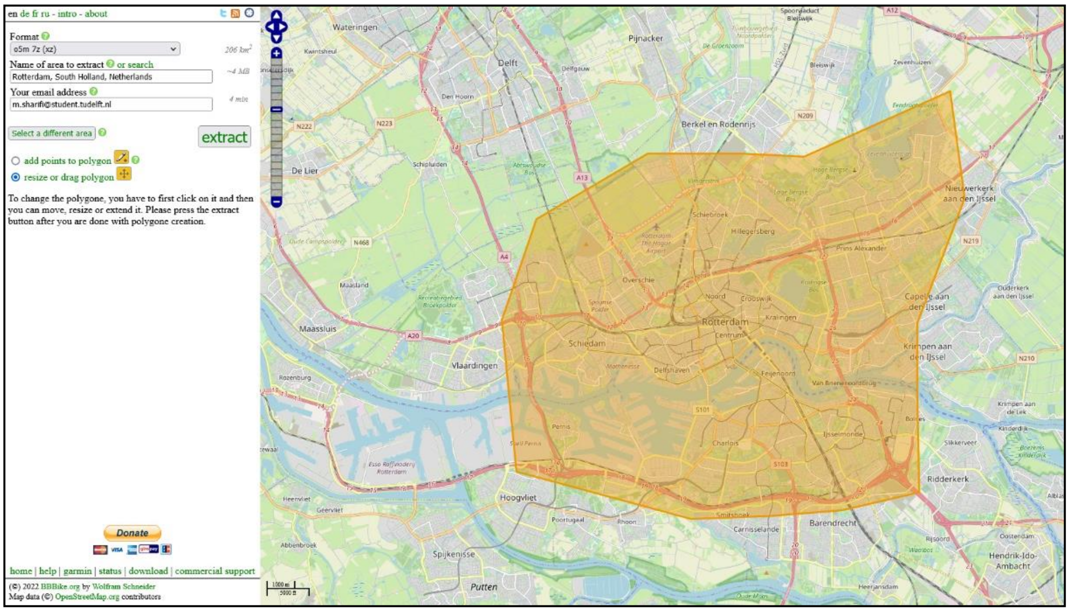
Figure 4. 3. Extended study area encompassing the Rotterdam city’s boundary

Thus, the purple line in Figure 4. 3. shows the boundary of this project’s study area. The next step is to map and create the entire road network file for SUMO.

4.1.2 Extracting the Network and Metadata

In this step, a SUMO network file should be created based on the roads and intersections within the marked study area, in which the traffic simulation could run on. SUMO terminology defines the intersections are Nodes or commonly referred to as “junctions”, and roads/streets are the “edges”, quite similar to graph definition in discrete mathematics. Each edge has a unique “id” that could be referred to and is a collection of lanes with geographical position, length, direction, and speed limit as their characteristics. Junctions contain information about their right of way and traffic lights regulating them.

To create the network file, first the OSM data of the study area polygon shown in Figure 4. 4. is exported to a zip file, extracted, and then converted to a filtered OSM file by a command line (see Appendix 9.1.2).



Format: o5m 7z (xz)

Name of area to extract: Rotterdam, South Holland, Netherlands

Your email address: m.sharifi@student.tudelft.nl

○ add points to polygon

● resize or drag polygon

To change the polygone, you have to first click on it and then you can move, resize or extend it. Please press the extract button after you are done with polygone creation.

(©) 2022 BBBike.org by Wolfram Schneider
Map data (©) OpenStreetMap.org contributors

Figure 4. 4. The study area to download from BBBike in rtm.o5m.xz format

The filtration command is meant to sift the network data file and only keep the specified road elements. After execution of this command, a filtered OSM network file containing only the desired elements is created, and without the unwanted entries like post_box, rail, tram, foot, bicycle paths, and etc removed that can now be used in SUMO's graphical network editor, netedit for making the further changes.

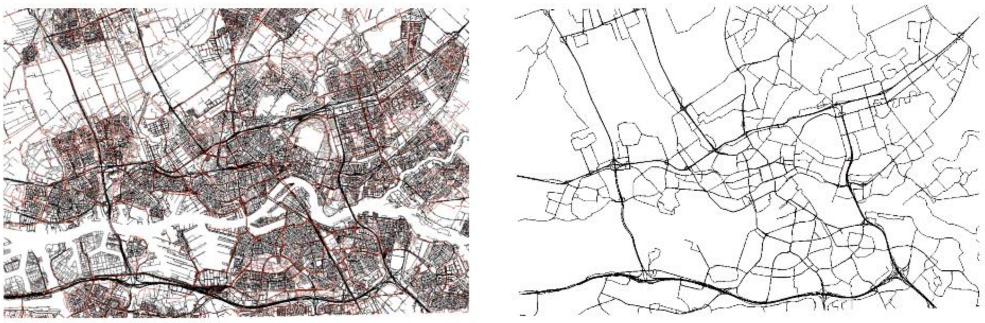
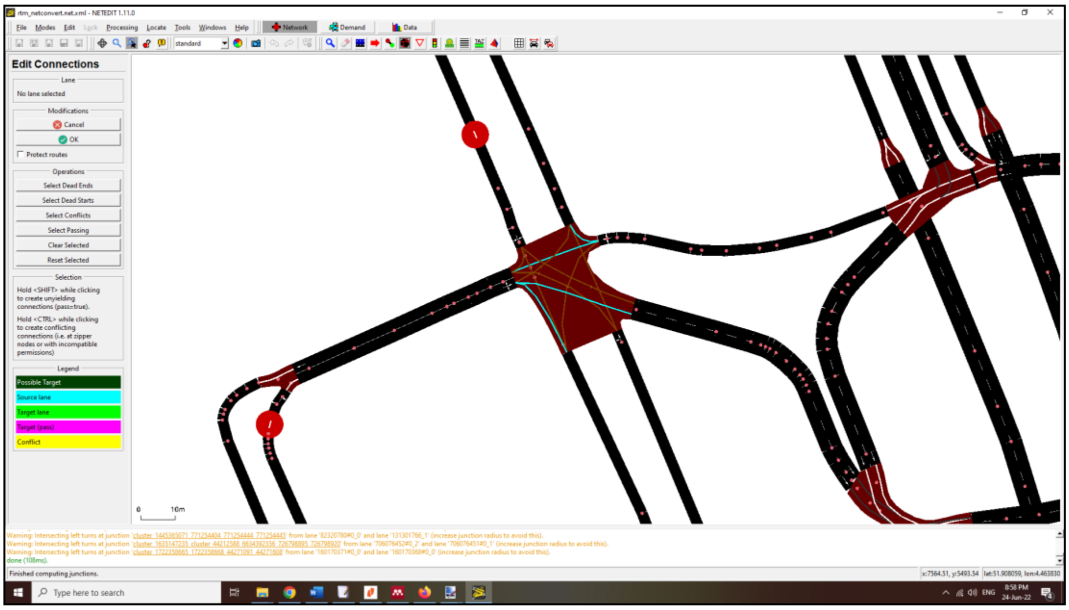


Figure 4. 5. Side by side comparison of the OSM network before and after the filtering

As apparent in Figure 4. 5., This is a crucial step in cleaning the network data, which if done manually and directly in netedit could take a significant amount of time considering there is much more finetuning required after this first step is complete.

4.1.3 Network Alterations

At this point in the process, the barebone road network is created. Although the OSM data is consistent with the actual network, in terms of the lane and junction directions, or the placement of the traffic lights, after filtering out lower-level connections like alleys and parking spaces, it could have had an effect on the accuracy of the network. For example, after removing a tram line, two parallel edges that intersect with another street, would form two separate junctions instead of one, and such a bug should be systematically search for and merged manually. So, every junction (nodes), where two or more lanes meet, has been manually checked on netedit.



Hold <SHIFT> while clicking to create unyielding connections (pass=true).

Hold <CTRL> while clicking to create conflicting connections (i.e. at zipper nodes or with incompatible permissions)

```
Warning: Intersecting left turns at junction 'cluster_1445365071_771254404_771254444_771254445' from lane '82320780#0_0' and lane '131301766_1' (increase junction radius to avoid this).
Warning: Intersecting left turns at junction 'cluster_1635147235_cluster_44212588_6634392356_726798895_726798920' from lane '706076452#0_2' and lane '706076451#0_1' (increase junction radius to avoid this).
Warning: Intersecting left turns at junction 'cluster_1722358665_1722358668_44271091_44271608' from lane '160170371#0_0' and lane '160170368#0_0' (increase junction radius to avoid this).
done (108ms).
```

Finished computing junctions.

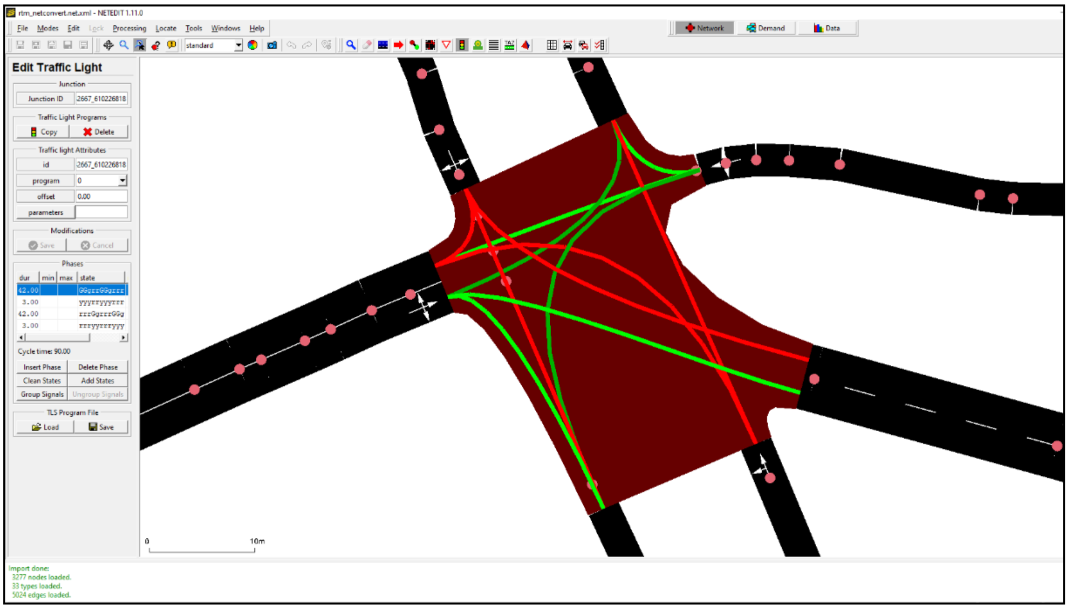
x:7564.51, y:5493.54

lat:51.908059, lon:4.463830

Figure 4. 6. Editing junctions in netedit environment

Another element that requires change is the traffic light system. Not only their positioning at the correct junctions, since not every intersection has a traffic light in Rotterdam and some operate based on following the right-of-way rules or vice versa when an intersection that should be traffic light controlled are wrongly set to uncontrolled, but their program which defines the phases of each light. There is also occasionally an issue with neighbouring nodes that should normally be controlled by only one traffic light system, are seen as separate and controlled by more. In this case either the nodes, aka the junctions, have been merged into one, or the traffic lights were synchronized.

The traffic light programs by default have a fixed cycle of 90 seconds, with the green phase divided equally and followed by a yellow phase that is determined based on the maximum speed of the incoming edges, and lastly ending with a red phase. All the characteristics of the programme are customisable and was switched to a more dynamic system. Where, the duration of each phase is determined by observation of the time gap between successive incoming vehicles. This approach better distributes the green phase and cycle duration based on the traffic conditions. For example, if a continuous stream of traffic is detected on one of the lanes, the phases would adjust to avoid creating a bottleneck. This traffic light programme is called “actuated” in SUMO and is assigned to each traffic light by changing its attribute type="actuated". A maximum and minimum duration can also be set to define the acceptable range of the total cycle duration.



rtm_netconvert.net.xml - NETEDIT 1.11.0

Junction ID: 2667_610226818

id: 2667_610226818

program: 0

offset: 0.00

parameters:

dur	min	max	state
42.00			GGgrrGGgrrr
3.00			yyyrryyyrrr
42.00			rrrGgrrrGGg
3.00			rrryyrrryyy

Cycle time: 90.00

```
Import done:
  3277 nodes loaded.
  33 types loaded.
  5024 edges loaded.
```

Figure 4. 7. Traffic light system phases (TLS program)

The last change in the network concerns the edges that are essentially dead ends. They could be entering parking spaces, residential area, or cut by the study area border. Since each trip origin starts on a random edge within an assigned zone of the network, if the vehicle pops up on the edge facing a dead-end it will be grounded and it will have no way to complete the trip. There are several ways to resolve this issue. Perhaps by making all the edges bidirectional, which is not compatible with reality, or to exclude these edges from ever being selected as the origin, which again would not be realistic and exclude a great portion of the network edges from originating trips, subsequently affecting the entire traffic flow. Therefore, it was decided that the most suitable solution would be to create a loop at each dead-end, shown in, so the vehicle could find a way back into the network and complete its trip. This is also more realistic considering the existence of out of boundary road network.

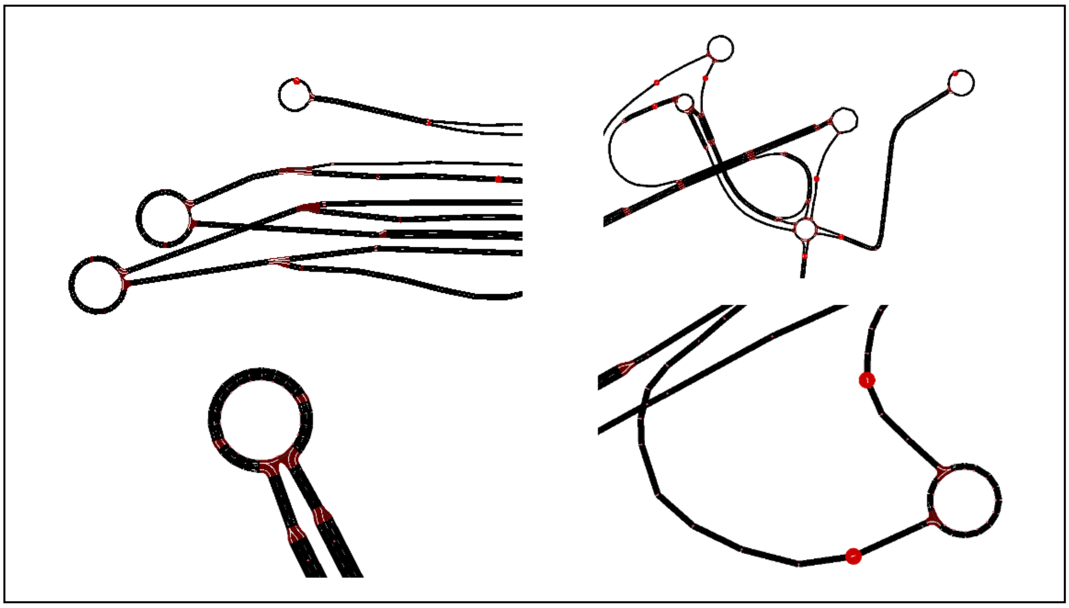


Figure 4. 8. Examples of loop solution to the dead-end edges

At this point the network file, *rtm_netconvert.net.xml* is complete and can host the traffic flow. The SUMO Rotterdam network edited for this research can be seen in Figure 4. 9.

Figure 4. 9. Rotterdam SUMO network

4.2 TRAFFIC FLOW

After crafting the network, to in fact be able to run a simulated traffic, vehicles should drive around in said network. A detailed description of these vehicle movements, traffic flow, is required including demand, OD matrix, and route files for the trips and will be set up in this section.

In each trip, a unique vehicle unit departs from the origin edge at a specific departure time and arrives at the destination edge following a dynamic route that seeks the shortest travel time. So, what needs to be determined here, is the total number of trips in the 24 hour long (one average day) period, how these trips are distributed throughout the day in an hour-by-hour basis following referenced distribution pattern structure, the number and zonal details of the network to assign the origin and destination zone for each trip, creating the route file for the trips that also includes departure times. The next step in demand production, is defining the zones from and to which the traffic should flow.

4.2.1 Zone Definition and Creation

Since the author did not have access to the Rotterdam Traffic Model at the suitable aggregation level for this study in SUMO, or observable traffic counts, the traffic demand must be generated manually. To create the OD matrix, which contains the total amount of vehicles departing from one edge and arriving at another during the simulation run time, first the *"Traffic Assignment Zones"* or TAZs must be created. These zones are necessary to determine the origin and destination of each trip. Each TAZ itself is comprised of edges falling within its boundary, and each edge could be a start or stopping point of a trip.

While the Rotterdam traffic model, in OmniTRANS, defines zones based on municipal zip codes (van der Veen, 2017), here they have been created uniformly as 750 m^2 blocks. Since this proposed ride-sharing service is meant as a convenient addition to the public transport network, the optimised line and stop spacing informed the size of zones here. Based on numerous studies, in terms of social welfare, reducing total travel time, and operational costs, the optimal stop spacing for a typical urban public transport network should be between 600-800 metres (Van Nes, 2000). This result also holds for cases where walking is the only access or egress mode to a stop, meaning that a zone of 750 m^2 is a small enough area where the distance between its edges does not have a significant impact on the overall trip duration. And we can also assume that no trips are happening inside the zone.

So, arranging the demand at this zonal level, reduces the size of the OD matrix and eventual trip calculations as well, since instead of attaching the origins/destinations directly to the 5024 edges, the trips are defined by their origin TAZ and destination TAZ from the total of 324 TAZs (zones). To create a grid of TAZs for the network with the specified 750 m side width, the SUMO tool gridDistricts.py is used (see Appendix 9.1.3) The created TAZ file, *taz_gd_sumo.xml*, overlayed on the network in netedit is shown in Figure 4. 10..

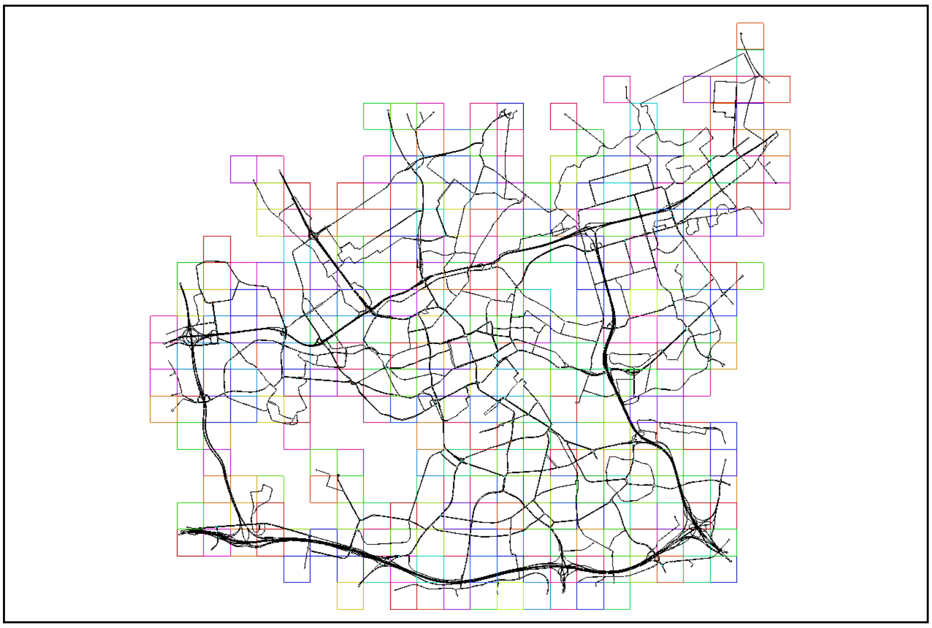


Figure 4. 10. Network with TAZs

4.2.2 Zone Attraction

Now that the TAZs have been defined, they need to be ranked based on the probability of each one being an origin or a destination throughout the day. That probability is called the attraction (weight) value of the TAZ. There is also a potential difference between the origin weight of a zone and its destination weight. For example, a zone that contains primarily residential areas, is more likely to be an origin and see a higher frequency of vehicles departing from it during the peak morning hours when passengers leave for work or school and see those vehicles arriving to the zone in the evening peak hours when those passengers arrive to their place of residents.

The next step is to determine the attractiveness value of each type of land-use element in the zone. These elements could be businesses, offices, schools, parks, etc. And this value, defined as how many people each element attracts, should be mathematically comparable and understood for the purposes of distributing trips.

First, all the land-use *"key"* values related to these elements were extracted from the network OSM file. The attribution system in OSM, includes description of all the map elements, and tags them by a so-called key. That key is usually a common word, but it is not standardised across all maps, so for Rotterdam's case, the key list must be extracted before the elements could be counted. Using the *osmfilter* command line tool, the list of all existing keys is found (see Appendix 9.1.4).

Each key represents a number of different elements on the map. For example, the key "amenity" includes parking, restaurant, school, etc that exists all over the study area. For each parent key, all the key values of its sub elements and their location have been extracted. Then these child-key values are used to create their corresponding GeoJson files, containing the geographical data of each element. In the example of the "amenity" parent key, one of the sub-keys (values) is "restaurant" and there are 671 elements tagged with this one key.

Not all the sub-keys extracted were relevant to the scope of this research, so they were omitted from the counting process. The remaining sub-keys were divided into five main categories of roughly similar attraction type, and a separate GeoJson file created for each sub-key[26]: The categories are Care Facilities, Recreational Facilities, Miscellaneous high importance (high frequency visits), Commercial, Food Industry, School, Leisure, and Tourism (see Appendix 9.1.5 for details).

Since the attribution of tags is not standardised, sometimes one location or element is tagged multiple times. Now that the geographical data of all the sub-keys have been extracted, these duplicates must be deleted so the true count for each sub-key is established. Checking the position of sub-keys against the boundaries TAZs, the number of them present in each TAZ is counted (see Appendix 9.1.5)

As mentioned before, the selected key list is not exhaustively comprehensive, partly due to the fact the not all elements tagged would attract a significant number of visitors, or that a negligible element sparsely even exists in the area like four animal training spots, or an element by itself would not be the purpose of a vehicles trip such as a public toilet. The goal is to approximate the real-world conditions using publicly available data and tools to the extent that supports an accurate analysis of the proposal, not to perfectly replicate the world.

This view also applies to estimating the trips, as in weight, per category of keys. To determine this weight, Institute of Transportation Engineers (ITE) Trip Generation 9th Edition is used, which expresses the rate of vehicle trips to an element during peak traffic hours based on the land-use type and type specific units of measurement. This reference work also concedes that some types of land-use do not attract traffic by themselves and are simply midpoint stops during longer trips, so they do not have a significant impact on the system and therefore are removed from the overall considerations in larger scale analysis. So, for each key:

---

[26] named OSM_keys_tag.geojson, for example for restaurant its file is named osm_keys_restaurant.geopjson

ITE traffic rate/unit of measurement * average key size = weight per key
For key “restaurant”:
ITE traffic rate --> 9.32 per 1000 square feet
Average restaurant size --> 5000 feet
Weight per restaurant --> 9.32 * 5000 = 46,600
Weight per category --> (average of weight per keys)/sum

So, for the main category “Food Industry” that contains the key “restaurant”, first the weight for the restaurant locations is calculated. Then, following the same process demonstrated above, the weight for all the other keys in the “Food Industry” category are calculated. Since the keys in this each main category are the same type of establishment, the weight of the category is the average of the weight of all the keys within it. These category weights are shown in Table 4. 1.

KEY CATEGORY	WEIGHT PER CATEGORY
Food Industry	0.135
Care Facilities	0.035
Recreational Facilities	0.148
Commercial	0.023
Miscellaneous_High_Importance	0.532
School	0.060
Leisure	0.064
Tourism	0.003

Table 4. 1. Attraction (weight) per key category

Now that the weight of each main category is calculated, and the number of the key elements present in all TAZs has been counted, the rank of each TAZ is determined using the Technique for Order of Preference by Similarity to Ideal Solution or TOPSIS (Hwang, Lai, & Liu, 1993). In this method our set of destination alternatives, TAZs, are compared using the weights for each criterion, weight calculated in the previous step for each key category, to calculate the multidimensional geometric distance between each TAZ and the ideal hypothetical TAZ and rank them based on their count in each key category. This method allows a trade-off approach to distribution of traffic amongst the TAZs, since a zone that is the closest to an ideal destination during the morning peak, is then a more probable choice for being the origin zone during the afternoon peak.

Simply put, those trips arriving at city centre to zones with higher scores in business land-use keys, in the morning, would most probably depart from those zones in the afternoon. And since the key category ranks were calculated as destination, the complimentary ranks refer to origin zones.

So, after these steps, each TAZ has a weight (c_rank) to be an origin, complement to its weight (t_rank) to be a destination. The python code for ranking the TAZs, is *TAZ_Topsis_Rank.py*. And while the TAZ ranks during the morning and evening peak hours are noticeably different, the weight of the zones in the rest of the day is equal meaning the traffic is uniformly distributed (see Appendix 9.1.6). Table 4. 2 and Table 4. 3, show the sample counts for some of the TAZs, and the complete TAZ ranking, attraction probability, result is visualised in Figure 4. 11.

TAZ_ID	RESTAURANT	SCHOOL	CAFE	PHARMACY	DOCTORS	LEISURE
10_10	4	4	5	0	0	7
10_11	3	6	1	0	1	13
10_12	0	0	0	0	0	6
10_13	0	0	0	0	0	5
10_14	2	1	0	0	0	1
10_15	0	2	0	2	1	0

Table 4. 2. Sample business count per key for number of TAZs

TAZ_ID	FOOD_INDUSTRY	CARE_FACILTIES	SCHOOL	RANK
10_10	16	1	4	31.993
10_11	17	1	5	16.556
10_12	0	2	0	15.44
10_13	0	0	0	0.839
10_14	3	1	1	1.107
10_15	0	3	2	5.735

Table 4. 3. Sample main category counts and TOPSIS rank for number of TAZs

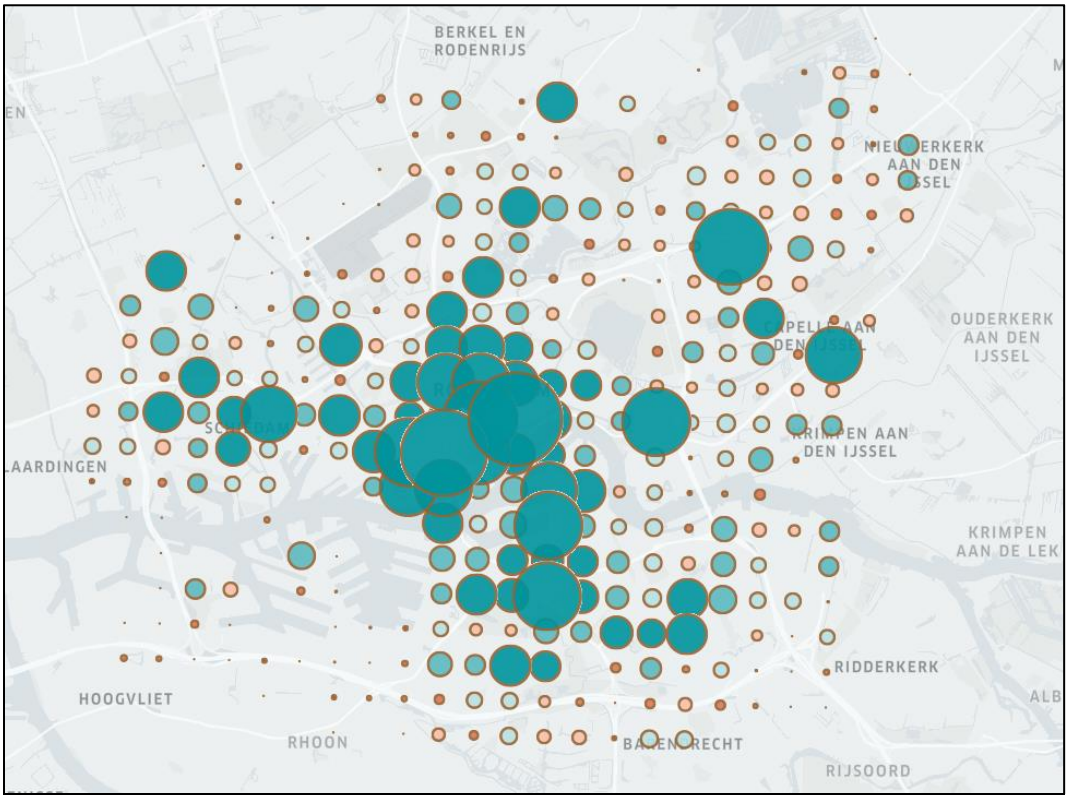


Figure 4. 11. TAZ rank density map (made by Kepler)[27]

---

[27] https://kepler.gl/demo

4.2.3 Trip Distribution During the Day

There is one more step before the OD matrices could be created, and that is determining the distribution pattern of trips based on time of day and total number of trips on an hourly basis.

Using Ward's hierarchical clustering and statistical analysis (Weijermars, 2007) in her research, Dr Weijermars maps typical traffic patterns throughout the year on different locations, including peak times and relative volumes. Her findings are also consistent with the average daily flow profiles previous literature, and as such is a reliable source for reference. On an average working day, there are two peaks in the traffic flow, one in the morning and a fairly higher and broader peak in the evening. These peaks are also location sensitive, depending on the key categories and subsequent TAZ ranking discussed in the 4.2.2 section. So, the main direction of the traffic is different in the peak periods i.e., to and from city centre.

These findings are also consistent with the available TomTom traffic index for the city of Rotterdam between 2019-2021, shown in Figure 4. 12..

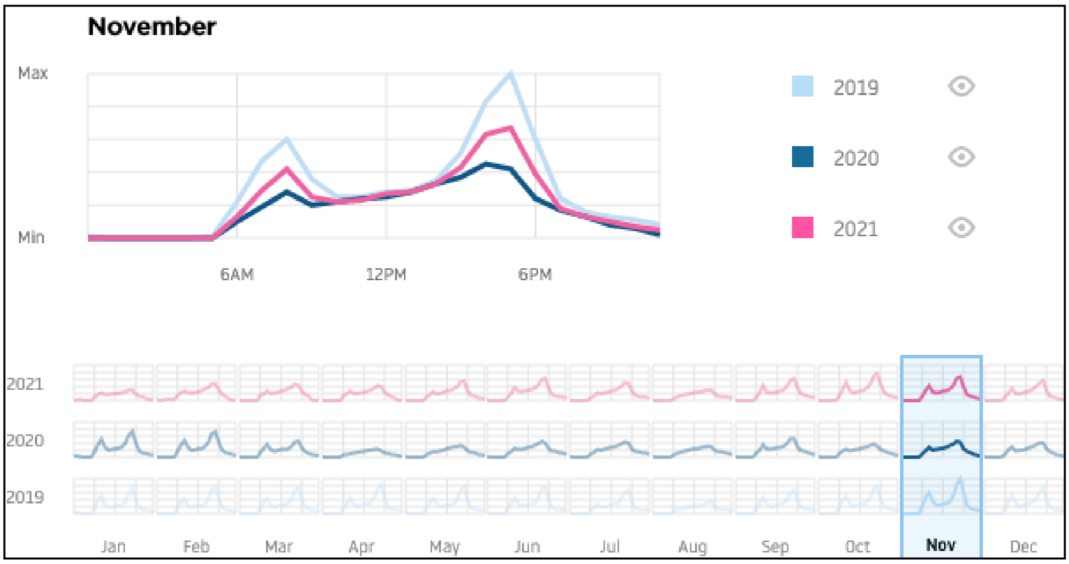


Figure 4. 12. Rotterdam working days travel patterns in 2019-2021 (TomTom, 2022)

The difference in traffic volume, 2019 showing higher number of trips, is due to changes in travel pattern during the COVID-19 pandemic, but the pattern and relations remain similar. Based on these sources, the daily traffic profile divided by hour for this case is shown in Figure 4. 13.

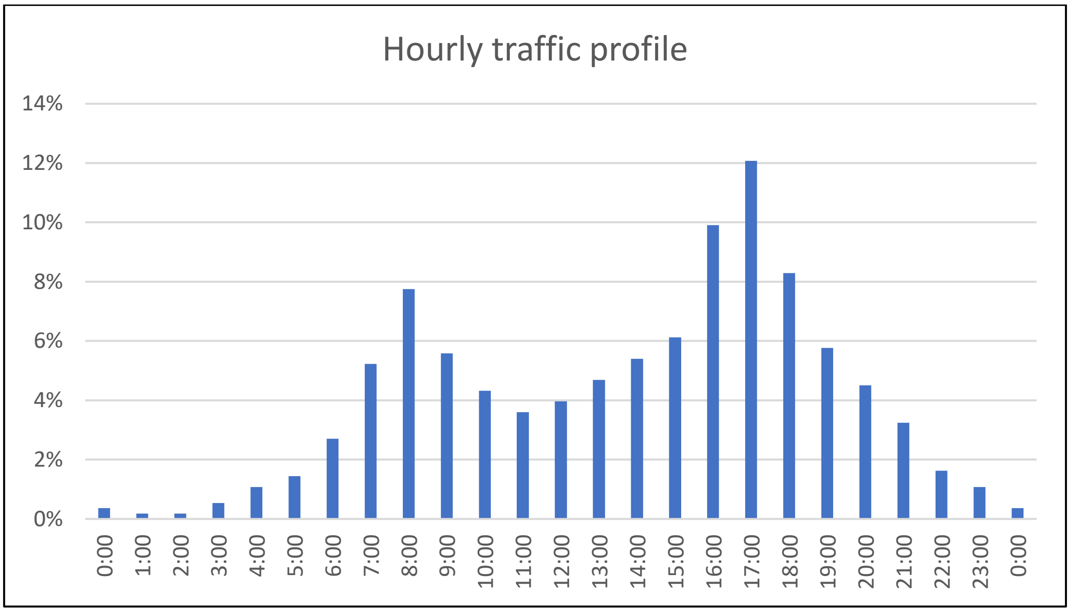


Figure 4. 13. Hourly traffic flow profile for an average working day in Rotterdam

TRAFFIC PEAKS	HIGHEST POINT	SHARE OF DAILY TRAFFIC VOLUME
AM PEAK 6:00 – 9:00	8:00	21.3%
PM PEAK 15:00 – 19:00	17:00	42.2%

Table 4. 4. Peak times and relative volumes

According to a report by Rotterdam municipality, in 2016 about 42% of trips where through 156,000 private vehicles per day (Gemeente Rotterdam, 2020). This absolute number is used as the total number of trips for the simulation. Knowing this total number and the hourly distribution, the number of trips per hour slot is calculated.

4.2.4 OD Matrix and Route Assignment

At this final stage, after defining the zones, their OD based weight (ranks), daily traffic flow distribution, and total number of trips for the entire day, the OD matrix files can be constructed.

In SUMO it is also possible to define the trip route completely by hand including intermediate edges. However, not only is it quite an onerous task for a network of this size, but it would also not allow for a dynamic traffic flow simulation. By defining, only the origin and destination edges and departure time, the vehicles within the simulation can take routes using shortest time (path) calculations considering network load and congestions. So, to do that a python code, *mht_taz_od_01.py*, was written to use the components from previous sections and create OD matrices for the entire day. After the execution of the functions in that code, twenty-four OD matrices are created (see Appendix 9.1.7).

To reiterate, in the OD Matrix file for each hour, every row includes origin zone, destination zone, the number of vehicles making a particular trip, and now the route file must be created for all these trips. The SUMO tool *od2trips* python code uses the xml network and OD matrix files as inputs to create the route file for the simulation. SUMO tool *od2trips* has an option to create random trips based on the OD matrix which is used to generate different trip sets for the simulation (see Appendix 9.1.8).

In the final step the SUMO configuration file containing links to the network xml file, the route file, and emission reference file are created. During the simulation the vehicles use a number of selected edges to reach their destination that allows them to have the minimum travel time/shortest path through the network. The routing algorithm used to find the shortest path is Dijkstra by default (see Appendix 9.1.8).

4.2.5 Summary

The summary of all the steps taken to populate the Rotterdam's network with vehicles completing trips for a full day are as following:

The traffic time slots are classified to 3 types. To generate OD matrices, the following algorithm (novelty of this work) is used for morning and afternoon rush hours (6:00 to 9:00 (weighted) and 16:00 to 19:00 (reverse/complement of morning)) and for the rest have distributed the trips randomly (uniform) between the TAZs. The file name has a letter (w: weighted-morning, c: reversed-afternoon, r-random) to be distinguished.

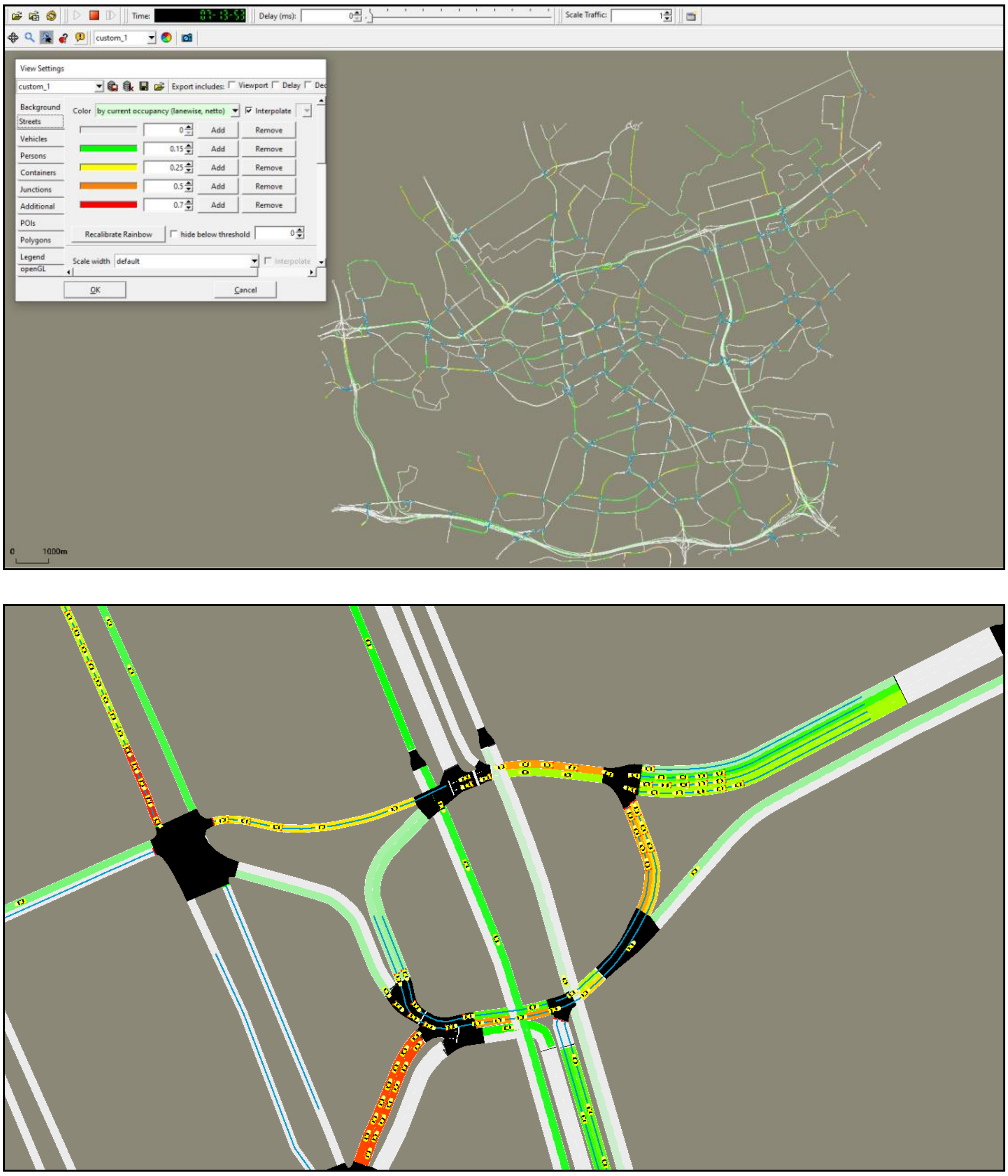
Algorithm for morning and afternoon rush hours:

```
1. Divide the boundary to the zones
2. Count business in each zone
3. Find the zone attraction rank (attraction to be destination)
    3.1 Weight businesses based on their importance
    3.2 Use TOPSIS method to rank the zones
4. Find the zone rank to be the origin (complement to the destination rank)
    4.1 So each zone has a rank to be the origin and has a rank to be the
    destination
5. Calculate number of trips in each time slot base on trip/time distribution
6. For each time slot
    6.1 Open the OD file (e.g. "od_700_800w.txt")
    6.2 Distribute trips to destinations zones (based on simple percentage)
    6.3 For each destination zone
        6.3.1 For each trip_count
            Find the origin based on the zones complementary rank
            (avoid same zone trips)
        6.3.2 Aggregate the Origin/Destination counts
        6.3.3 Write the OD rows to the OD file
```

4.3 BASELINE'S MODEL OUTPUT

As demonstrated at the end of section 4.2.4, to run the simulation a SUMO configuration file must be created. This xml file, contains in it system values such as lane change settings, as input the path to the network file, the route file, and additional file for aggregating the emission, the simulation time frame in begin/end values, as an output after the completion of the simulation the trip information (trip id, departure time, departure edge, arrival edge, duration, etc), statistical (like vehicles loaded, safety violations, collisions) and summary (actions per simulation step) files. These output files contain details of each trip stored during the simulation.

SUMO offers a graphical user interface, sumo-gui, to visualise the simulation of the defined scenario. This windows-based application also takes a SUMO configuration file as input and generates the same specified output as SUMO command line version. The application screenshots can be seen in Figure 4. 14. The colour gradient on the network represents the edge occupancy levels but can be adjusted to reflect other parameters.



Time: 07:13:53

Delay (ms): 0

Scale Traffic: 1

custom_1

Export includes: ☐ Viewport ☐ Delay ☐ Dec

Color: by current occupancy (lanewise, netto) ☑ Interpolate

⬜	0
🟩	0.15
🟨	0.25
🟧	0.5
🟥	0.7

☐ hide below threshold 0

Scale width: default ☐ Interpolate

Figure 4. 14. Simulation run in sumo-gui environment

4.3.1 Validation and Verification

Before sorting through the output files for relevant analysis variables, the issue of model validation must be addressed. This was done following the Verification, Validation, and Accreditation[28] or VV&A framework adjusted for evaluation of this modelling work (Law, 1983; Masys, 2006; William Hunt & Phillips, 1979). This model was loaded and run successfully in SUMO without errors. Both its network structure and traffic flow, trip quantity, and location/time distribution were developed based on the data available for Rotterdam. The hourly trip distribution from the SUMO trip output file in Figure 4. 15., after the completion of the entire run, matches the distribution conceptualised from real data in Figure 4. 13.

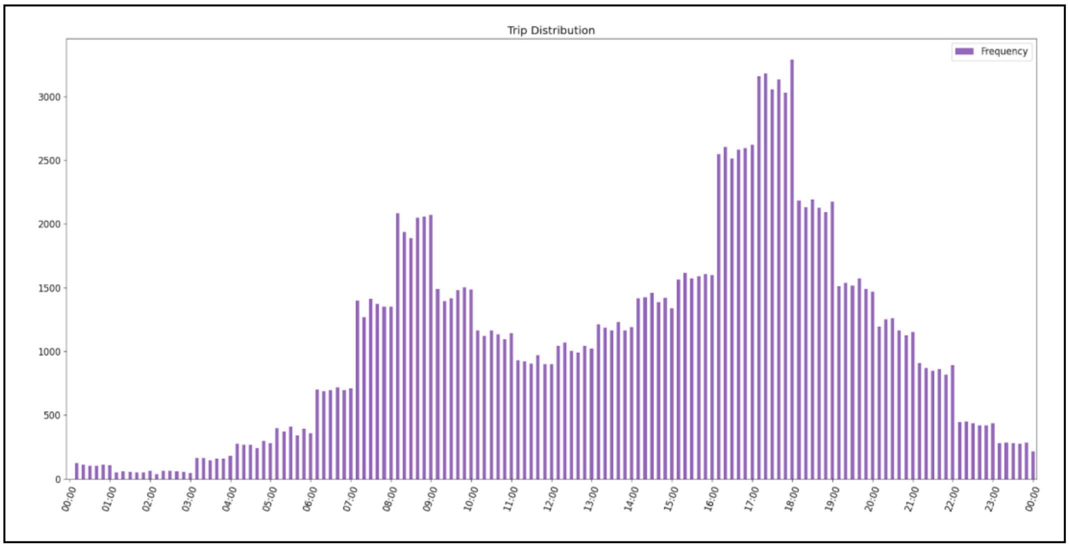


Figure 4. 15. Hourly trip distribution from baseline simulation trip output

As is also understood when engaging with real world occurrences, a pattern cannot be detected based on only one observation. Therefore, after the validation question is settled, an analysis still cannot be based on only one simulation. So, the next step would be to discover how many simulations would yield steady results. Here, two indexes were utilised, the mean variability and standard deviation. The former, will decrease after a certain number of simulations and demonstrates that further samples are not required. The latter, standard deviation, refers to the distribution the sample data around the mean. The sample output data used for this purpose is total emission per run, and in each simulation run the origin and destination edges, and departure

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[28] Accreditation in A. Law’s work is referred to as “Credibility”

times are randomised, resulting in unique route file for each run as the uncertain variable.

To begin with, ten simulations were run, and that number proved to be a sufficient sample size. For each line of the OD matrix, the number of trips remain the same while the random elements amongst different simulation runs are trip departure times, and while the TAZ origin destinations also remain the same, the origin and destination edges are random as well. Both the mean and standard deviation of the total emission was stable, so carrying out with running more simulations would not change the results significantly. In the table, the total number of trips per simulation run that were completed are shown. As evident, each run's trips are consistent with the trip input which was 156,000.

SIMULATION	COMPLETED TRIPS
Baseline Run 001	155,632
Baseline Run 002	155,611
Baseline Run 003	155,587
Baseline Run 004	155,581
Baseline Run 005	155,602
Baseline Run 006	155,618
Baseline Run 007	155,588
Baseline Run 008	155,595
Baseline Run 009	155,546
Baseline Run 010	155,621

Table 4. 5. Completed number of trips per baseline simulation run

Figure 4. 16. shows the distribution of the emission outputs computed for ten simulations, using their unique route files. The average of the data points, total emission for each simulation run, is stable. The standard deviation is 2.495 over the mean marked by the orange horizontal line which is 380.486 kt CO_2 and is quite low.

So, most of the data points are very close to the mean and therefore now that the output patterns have been stabilised, the results could be used as the baseline for comparison.

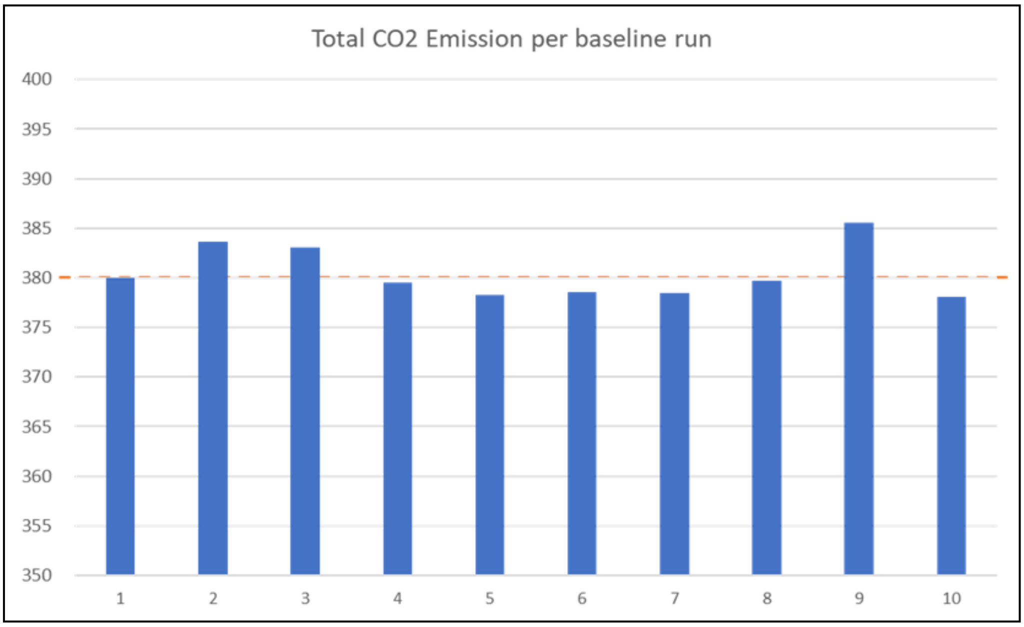

Figure 4. 16. Total CO_2 emission per baseline run

To evaluate the effectiveness of the ride-sharing service the aggregated emission output on each TAZ is measured, and the results are compared with the average emission output of all baseline simulations.

4.3.2 Emission Output

In SUMO the emission is calculated based on the defined type of vehicle in the network and expressed per edge. So, to determine the emission output per TAZ and for the network as a whole the edge emission have to be aggregated. It should be noted that some edges are long enough to span multiple TAZs like the example in Figure 4. 17., so the first step is to establish what share of edges each TAZ has.

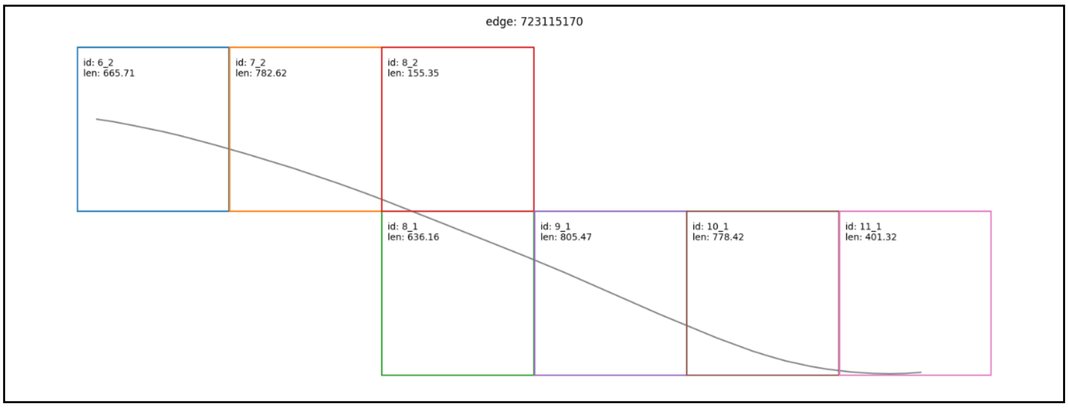

Figure 4. 17. Example of an edge crossing multiple TAZs

For this purpose, the *mht_emission2taz.py* script must be executed once. This code will create the *edg_taz_share.txt* file that contains these shares and is then used as the reference when calculating emission output per TAZ. The average emission output results of the ten simulations can be seen in Figure 4. 18.

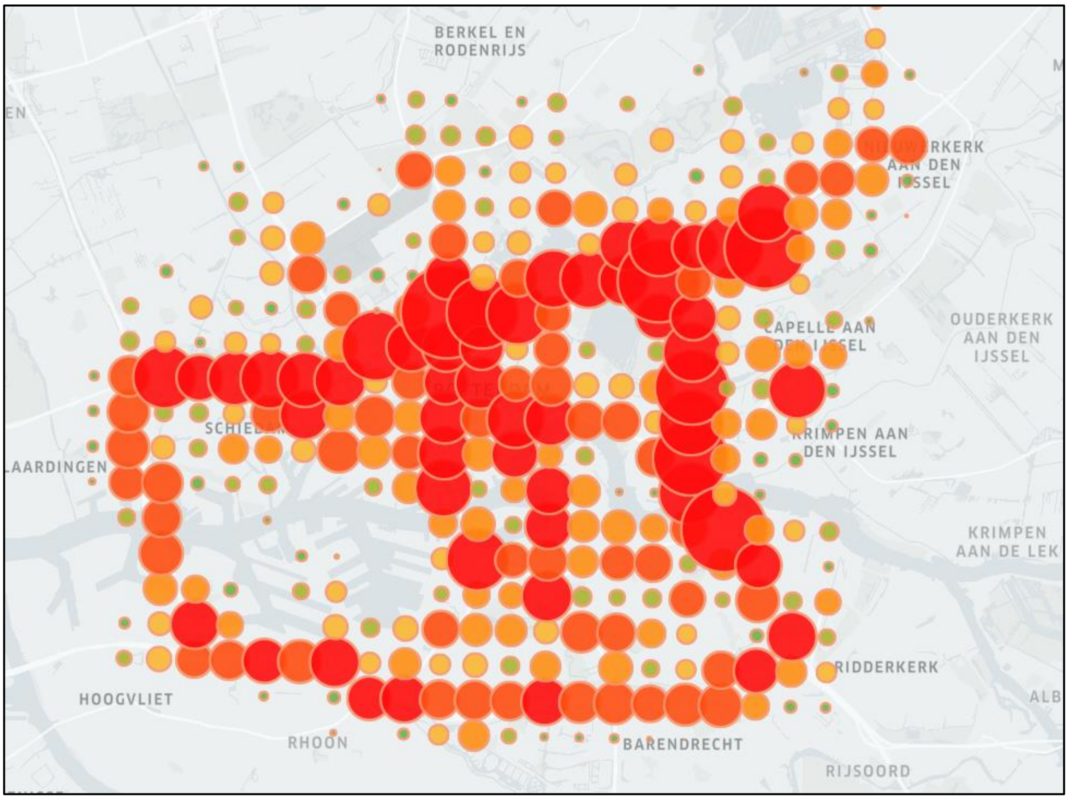

Figure 4. 18. Baseline model emission output per TAZ

5 DESIGNING THE RIDE-SHARING SERVICE

Lorem ipsum In the previous two chapters, a model and the road network of the Rotterdam's private vehicle traffic on an average day, primarily based on publicly available data from 2016 was conceptualised and implemented in SUMO. The result of this model is a pattern of travel exhibited by those owning vehicles in Rotterdam and the amount of CO_2 emission produced by this mode of choice. In this step, we have finally arrived at the point to consider how this volume of traffic could be altered, using an AV ride-sharing service and how much would such a change affect the CO_2 discharge.

The proposed AV ride-sharing service for this research, could potentially be very well suited to the repetitive morning trips to work and afternoon rush hours to drastically reduce the number of one-two passenger private vehicle fleet and provide a door-to-door service that holds the convenience a car and make trips that would otherwise require multiple mode changes and transfers when using public transport into a direct and efficient form of travel. Furthermore, since the AV considered here is hypothetically level five and fully automatic, unlike currently available ride-sharing services like Uber-pool, does not require a dedicated driver or one of the passengers to surrender their vehicle for the use of other passengers.

5.1 CONCEPT

This AV ride-sharing service is meant to operate as the following: There is a user interface component that allows the travellers to register their request for a trip, indicating their origin and destination address, and the designated time of departure. Then these requests are compiled and fed into the trip merging components which searches for and combines the compatible trips, and finally the travellers would be picked up and delivered to their destination.

The user interface component could be likened to the 9292.nl platform, available via the website and mobile app, where the users can select from and to which location they would like to travel and when they would like to depart or arrive. Based on these choices the available public transport options are made known to them. In this research's system after requesting a vehicle for their trip, the user is no longer asked to make any choices, and the assigned AV vehicle would arrive at their predetermined origin, access point, within an acceptable window of the specified departure time.

So, the research conducted here was not focused on "real time" or short notice rides, but the group selected for this proof of concept is specifically targeted to travellers who have a prior knowledge of their upcoming trips and register their requests to the system for example a day in advance. Firstly, due to the fact that the real time user data was not available, so the demand pool had to be constructed from scratch in chapter three. Secondly this service is meant to entice the groups of people most likely to experience increasingly long traffic jams during their morning and evening commute to/from work and subsequently perhaps more likely to transition to a counter solution that not only offers a hassle free more environmentally friendly transport but still allows them to utilise their commute time with things other than driving in addition to avoiding the problem of finding parking. Although the research on the potential relation of ride-sharing service usage to user demographics is in its earlier stages and it differs strongly based on the quality of service provided and local conditions, some of the data also supports this direction. For example, according to

Statista[29] only 24% of Americans earning less than 30k$ annually use ride-sharing services in the country with the people earning 75k$ annually taking the top spot on the users list. So those who upper-middle class, own private vehicles and make predictable trips in the urban area during peak hours have high potential to join the service. Ensuring The luxury of car travel and the utilitarian vision of public transport.

So, the traffic flow determined earlier is used as the demand input for the merging component that has been developed by the author and is the focal point of this chapter.

5.2 TRIP MERGING CRITERIA

The goal here is to develop an algorithm that can hopefully find the best two trips that could be combined into only one and therefore completed using only one vehicle instead of the original two. The reason for choosing to only match two trips together, is that although the assumption is that much of the private car fleet is comprised of one or two passenger cars, the passengers were not defined as a separate agent in the model therefore their exact number in each vehicle is unknown. Outlook in this case has been steered to more conservative margins to avoid overstating the hypothetical benefits of the service by reducing four or five assumed one-passenger vehicles to one.

To complete the central task in this component, suitable pairing candidates must be found for a trip based on a set of criteria and then merge the original trip with the best candidate. Naturally, combining trips comes with trade-offs. The passengers would have to potentially take a detour, since merged trips do not always originate from and arrive at the same location. And there might be some delays in comparison to the original intended departure time before a dispatched vehicle reaches the second traveller for pick up. These two constraints, added vehicle-kilometre travelled (VKT) and waiting time for departure, have an effect on the total travel time, requested vs after merge departure time, and the apparent condition that a passenger leaving in the

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[29] https://www.statista.com/markets/419/topic/2576/public-transportation-mobility-services/#overview

morning cannot be paired with a passenger leaving in the afternoon even if they do happen to have identical O/D TAZs.

In the merging algorithm, these criteria are expressed in terms of the acceptable window for waiting time, from preferred departure time, and total time loss, waiting time plus additional time due to detour, that the travellers may experience due to small deviations their original trip route when sharing part of it with other travellers. It is also to follow a standard or industry practice values for traveller's tolerance or determine the waiting time and total time loss bandwidth as a function of the trip length. In this case the former approach was selected, and the bandwidth is set as following:

RANGE	WAITING TIME	TOTAL TME LOSS
MERGING ALGORITHM SELECTION CRITERIA	5 up to 10 minutes Or 3 to 12 kilometres	7 to 15 minutes
DETAILS	The acceptable difference between merged and original preferred departure time	Waiting time + Detour time

Table 5. 1. Trip merging criteria specification[30]

So, when searching for candidate trips to combine, the potential merged trip should be compared to the two original trips to check if the waiting time and total time loss are within the acceptable window. These bandwidths are currently set to a lower conservative bound in order to ensure the service maintains maximum value for the current car owners, but it can be adjusted according to whom the service is being optimised for.

Continuing the task of pairing trips, two greedy algorithms were developed that will be described further.

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[30] Range based on International Transport Forum's on shared mobility (Viegas et al., 2016)

5.3 BEST PAIRING CHOICE

Figure 5. 1 is a graphic representation of two separate trips, starting from origins at a1 and a2, and reaching destinations at b1 and b2:

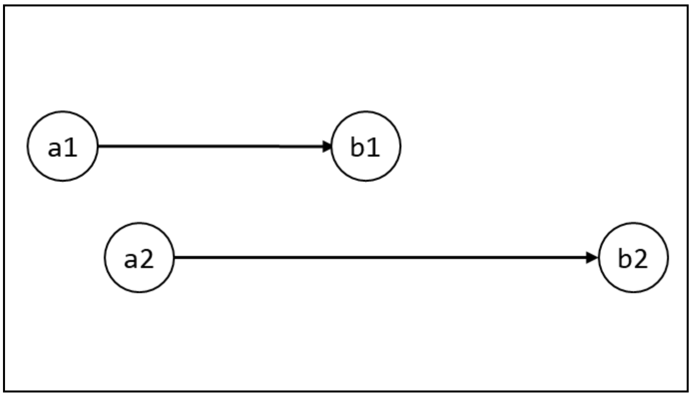


Figure 5. 1. Graphic representation of two trips

Without any constraints, considering the nodes only from mathematical standpoint they could be combined in all the variations listed in Table 5. 2.

Not every combination in this set is of equal value or valid as a trip. For example, the b1 --> a1 --> b2 --> a2 arrangement does not register as a legitimate trip, since it suggests that the vehicle starts from the destination and then arrives at the origin. Depending on the position of the origin destination nodes, and each trip to its counterpart, some combinations could render utility and some result in loss in terms of the final length of the route going through all nodes vs before combining.

a1 --> b1 --> a2 --> b2	a2 --> a1 --> b1 --> b2
a1 --> b1 --> b2 --> a2	a2 --> a1 --> b2 --> b1
a1 --> a2 --> b1 --> b2	a2 --> b1 --> a1 --> b2
a1 --> a2 --> b2 --> b1	a2 --> b1 --> b2 --> a1
a1 --> b2 --> b1 --> a2	a2 --> b2 --> a1 --> b1
a1 --> b2 --> a2 --> b1	a2 --> b2 --> b1 --> a1
b1 --> a1 --> a2 --> b2	b2 --> a1 --> b1 --> a2
b1 --> a1 --> b2 --> a2	b2 --> a1 --> a2 --> b1
b1 --> a2 --> a1 --> b2	b2 --> b1 --> a1 --> a2
b1 --> a2 --> b2 --> a1	b2 --> b1 --> a2 --> a1
b1 --> b2 --> a1 --> a2	b2 --> a2 --> a1 --> b1
b1 --> b2 --> a2 --> a1	b2 --> a2 --> b1 --> a1

Table 5. 2. All possible mathematical node to node combinations

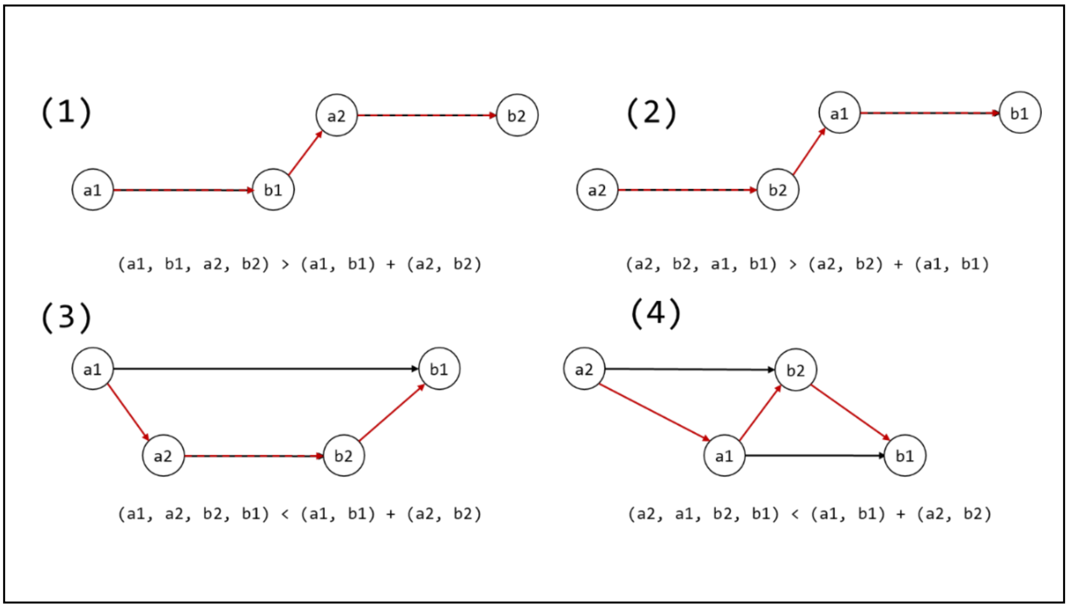


Figure 5. 2. Combination sets with or without utility

This concept is shown in Figure 5. 2 with two sets (1) and (2) returning a loss since the final "trip" length, marked with red, connecting all the nodes is larger than purely adding the length of the two individual trips; while in sets (3) and (4) since there is an overlap between the trips the final combination trip length might have a shorter length than adding the length of the two trips together. Looking back to Table 5. 2, the a1, a2 stands for origin edges and b1, b2 for destinations edges while the line going from an origin to a destination represents all the intermediate edges making up a trip. All the O/D and route edges represent streets on the road network.

This "overlap" is what functions as the utility variable used to determine the best candidate for pairing amongst the potential candidates' pool. Considering this difference variable, the next step of developing the merging component is building the search algorithms. Two approaches were explored for the search algorithm with a variation on the second algorithm functioning as a separate third option, and as mentioned before all fall under the category of greedy algorithms. To summarise, in a greedy algorithm a "problem", in this case starting trip, is selected and then the best option for solving it, best merging candidate trip, is determined in the moment of conducting the search. This is a top-down approach that prioritizes finding the best solution for the current trip and not that the solutions would result in the best overall outcome. After a selection has been made, two trips merged, they are removed from the rest of the trip list and considered resolved, and the algorithm moves to finding the pairing solution for the next trip candidate. So, the four types of valid combinations of trips out of all the theoretically available pairing orders in Table 5. 2 are:

a1 --> a2 --> b1 --> b2
a1 --> a2 --> b2 --> b1
a2 --> a1 --> b1 --> b2
a2 --> a1 --> b2 --> b1

There are in total about 156,000 trips for one day. Every trip on this list must be checked for the possibility of being merged with another suitable trip. Simply comparing each possible pair of trips with all others to find the potential best match, is an extremely time-consuming process. The following combination formula shows just how much time:

nCr = n! / (r! (n - r)!): 12,167,922,000

100,000 check/second: 121,680s ~ 34h

With an Intel Core i5 processor and 8GB of Ram, it takes about 34 hours to evaluate a selected first pair with all the other pairings and determine which one is the optimal matches. So, this approach is not feasible within polynomial time, rendering the problem essentially unsolvable in this manner. As in, the merging component would not be able to provide a response to a user who has requested a ride-sharing service if the computation takes more than a day to complete for just the first pair.

Going back to the discussion on the pairing constraints, one might argue that perhaps the search could be simplified by isolating it to sections within specific departure times; for example, comparing all the pairings in a ten-minute window of 8:00 am to 8:10 am. The first issue with the approach is that during morning and evening peak hours, there are more than 1600 trips made in a ten-minute window. Even reducing the size of the window and sectioning the search for smaller and smaller trip numbers would result in the following computation time, looking for the optimal solution for the pairs in that section and overall:

Section size 1000 trips, 156 sections in total

Full comparison → 83,458,250 * 156 = 13,019,487,000 ~ 36 hours

Section size 500 trips, 312 sections in total

Full comparison → 10,447,875 * 312 = 3,259,737,000 ~ 9 hours

Section size 250 trips, 624 sections in total

Full comparison → 1,309,875 * 624 = 817,362,000 ~ 2.3 hours

The computation time only starts showing improvement when attempting much smaller sections, less trips and subsequently les pairs to compare, and by that point we have moved much further from the optimal solution due to arbitrary separation of trips that are otherwise within an acceptable departure time window and could be each other's perfect merging choice. Hence the following heuristic algorithms were developed to reduce the computational complexity of the search for best merging option for a trip, by speeding up the selection through attempting to approximate the most optimal solution.

5.3.1 First Algorithm

The approach in algorithm 1 is to arrange the trips according to departure time (t_d), set the current trips (trip a) starting from 00:00 hour in ascending order, create a valid potential candidate (trip b) trip class (group P) out of the trips which departure time $t_d(b)$ is between the departure $t_d(a)$ and arrival $t_a(a)$ of the current trip. So, a trip is considered a potential merging candidate for the current trip if:

$b \in P$ if $t_d(a) < t_d(b) < t_a(a)$

Therefore, instead of comparing pairs with other pairs, a merging option is weighted for one trip at a time. The algorithm runs the following logic:

```
Based on the merging function
(trips are sorted based on departure time)
new_trips_list = []
For all trips select current trip:
             select valid candidates for current trip
             select best candidate
                combine trips into new 3 trips
                new_trips_list.apped(new 3 trips)
 set the processed_flag for the combined trips
```

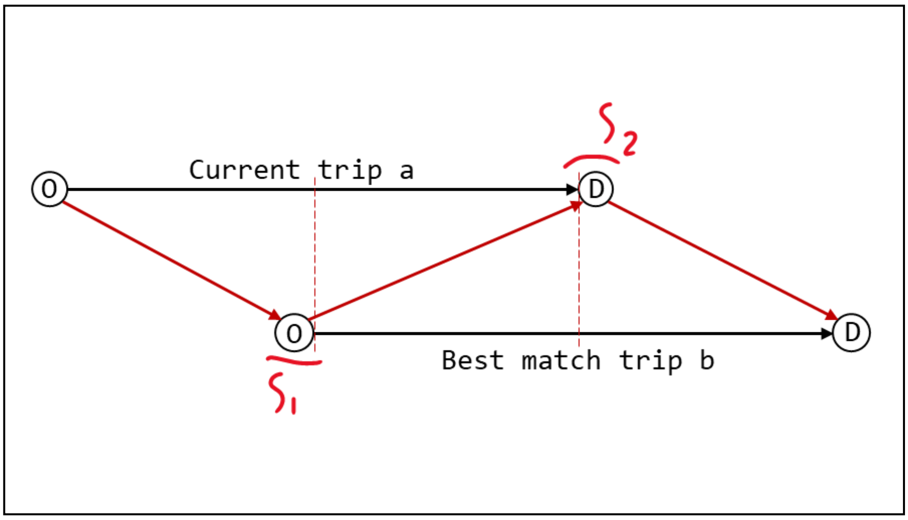


Figure 5. 3. merging two trips using algorithm 1

The best candidate out of the potential group is the one with the most route overlap with the current trip. It should be noted that to accelerate the selection of this best match, the distance between the start and end of all the edges to one another has been computed once by running the *mht_edge2edge_turbo.py* code. This edge-to-edge length calculation comes into play when the algorithm checks whether the tolerance window for waiting time and total time loss is satisfied during the "gain", route overlap, comparison between suitable candidates. Also used to check whether the gain is positive and $O_a \rightarrow O_b$ and $D_a \rightarrow D_b$ are small enough, using the waiting time and total time loss as reference.

The gain is the distance between the two red dashing marks minus $O_a \rightarrow O_b$ and $D_a \rightarrow D_b$ detour in Figure 5. 3, and represents the VKT reduction due to completing two trips with one vehicle. After the best match is selected the current trip is merged with the match, so two trips that were originally completed by two separate vehicles are now completed with one and treated as one trip. The line referring to combining two trips to three, refers to a technical choice in the merging component to keep track of the intermediate access/egress points of the joined trip. In the featured visualisation the red arrows have now replaced the two separate black arrow routes, so the AV vehicle must not only complete the trip from origin of a to destination of b but stop at two points on the way for origin of b, marked as S_1, and destination of a, marked as

S_2 in the image. Hence, the wording of "three" trips more so refers to the three legs of the combined trip. After two trips are merged, they are moved to the merged list of trips, and the algorithm continues up to check the remaining trip list for potential pairing opportunity.

The issue with this first algorithm is that since the current trip assignment order is first come first served, moving through the list based on departure times, an opportunity for higher gaining pairs might be lost. As a reminder during peak hours there are thousands of trips completed within a very short window of time, so it's possible that a current trip is merged with the best match that simply comes next in the departure time order; while its match could have been the best option for another trip departing later and gained a longer overlap. The more optimal pairing would not be possible since the algorithm does not loop back to trips that are already merged. This issue is visualised in Figure 5. 4.

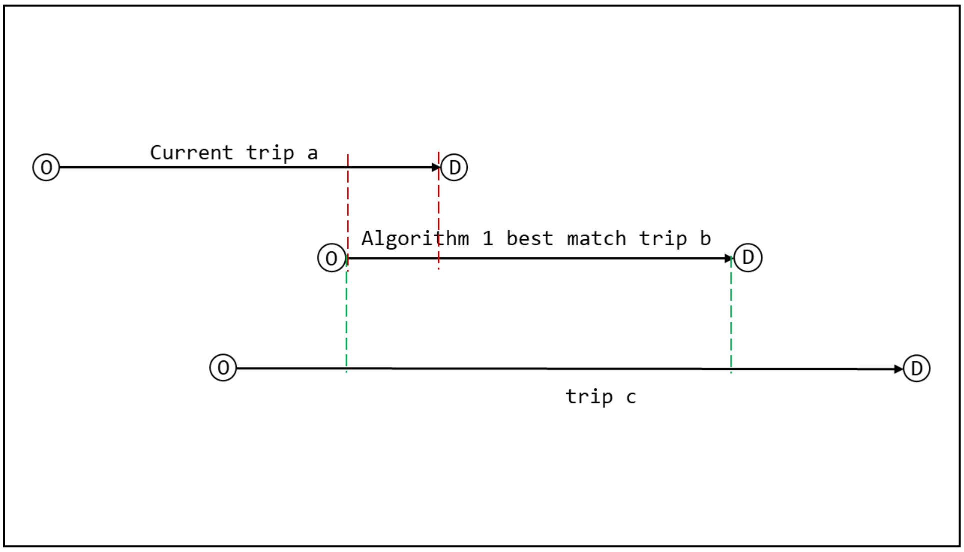


Figure 5. 4. Missing the optimised choice

In this example:

$t_d(a) < t_d(b) < t_a(a)$
$t_d(b) < t_d(c) < t_a(b)$ and $t_a(a) < t_d(c)$

Although trip b and trip c would be a more beneficial pairing, they cannot be merged since trip b has already been merged with trip a. This opportunity has been lost. To resolve this issue and get closer to the "best solution", a second algorithm was concocted.

5.3.2 Second Algorithm

Unlike the previous approach, algorithm 2 arranges the trips based on their length in descending order so that the longest trip out of the remaining trips is selected as "current trip" and the search is set out to find the best match for it. The valid candidate group in this algorithm also follows the departure time constraint. The algorithm step by step process is identical to algorithm 1 after this key difference:

```
Based on the merging function
(trips are sorted based on descending trip length)
new_trips_list = []
For all trips select current trip:
             select valid candidates for current trip by
             determining gain
             select best candidate with highest gain
                combine trips into new 3 trips
                new_trips_list.apped(new 3 trips)
 set the processed_flag for the combined trips
```

After all the trips are processed, for the merged trips the intermediate access/egress stops lasting for 30 seconds each are also added to the new merged trip.

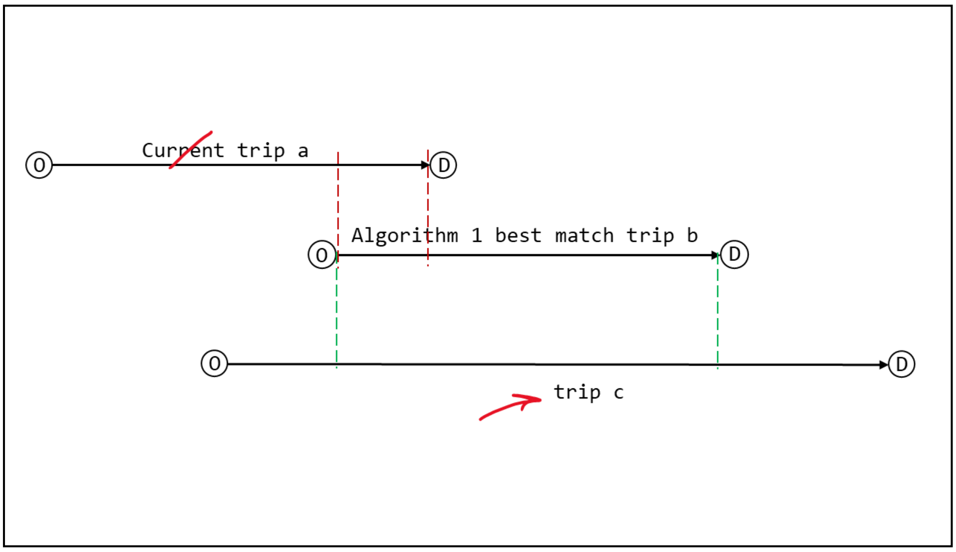


Figure 5. 5. Algorithm 2 best match selection

This time around instead of trip a, trip c is first in line to be merged which results in a higher utility for the system than algorithm 1 had to offer. The question might arise over why the trips that overlap completely, have the same origin and destination zone, are not paired first since at first glance it seems like a simple way to reduce the unprocessed trips load. The issue with this method is that although in theory travel between origin edges in the same TAZ should not be counted as a notable "trip" due to the short 750 meters proximity, in practice the vehicle does not always have a direct route between the two. Consider the two origin edges depicted in Figure 5. 6.

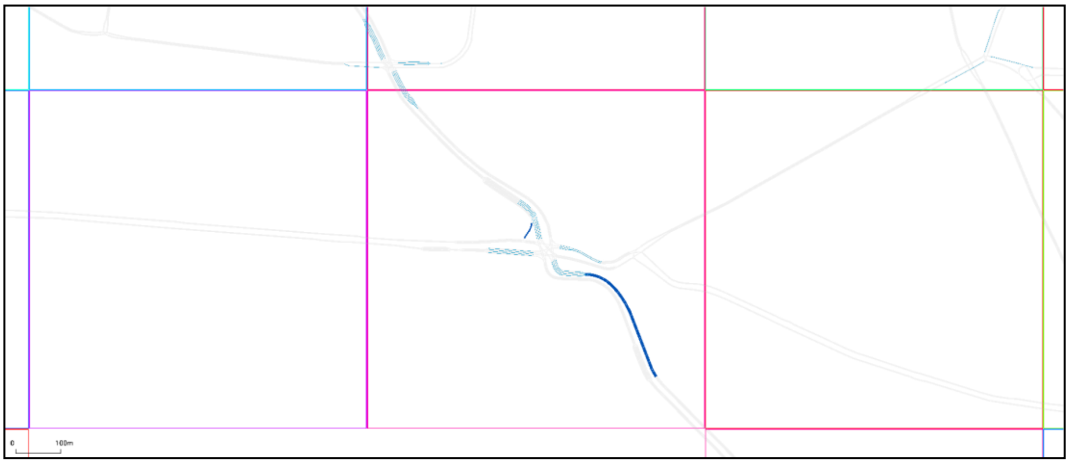


Figure 5. 6. Two origin edges within the same TAZ border

Since they are both inside the boundaries of one TAZ, hasty evaluation may suggest that one vehicle could pick up a passenger from one edge, the other passenger from another edge without it significantly affecting the total trip duration or VKT. But during the simulation, the route depicted in Figure 5. 7 is what occurs. Instead of finding a path between the edges within the TAZ, the extended route shown becomes the trip that a service vehicle must complete only to pick up two passengers who were within or less than 750 meters of one another.

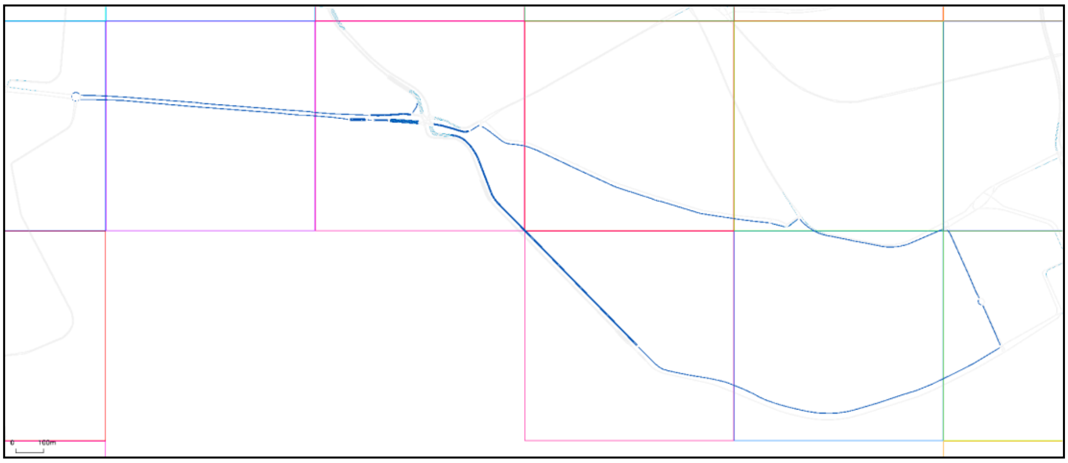


Figure 5. 7. service route between two edges of the same TAZ

This is partially due to the network structure and partly due to the elimination of lower-level roads, alleys, and such, that creates this additional travel, completely undermining any predicted gain from this merge. So, all trips are treated using the aforementioned algorithm.

5.3.3 Second Algorithm Without Blocking

When running the ride-sharing service based on algorithm 2 on the network, it became apparent that during the intermediate stops of shared trips on one-lane roads, the vehicle stopping for access/egress was blocking the traffic behind it. Although the stop is scheduled for 30 seconds, this is still an artificial interference since in actuality there is roadside or parking space for vehicles to stop and they would not influence the traffic flow. This blocking effect is shown in Figure 5. 8.

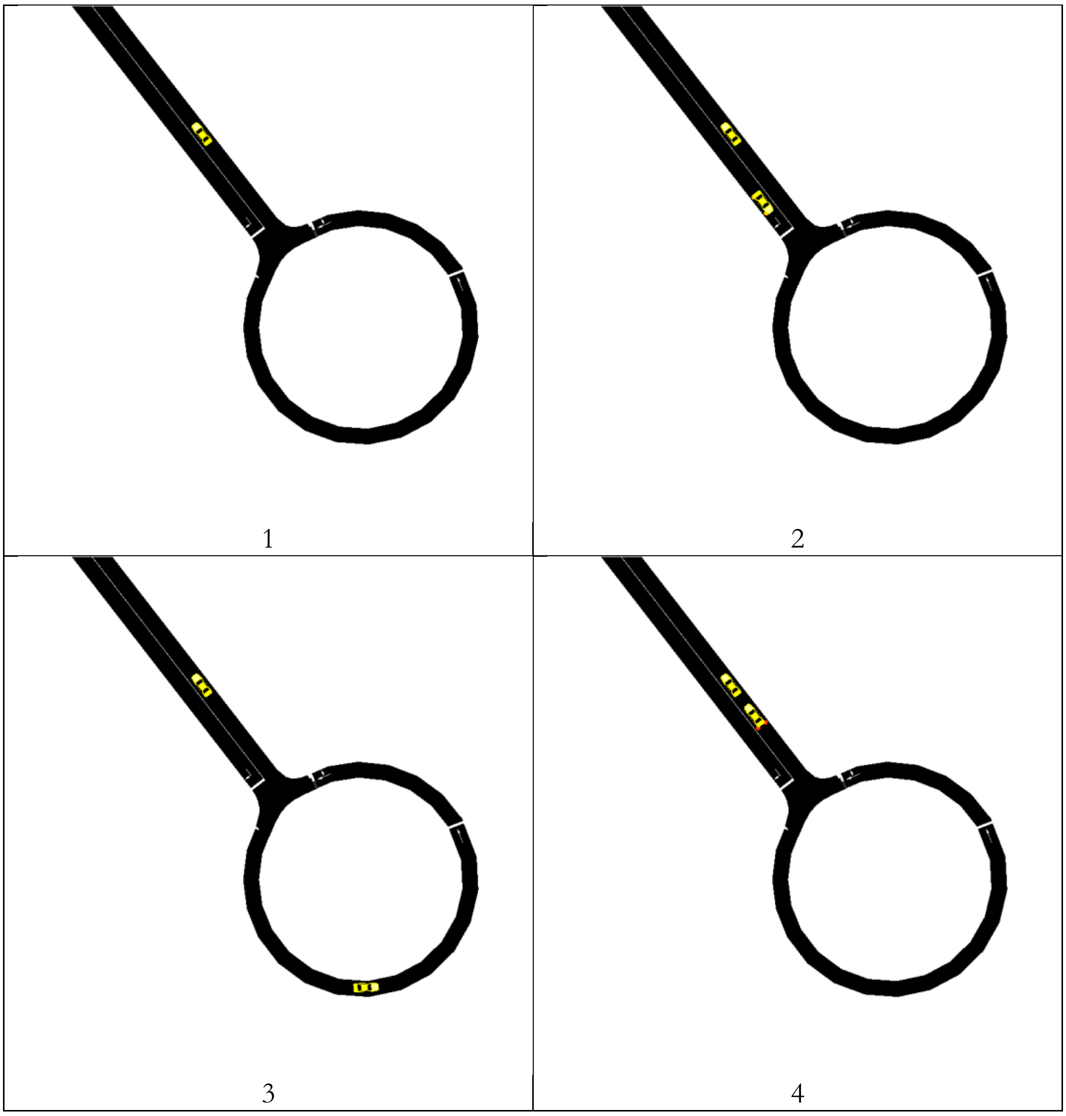


Figure 5. 8. SUMO screenshot of a blocking incident sequence

One could resolve this issue by not programming the vehicle to make a stop during the shared trip but add the stopping time to the total travel time at the very end of the trip manually. However, that too would be an inaccurate representation of the vehicle agent in the simulation. So, it was decided to instead take advantage of SUMO's treatment of its vehicles. In SUMO after the vehicle completes its trip, no longer have a request to fulfil, it "disappears" from the network; just like in reality when a car is parked at the end of a trip. As in, the inactive time of a vehicle that it spends parked is not simulated. Therefore, if a shared trip is broken down to its three legs, from origin to first stop to second stop to destination, and the departure times from the intermediate stops are planned with accordance to their original shared trip schedule then when a vehicle completes the first leg it vanishes and would not disrupt the traffic.

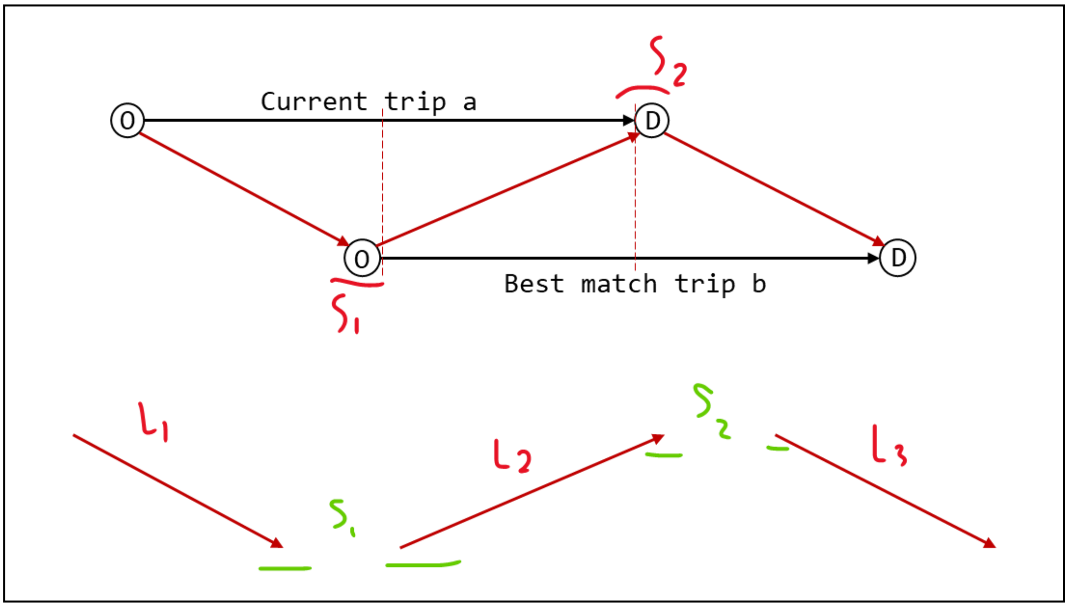


Figure 5. 9. Visual example of the "relay" style solution to blocking

In the example depicted in Figure 5. 9, a merged trip is seen with its two scheduled stops S_1 and S_2. When it is broken down to its three legs, the first stop concerns the second leg's departure time $t_d(L_2)$ which is calculated based on the estimated arrival time of the first leg $t_a(L_1)$, since the vehicle was supposed to complete the first leg L_1 then stop for 30 seconds, now that 30 seconds should be added to the $t_d(L_2)$ and same logic applies to the second stop. With this solution the vehicles still interact with traffic as they might have done when completing only one shared trip. To recap, a vehicle should complete the L_1 leg and exits the system, then a second vehicle must depart from L_2 using the following formula's results as its departure time:

$t_d(L_2)$ = estimated $t_a(L_1)$ + 30 seconds
$t_d(L_3)$ = estimated $t_a(L_2)$ + 30 seconds

This approach could be likened to a game of relay with three sections where vehicles take turn completing part of the route. At this point, keen observers might notice that this could result in an internal inconsistency in the model since during the simulation the vehicle completing L_1 might not arrive at its destination at the exact time estimated due to traffic or road obstruction, but the vehicle tasked with L_2 would still depart at the predetermined time, before the first vehicle has arrived. Following the relay example, the second athlete has taken off before the first athlete could hand over the "baton". This inconsistency was deemed acceptable by the author in favour of closer approximation to real traffic behaviour.

```
<trip id="2151091-150804" depart="79041.14" from="130098568" to="771927898" via="7518834 7325180" departLane="free" departSpeed="max">↓
    <stop edge="7518834" endPos="516" duration="30"/>↓
    <stop edge="7325180" endPos="252" duration="30"/>↓
</trip>↓



<trip id="2151091-150804-0" depart="79041.14" from="130098568" to="7518834" arrivalPos="516.0" departLane="free" departSpeed="max"/>↓
<trip id="2151091-150804-1" depart="79348.39" from="7518834" to="7325180" departPos="516.0" arrivalPos="252.5" departLane="free" departSpeed="max"/>↓
<trip id="2151091-150804-2" depart="80670.35" from="7325180" to="771927898" departPos="252.5" departLane="free" departSpeed="max"/>↓
```

Figure 5. 10. Algorithm 2 with and without blocking in route file

Figure 5. 10 shows the difference between a shared trip characteristics before and after algorithm 2 without blocking has been applied to it. The author is aware of the parking availability in SUMO but using that entity was inessential as the simulation results are already satisfactory and it required massive amount of work in exchange for very little effect of merged trips synchronization on the results (see Appendix 9.1.10).

5.4 OVERVIEW AND EXPECTATIONS

To summarise the merging component is applied following these steps:

Step I
Choosing and implementing a merging approach to process trips (one of three)
    Algorithm 1
    Algorithm 2
    Algorithm 2 without blocking
Step II
    Joining the new processed trips to the remaining un-processed trips

Step III
Sorting all trips based on departure time
Step IV
Writing the new trips to new route file

The three algorithms make up comparative scenarios for assessing the AV ride-sharing service's impact on the baseline CO_2 emission for 2016. It should be noted that there is no difference in terms VKT between algorithm 2 with and without blocking since there is no change in overall trip lengths. So, based on the estimations during the merging process, the reduction in total kilometres travelled for the two algorithms, are:

Algorithm 1 compared to baseline: 32%
Algorithm 2 compared to baseline: 35.5%

So purely going by total VKT reduction, algorithm 2 is expected to perform better in emission reduction that algorithm 1. After the new route files are created the ride-sharing service could be simulated in SUMO the same way as the baseline run including ten simulations per scenario, since the service was employed for all ten baseline simulations, and it remains to be seen how these projections would turn out, in the next chapter.

6 RESULTS AND DISCUSSION

This study took on the challenge of adjusting urban mobility systems in line with the local, national, and international goals to contain and reduce the GHG emissions' effect on global warming, through introduction of an AV based ride-sharing service. As stated in previous chapters, such service is theorised to be able to greatly reduce CO_2 emission in developed vehicle dependent urban areas and by extension improve traffic flow in the highway rings and exit ramps passing through them.

Considering the urgency of the call for deploying mitigation measures to ensure we may still manage to limit global warming to 1.5°C by 2030, the evaluation of any intervening strategies in a timely and reliable way is of utmost importance. For this work's choice of policy, the potential combination of yet to be fully realised autonomous vehicles and ride-sharing were tested as a first step before committing to its implementation.

To determine whether an AV ride-sharing service tackling the personal vehicle fleet in an urban setting would reduce the associated CO_2 emission significantly, it must be demonstrated and the process leading up to said results must be replicable on any preferred network. So, in chapter 4 the work of selecting a case study for proof of concept, intricacies of data extraction for building the network and creating the synthetic traffic flow was described. In this chapter of the thesis, the results of testing the developed methodology on the city of Rotterdam are examined. This proposal then ends with the conclusions and the implications for future research on this topic in the next chapter.

6.1 COMPARATIVE SIMULATIONS' RESULTS

The city of Rotterdam with its ambitious plan to reduce its GHG emissions by 49% and the share of private vehicles in the city centre from 42% to 32% in 2030 (Rotterdam, 2019), was selected as the case study for exploring the impact of the ride-sharing service. The road network characteristics, and much of the data used for constructing the baseline conditions were obtained from publicly available resources from 2016, since the most consistently sourced data belonged to official documents from this year.

What was especially important, was the transport modal share of trips to and from the city centre area and the volume of the private vehicles. These numbers dictated the traffic assigned to the model, of the daily vehicular traffic on the network. There are fluctuations in terms of traffic levels during the week and in span of a full year, but since the numbers available are the median of the city's data set and this evaluation is concerned with the overall impact on the system, a degree of separation is considered acceptable. So, the following comparative results of full day simulations could be extrapolated to the whole year.

The baseline, Rotterdam's average daily private vehicle traffic in 2016, behaviour constructed by this methodical data driven approach is compared to the three scenarios of merging trips using the ride-sharing service. These scenarios' performance, in terms of total VKT and trade-off through average passenger time lost, and impact on CO_2 emission are detailed below. The three scenarios refer to the different merging algorithms, algorithm 1, algorithm 2, and a variation of the second algorithm without blocking.

6.1.1 Impact on Traffic Variables

SUMO simulations can generate a wide variety of output files containing different measurements of the network and its agents' performances. These files contain any number of selected information like vehicle positions in each simulation step, trip information, route information, and overall network statistics. For this research the most valuable evaluation metric for passenger satisfaction and merging component quality check, is the travel time comparison.

Through extraction of the *o_rtm.trip_output.xml* file, two SUMO designed variables "waitingTtime" and "timeLoss" could be known for every trip completed during the runtime. These variables are defined as such:

> waitingTime: Recorded time that vehicle speed drops to or below 0.1m/s, effectively standstill, during the trip. This number does not include scheduled stops
>
> timeLoss: Extra time incurred during the trip calculated based on incidents when vehicle speed dropping below the ideal speed, due to traffic or road obstruction.

For every trip along with its id, departure time, trip length, arrival edge and other information is documented. The unscheduled extra time that a vehicle has had to stop or slow down due to congestion has also been recorded in two variables. Combined, they represent the difference between a trip's theoretical duration, when following a car commercial logic of driving through an empty city, and the actual duration of said trip on the road network interacting with and influenced by traffic. In this text, this concept is represented by *"Total Time Lost"* and calculated as the following:

Total Time Lost = SUMO output waitingTime + timeLoss

The metric *"Total Time Lost"* is calculated for every trip in all ten baseline simulation runs separately, without ride-sharing. Then the average of those numbers amongst the ten simulations, is used to chart the distribution of time lost. The same procedure is repeated for two ride-sharing scenarios, algorithm 1 and 2. The two graphs can be seen in Figure 6. 1.

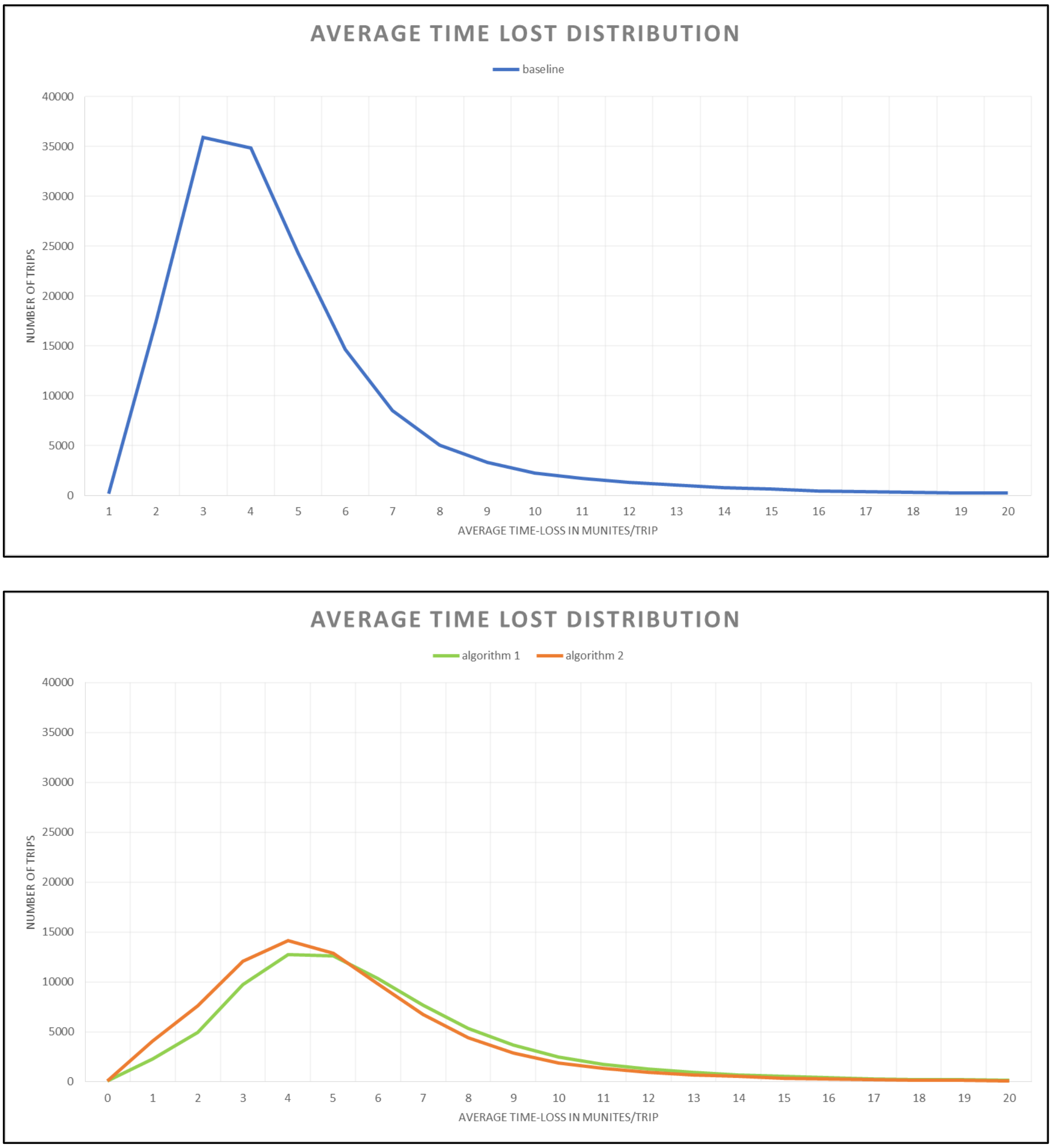


Figure 6. 1. Average time lost trend in baseline, and then in algorithm 1, and 2 simulations

In the average time lost graph, the y axis shows the number of trips experiencing a certain amount of extra time added to their trip duration, expressed in minutes on the x axis. For example, during any baseline run on average 34,850 of the trips will encounter an additional 3 minutes of extra travel time. In fact, in all three network states, there are very few trips that do not experience any loss of time, less than 500 in each run, and arrive to their destination precisely as scheduled.

With the estimated reduction in the number of vehicles in the network and VKT, it was predicted that merging of half of the trips would not significantly change the quality of the trips for the passengers who transferred from their private vehicles to a shared ride. The Table 6. 1 shows the average number of trips completed, the estimated reduction in VKT that was calculated before simulation, and the observed VKT reduction from the baseline recorded after the simulations were completed:

SCENARIO	TRIPS COMPLETED	VKT REDUCTION ESTIMATED	VKT REDUCTION OBSERVED
BASELINE	155,598	-	-
ALGORITHM 1	79,634	32.15%	21.27%
ALGORITHM 2	82,401	35.53%	24.91%

Table 6. 1. reduction percentage in VKT for baseline, and two ride-sharing scenarios

So, the passengers who had to take a detour due to sharing their ride, would overall not experience a significant addition to their travel time. That is because the network becomes less crowded and subsequently has a smoother flow of traffic. The time lost result confirms that assumption, since the peak of the merging scenario graphs, representing the time lost experienced by the highest number of vehicles, remains close to the peak in the baseline state. The merging and baseline graphs were separated for better visualisation, since the drop in the number of trips experiencing time lost is in most part due to the fact that the number of trips in total was almost cut to half by ride-sharing. The average number of trips completed by each algorithm can be seen in the second column of Table 6. 1.

With this metric algorithm 1 is performing slightly better only in terms of reducing the number of trips with lost time around the peak. Algorithm 1 manages to find more pairs to match, therefore winds up with less trips. But the second algorithm makes more optimised matches, and subsequently has a higher VKT reduction rate, and its time lost peak is lower at 4 minutes. The average extra time that a trip might experience in each network run is also shown in Figure 6. 2. The question that might be raised here is that considering the decrease in the number of cars and in traffic, why has the time lost increased in the merged trips scenarios?

The explanation is that although the distance of the combined trips is shorter than the sum of the distances of the two original trips, it is still greater than either of them separately. Thus, more time is spent on the route. This clearly shows itself in the difference between the lost time of algorithm 1 and 2 since algorithm 2 combines trips using a more ideal selection process. Also, this is roughly the lost time for two trips and could be divided by two in reverse.

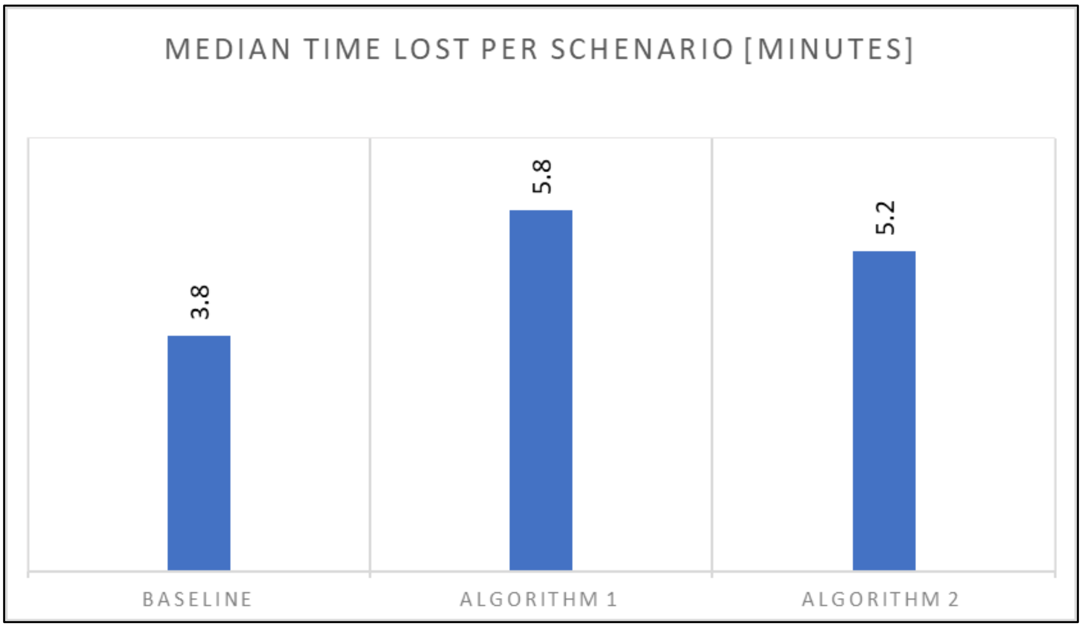


Figure 6. 2. Median lost time for baseline and all scenarios

The third scenario, algorithm 2 without blocking, was not included in the distribution graph, or median time lost. The reason is that to avoid the blocking issue merged trips were divided into their three legs, which synthetically triples the total number of the processed trips, so it could not be easily compared with the other scenarios in terms of sheer trip numbers. Nor could the median average time lost be included in the analysis here since the trip output file for this third scenario shows the statistics for the separated trip legs.

It is theoretically possible to track the three legs of each merged trip in algorithm 2 without blocking scenario, to determine the time lost for each leg and then aggregate the values for the entire shared trip. When done, it could decidedly be compared with the other two scenarios. But that would involve a separate lengthy process just to confirm that those aggregated numbers would not significantly deviate from the algorithm 2 results in this segment.

The third scenario is a slight deviation from the second. The difference is not in terms of how the matches are selected and trips are paired, but how the vehicles behave in the network. In the third simulation series, the vehicles behave as they would in real life when stopping for access/egress. As in, they do not block the on-going traffic, but simply pull over to the parking area on side of the road. The third scenario emulates this specific behaviour and is otherwise identical to algorithm 2 in terms of merging process. Though, SUMO includes a parking entity module, using that entity was inessential as the simulation results are already satisfactory with the non-blocking option.

The last observation based on these variables is that the merging mechanism works as intended for all scenarios. Meaning that the passenger's tolerance window for departure time delay and increased total travel time incorporated in the design of the pairing mechanism has worked in practice too. And algorithm 2 is confirmed as the better option, with lower average time lost, and higher VKT reduction rate.

6.1.2 Impact on CO_2 Emission

Moving to the main alure of the ride-sharing service, its impact on the CO_2 levels, the aggregated edge-based emission is gathered for all the TAZs (see Appendix 9.1.12), and the baseline is compared to network's state after the three merging algorithms have been applied to the trips. Images below show the changes in CO_2 levels, visualised in kepler, shown in Figure 6. 3.

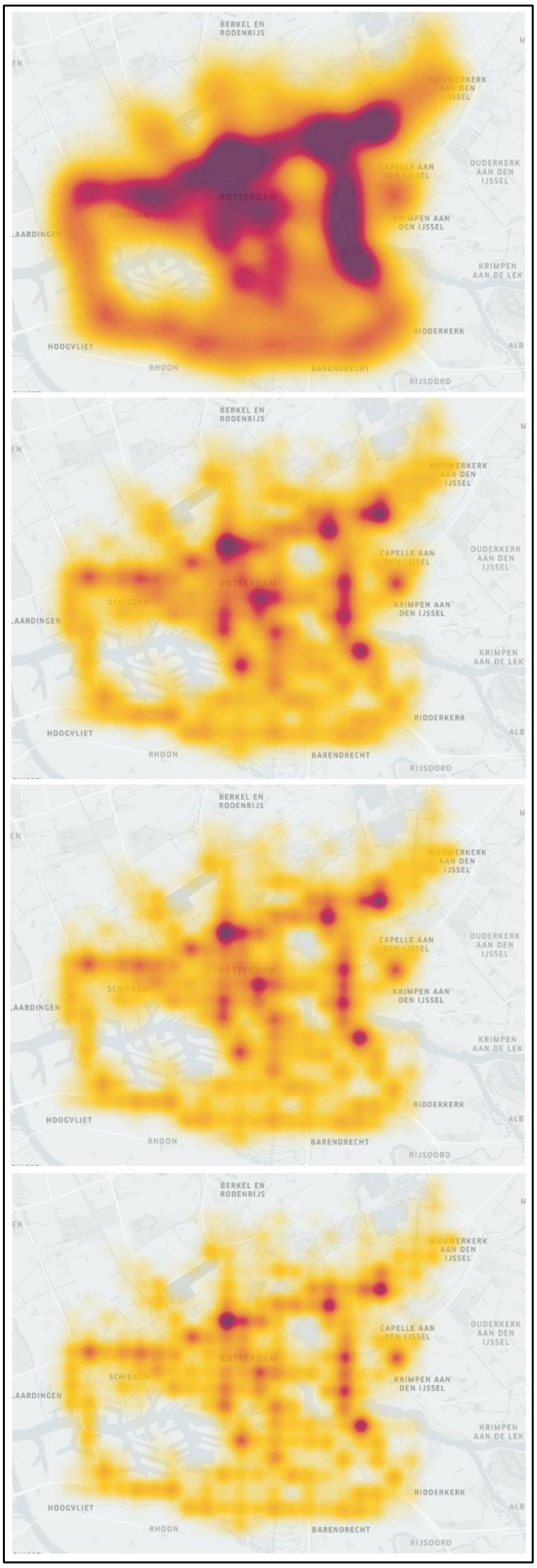
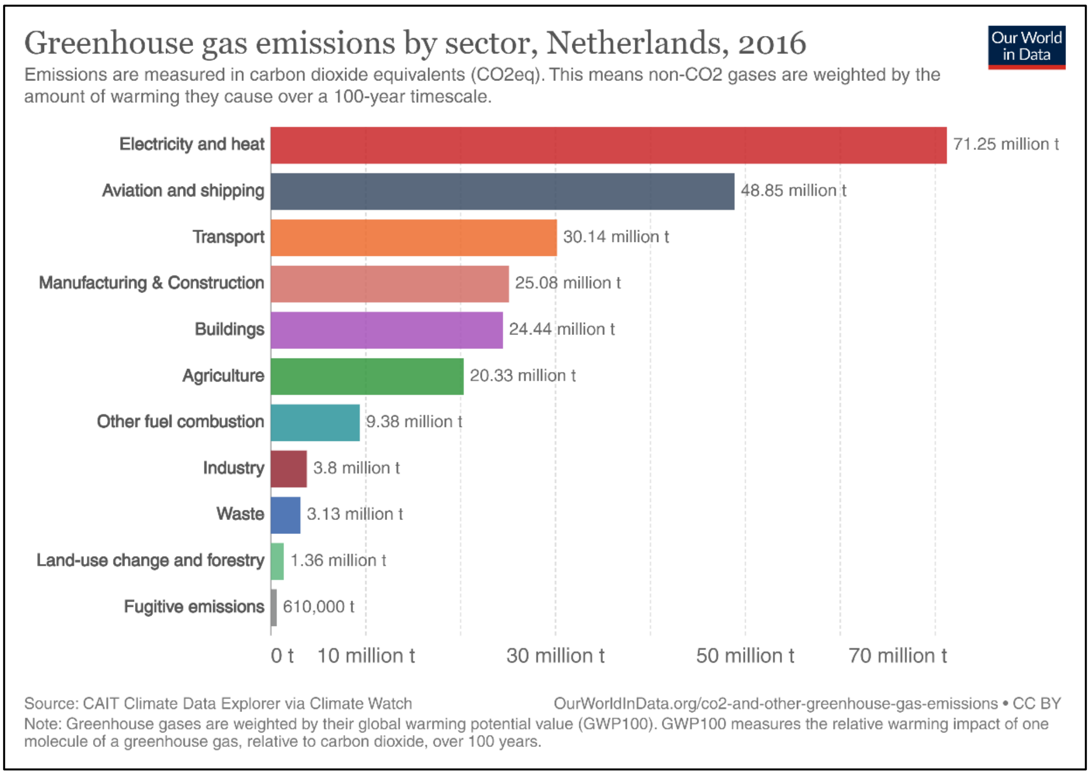


Figure 6. 3. CO_2 emission levels in baseline, algorithm 1, algorithm 2, and algorithm 2 without blocking



Source: CAIT Climate Data Explorer via Climate Watch OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY
Note: Greenhouse gases are weighted by their global warming potential value (GWP100). GWP100 measures the relative warming impact of one molecule of a greenhouse gas, relative to carbon dioxide, over 100 years.

Figure 6. 4. Yearly CO2 emission per sector in the Netherlands

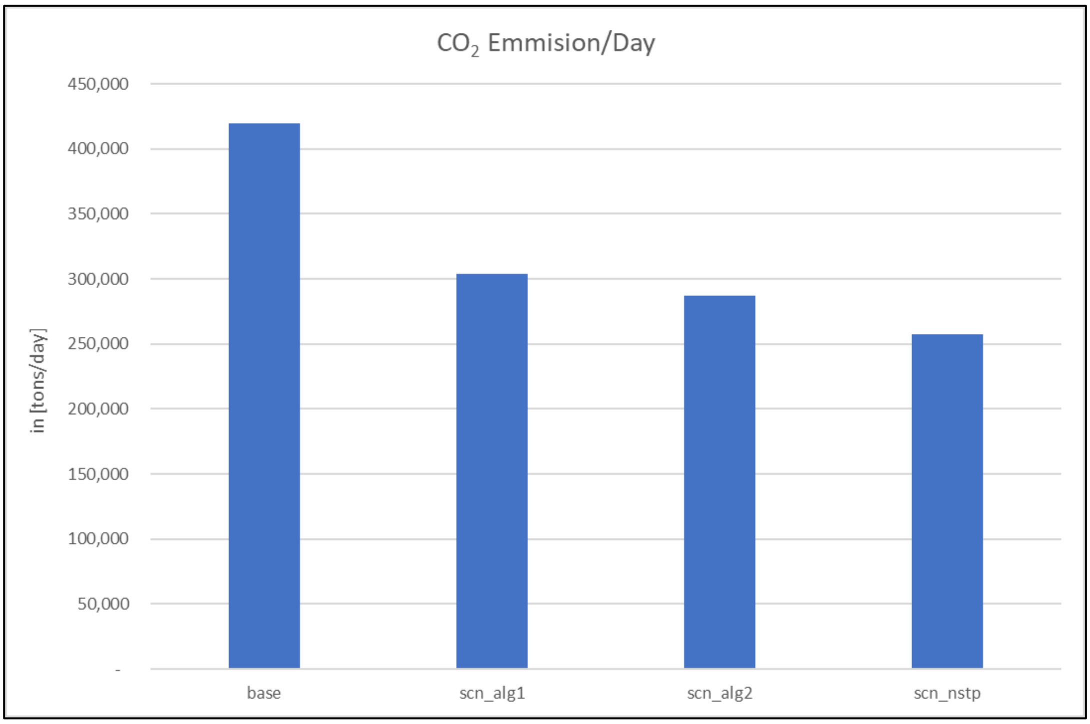


Figure 6. 5. Total daily CO_2 emission per scenario

The total emission per day for the baseline, and ride-sharing scenarios are depicted in Figure 6. 5. The Figure 6. 4 is included as a reference and shows the recorded CO_2 emission for the Netherlands in 2016 per each sector. Following the relations between Rotterdam's vehicular CO_2 emission and the national levels, elaborated upon in section 2.1.2, the baseline simulation's emission turns out to be around a third of the reference volume.

This is due to several reasons; Firstly, the constructed traffic model does not include public transport vehicles like bus and tram which share the street level network with private vehicles in Rotterdam amounting to more traffic jam in reality. Secondly, the reference CO_2 level for 2016 also includes non-CO_2 gasses expressed in carbon dioxide equivalent, while the SUMO output is only the CO_2 emission. The emissions from road freight, and diesel vehicles were also not included in the simulation. All standard vehicles loaded in simulation were set to run on gas. Lastly, the reference used for the volume of the daily private vehicle traffic in Rotterdam, around 156,000 cars, did not contain the CO_2 levels recorded. Those levels had to be obtained from another source. So, there might also be a disparity in reference data due to varying measuring standards.

Overall, this difference is not cause for concern, especially since the absolute emission numbers themselves are not a point of interest but the focus is on the relative changes after the utilisation of the different ride-sharing scenarios and their corresponding performance.

This series clearly shows that the CO_2 levels progressively decrease more and more as the merging algorithm gets closer to the optimal solution. The percentage of total reduction in comparison to the reference baseline levels, per scenario is as following:

SCENARIO	CO_2 EMISSION REDUCTION
ALGORITHM 1	28%
ALGORITHM 2	32%
ALGORITHM 2 WITHOUT BLOCKING	39%

Table 6. 2. CO_2 emission reduction percentage in each ride-sharing algorithm

It should be noted that the decrease in emission production is the cumulative result of fewer vehicles on the road, less VKT, and better flow of traffic resulting in more efficient fuel consumption. Since the vehicles can better utilise, the maximum permitted, different per edge based on traffic regulations, and more consistent speed during their trip. Based on these results and the quality considerations in the previous section, the third scenario, algorithm 2 with realistic stop and go mechanism, achieves the best result. Also, the strategy of focusing on pairing longer distance trips first, brings us closer to better emission reduction percentage.

7 CONCLUSION

In this last chapter, the research question, implications of this work, and what still remains unanswered are discussed and finally recommendations for further research in this field are included.

7.1 CONCLUSIONS

In this thesis, a method for examining the impact of autonomous ride-sharing service on the CO_2 emission levels in an urban area was developed. The process started by building a complete synthetic traffic flow model based around core and minimal observed data in Rotterdam. Then, the road network is constructed and cleaned. And two near optimal merging algorithms and a variation on the second algorithm are programmed for the merging component of the ride-sharing service. Finally, the algorithms are simulated in SUMO and their effect on network variables, and CO_2 emission documented.

The result of this process confirms the great potential of such a service in reducing CO_2 emission in an urban setting and showcasing its alignment with the local trajectory goals for climate change mitigation. Considering that in this research the tolerance window for passenger time loss trade-off were set in the lower bounds, and that calculations are based on merging of only half of trips without yet determining the true potential size of the fleet or secondary level impacts on emission due to changes in land-use, less parking space, the ride-sharing as a new hand of the public transport holds likely value. Table 7. 1 summarises the results.

SCENARIO	TRIPS COMPLETED	MEDIAN TIME LOST	VKT REDUCTION OBSERVED	CO_2 REDUCTION
BASELINE	155,598	3.8 min	-	-
ALGORITHM 1	79,634	5.8 min	21.27%	28%
ALGORITHM 2	82,401	5.2 min	24.91%	32%
ALGORITHM 2 WITHOUT BLOCKING	-	-	Same as alg2	39%

Table 7. 1. Network variables in all scenarios

Most of the passengers will be satisfied with their shared ride and arrive at the destination having not lost a great deal of their time on the trip, that could have been avoided if they used their own vehicle.

Thereby the proposed research question, *"How would adopting a shared autonomous vehicle service in a city affect the co2 emission?"*, was answered by developing a adaptive and adjustable blueprint for localised testing of a ride-sharing system, and the proof of concept for the city of Rotterdam including the performance evaluation of the different merging components and the final overview of the benefits. This work can therefore be used by transport authorities as a preliminary step to systematically evaluate and rank proposed ride-sharing technologies and open the door for successful deployment on the real network.

There of course remains some concerns and unaddressed questions. This thesis did not incorporate existing public transit fleet in the network and therefore the private vehicle traffic was studied separately; The assumptions with regard to the selection of study area, aggregation levels, changes to the network structure, assumptions and choices made to resolve the lack of observable data while supported by at time compelling arguments can still be subject to rebuttal; It is not clear how much passenger/user behaviour could impact the demand for the service or what would be the effect of it on people who currently do not own vehicles and primarily use PT but would become interested in using such service when it becomes available.

The most important contributions of this research are: the complete ready to use network of Rotterdam created in SUMO, three different heuristic merging algorithms written in python for a MaaS ride-sharing service, proof of concept and confirmation on the proposed AV ride-sharing mobility solution's impact on CO_2 reduction. So, the developed methodology framework has proved *effective* in providing insights on service performance and impact analysis, can be used as a *tool* for transport authorities to assess emerging mobility trends, is *adaptable* to chosen network's characteristics and integration of relevant agents.

7.2 RECOMMENDATIONS

This research can be expanded and upon in various stages and considerations. The next logical step in the evaluation of a service of this kind, if it is to be combined with the existing public transport network structure, is the inclusion of mode choice in the model. The research on the interaction of a publicly operated ride-sharing service with the bus, tram, metro, and intercity train service, be it as a standalone mode or complimentary to these services in fulfilling the last-mile requirements of trips leaves so much room for further exploration. It is important to flesh out the supposedly positive impacts of the system against its potential to syphon users away from the public transport services and increase the demand for smaller taxis. Inadvertently reversing the initial emission reduction by increasing road traffic in the end.

The second perhaps more pressing issue is the inclusion of the private vehicle owners' attitude towards joining these types of services. In this research the entirety of the vehicular traffic was used as a demand input for the service. This is not the case for existing taxi or car-pooling services. So, evaluating the age, cultural background socioeconomic, or disability status of the target population and the relation of each metric to their likeliness in using the service would create a more realistic view of its likely performance.

Exploration of tariffs and subsidy schemes is another important area for further exploration. For example, incorporating ride-sharing with the currently operational OV door-to-door shared car initiative, incentivising the use of AV ride-sharing as an extension of PT and encouraging the use of the service in a way that brings the passengers back to PT modes instead of competing with it for end-to-end trips. Pushing the users more towards the use of service for longer trips with higher fees for shorter ones and generally higher costs than buses or metro, walking or cycling, while also making private vehicles a less attractive option. How the pricing affects demand is an extensive subject that also includes changing the system's choice variables to utilise the user's behaviour spectrum. For example, some passengers might have a wider window of time lost tolerance and would be willing to wait longer or take further detours in exchange for lower prices. But these types of cost to demand and service quality research must be combined with ethical and social considerations so that a service discount does not inadvertently become a punishment for lower income users and abuse their flexibility.

The design of the user interface component of the service, and its accessibility was also outside of the scope of this research. It is important to remove obstacles when introducing a new service to the public and make the use of it as simple and intuitive as possible, also considering accessibility issues for disabled users, not only in terms of the requesting platform but the vehicles as well, language and technology barriers for older or non-local users.

In its current phase, this approach could already be of use to transport authorities and local/regional governing bodies. However, it is a primary tool and by itself cannot directly and definitively inform concrete policies. One major obstacle standing in the way is the uncertainty around when or if AVs will become ubiquitous, and how soon after could they become a public transportation mode player. This issue could prevent a decisive move towards AV dependent designs in the ride-sharing category.

Larger and varying solutions could be explored even without waiting for more promising steps in making full AVs a reality, and this methodology offers a decent path in succinct exploration of each policy, independent of the particular technology enabling it. So that efforts may be better and more accurately directed toward the most promising ideas when developing policy roadmaps.

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9 APPENDIX

9.1 PYTHON CODE

This appendix section details the entire process of creating the case study model and the subsequent simulation runs for the base case and alternative scenarios. It is in accordance with the Figure 3. 1. methodology in picture. The python code crafted by the author is uploaded to the TU Delf's dataset repository and is accessible through the assigned DOI.

9.1.1 Defining the City Boundary

Official administrative boundary could be viewed via:

https://haoliangyu.github.io/boundary.now/

Then the BBBike Rotterdam is used for the extended study area:

https://extract.bbbike.org/?sw_lng=4.355&sw_lat=51.858&ne_lng=4.609&ne_lat=52.002&format=o5m.xz&coords=4.363,51.874|4.459,51.858|4.501,51.859|4.542,51.861|4.584,51.867|4.583,51.901|4.583,51.924|4.609,51.966|4.601,52.002|4.521,51.98|4.488,51.981|4.435,51.981|4.374,51.959|4.355,51.925&layers=0B00T&city=Rotterdam, South Holland, Netherlands&lang=en

9.1.2 Downloading OSM Data

The area is downloaded from BBBike, and renamed to simpler file name as:

```
rtm_network.o5m.xz
```

The xz file is extracted with WinRAR into its corresponding folder, which will be *rtm_network.o5m* or could be renamed to *rtm_network*, or a different name related to various case study cities. The network is then converted to a filtered OSM using the *Osmfilter* command as following:

```
osmfilter: https://wiki.openstreetmap.org/wiki/Osmfilter
```

Executed line in Command Prompt (cmd):

```
..\osmfilter rtm_network.o5m.o5m --parameter-file=
NetworkSimplify_filter.txt -o=rtm_filtered.osm
```

The resulted *NetworkSimplify_filter.txt* is included in the repository data set collection. This filtered OSM file is then imported into the Netedit environment. The only difference between *netconvert* and *rtm_final_sim* file is that the *rtm_final* file is broken into plain files to change the traffic light control system to dynamic. After this change is made the plain files are once again combined into the network file *netconvert*. If the traffic lights are not changed in this way, it would have to be done individually and one by one in *rtm_final*. The command to complete the traffic light conversion and creating the final network form file *rtm_netconvert.net.xml* is as following:

```
    %sumo_home%\bin\netconvert -e rtm_plain.edg.xml -n
rtm_plain.nod.xml -x rtm_plain.con.xml -i rtm_plain_db.tll.xml -t
rtm_plain.typ.xml -o rtm_netconvert.net.xml --ignore-errors.edge-
type
```

9.1.3 Defining TAZs

In cmd changing the directory to the location of the rtm network file and in the next step the following command is run:

```
d ..\net_files

Python %sumo_home%\tools\district\gridDistricts.py -n
rtm_netconvert.net.xml -o taz_gd_py.xml -w 750
```

The resulted file *taz_gd_py.xml* is loaded in Netedit over the network and then saved as *taz_gd_sumo.xml*.

9.1.4 Extracting Land-Use Data

First all OSM keys are extracted to *rtm_keys.txt*:

```
osmfilter rtm_pg28.o5m --out-count >rtm_keys.txt

osm_keys = [
    ['restaurant', 'rtm_val_restaurant'],
    ['fast_food', 'rtm_val_fast_food'],
    ['school', 'rtm_val_school'],
    ['cafe', 'rtm_val_cafe'],
    ['amenity', 'rtm_val_amenity'],
    ['place_of_worship', 'rtm_val_place_of_worship'],
    ['bar', 'rtm_val_bar'],
       .
       .
       .
    ['station', 'rtm_val_station'],
    ['retail', 'rtm_val_retail'],
    ['residential', 'rtm_val_residential'],
    ['commercial', 'rtm_val_commercial'],
    ['tourism', 'rtm_key_tourism'],
        ]
```

* First element is OSM key and second is used as a file name for the extracted data

In the next step for every extracted key all sub values are found, for example all values under the key "amenity" could be listed using the command below and stored under *rtm_key_amenity.txt*:

```
..\osmfilter rtm_pg28.o5m --out-count=amenity
>rtm_key_amenity.txt
```

For each of these sub-keys GeoJson File must be created and saved; this file contains various geographic data related to that key. To query OSM and export it to GeoJson format the following online tool is used. The following showcases multiple examples for multiple sub-key values. The (51.858,4.355,52.002,4.609) corresponds to the study area polygon points:

https://overpass-turbo.eu/ keep file name pattern.

either a “key” or “key = value” is used
examples:

```
// to extract all golf entries, (257    golf)
// file name is:    rtm_key_golf.geojson
[out:json];
nwr['golf'] (51.858,4.355,52.002,4.609);
out center;

// to extract pharmacies
// file name is:    rtm_val_pharmacy.geojson
[out:json];
nwr['amenity'='pharmacy'] (51.858,4.355,52.002,4.609);
out center;

// to extract theatres, banks and libraries (21+20+19 entries)
// file name is:    rtm_val_misc_1.geojson
[out:json];
nwr['amenity'~'theatre|bank|library']
(51.858,4.355,52.002,4.609);
out center;
```

So, the general format to check the presence of a certain key or key/value in a small area, to avoid loading error with selecting too large of a sample, using overpass is as following:

```
// zoom to centrum until map scale is about 30m
[bbox:{{bbox}}];
nwr["capacity"];
out center;

// zoom to centrum until map scale is about 30m
[bbox:{{bbox}}];
nwr["leaf"];
out center;

// zoom to centrum until map scale is about 50m
[bbox:{{bbox}}];
nwr["highway"="traffic_signals"];
out center;
```

9.1.5 Land-Use Element Count per TAZ

To determine what businesses and other commercial or leisure elements exists in each TAZ, the file *mht_taz_count.py* was written and run as a called function. This code counts all business within each and all TAZs and copies the numbers to the clipboard which could then be pasted manually in an excel sheet right away:

```
Python mht_taz_count.py
```

The individual counted land-use elements per TAZ can be seen on "business count per TAZ" and the count for each constructed main category is on sheet "Count per Category" in the *business_count_rank.xlsx* file that is also included in the available dataset. The main categories are as following:

Care Facilities:

pharmacy, kindergarten, dentist, medical-dental office building, doctors, nursing home, childcare, clinic

Recreational Facilities:

place of worship, social facility, recreational community centre, community centre, library, arts centre, cinema, social centre, studio, conference centre, dog racetrack per attendance capacity

Miscellaneous high importance (high frequency visits):

college, hospital, townhall, government office building, marketplace shopping centre, university, station, P&R lot with bus service

Commercial:

Retail, specialty retail centre, department store, apparel store, shop, variety store, free standing discount store, shopping centre, supermarket, sporting goods superstore, electronics superstore, toy / children's superstore, pet supply superstore, arts and craft store

Food Industry:

restaurant, quality restaurant, high turn-over (sit down) restaurant, fast-food, fast-food restaurant without drive-through window, fast food restaurant with drive-through window, fast food restaurant with drive-through window and no indoor seating, café, coffee/donut shop without drive-through window, pub, bar, casino/ video lottery establishment, drinking place

School

elementary school, middle school/junior high, high school, private school

Leisure

city park, miniature golf course, bowling alley, amusement, health / fitness club

Tourism

hotel, museum

9.1.6 Calculating TAZ Attraction Rank

To calculate the significance (weight) of each main land_use category a reference sheet is used and the calculations can be found in detail in "Weight per Category calc" sheet in *business_count_rank.xlsx* file.

In the next step, to simplify the TAZ rank computation the main category count per TAZ is read through function *get_rtm_arr()*. The weights for each category is added in the *rtm_wght_demand* array, and since all the criteria here are benefits hence their increase positively impacts the dynamic, +1, they are defined in *rtm_app* are hard coded in python file *TAZ_Topsis_Rank.py*.

By running *TAZ_Topsis_Rank.py* the resulted ranking values are copied into the clipboard and could be pasted manually in an excel sheet. In this work, the “Count per Category” column M shoes the rank for each TAZ id.

9.1.7 OD Matrix

Running the following command, calling the *mht_ODMatrix.py* code, creates OD matrix files for each planned 24 simulation hours from 0:00 to 23:59 and saves them all to the *od_files* folder.

```
Python mht_ODMatrix.py
Saved in ..\net_files\od_files
```

9.1.8 SUMO OD to Trips

When saving the essential files such as network and route cfg files, they have to be in one assigned folder, named *net_files* in this case. It should be noted that the *base_path* referenced in the python code for accessing those network files needs to be absolute, since the used SUMO version 1.11.0 does not support relative paths.

The following codes must be run in cmd to create relevant simulation folders for the base_run, scenario algorithm 1, scenario algorithm 2, and scenario algorithm 2 without blocking, in the parent folder sim_runs. After the second command all the route cfg and route xml files for all base_run simulations are made as well.

```
Python mht_CreateFolders_cfg.py
Python mht_od2trips.py
```

At this stage, the base-run simulations could technically be completed but running the actual simulations are relegated to the end after the merging of trips using different scenarios are also done. To make the route files for trip merging scenarios more steps are required and are listed below.

9.1.9 Edge to Edge Distance

When considering different combinations of trips to merge, the important selection factor for picking the best combination is the subsequent mileage overlap when two trips are combined into one or the "gain". To do that distance between starts and end of all the selected trip's edges must be calculated. which would have been heavily repetitive and cumbersome to do every time when merging the trips, so it was calculated once for all edges to save time and used as a reference since it remains static and is based on the network structure.

To benefit from faster processing of the edge-to-edge matrix is an integer array, so to preserve the accuracy the distance unit is centimetre. This edge-to-edge matrix has 5024*5024 = 25,240,576 cells and about 100 MB of data. To increase the efficiency even more, the operation is partitioned to 200 row sections which can be parallel processed separately using *mht_edge2edge_turbo.py*.

The *rtm_edg_ids.txt* is a sorted list for binary search and is created automatically through the *mht_edge2edge_turbo.py* and all the edge-to-edge distances are sorted in sections of 200 entry hex files.

```
e2e_0000_0200.hex
e2e_0200_0400.hex
e2e_0400_0600.hex
.
.
.
```

All these hex files are in the folder *e2e_files*. This folder also contains the length of each individual edge in the *rtm_edge_len.txt*.

9.1.10 Merging Trips

The trips are merged using three different methods, scenarios, through running the mht_TripFusion_all.py. After that the route cfg files for all the simulations are created and they can be run one after the other. Ten simulations per scenario including the base network with original trips.

```
Fusion:
        Python mht_TripFusion_All.py
Simulation:
        Python mht_SUMO_Run.py
```

```
Warning: Running each simulation will take around 30 minutes and
there are in total 40 simulations, so the overall running time of
this code is about 20 hours - subject to hardware specifications.
```

9.1.11 Edge to TAZ Share

To determine CO_2 emission per TAZ, the share of the edges falling in each TAZ must be determined first. Refer to the Figure 4. 17. For an example of an edge crossing multiple TAZs. The code file *mht_edge_taz_share.py* is called during the aggregation process in section `9.1.12.`

This code establishes what edges or parts of one edge exactly fall in which TAZ, and also converts the simulation emission output xml files for each simulation to csv in their corresponding folder. There is also a visualization test section to check the individual edge's TAZ share which is used to create Figure 4. 17.

```
..\python_code_files>python
>>> from mht_edge_taz_share import *
>>> edge_share_test(edge_id = '723115170')
```

9.1.12 Emission Aggregation

The *mht_EmissionAgg.py* is written and when its steps are run they create intermediate *o_emissions.csv* `files then` gather the emission output from all simulation scenarios for all TAZs and save them in three separate csv files, *taz_emm_run.csv*, *taz_emm_statistics.csv*, and *timeloss_statistics.csv*, in their corresponding *Results* folder.

```
Converting simulation emission output xml to csv
example in fourth run of algorithm 1:
      Folder alg1_run_004
      o_emissions.xml --> o_emissions.csv

base_run  --> results
scn_alg1  --> alg1_results
scn_alg2  --> alg2_results
scn_nstp2 --> nstp_results
```

These aggregated results could then be combined and compared manually to draw conclusions, as was the case here.

9.2 RESULT'S EXCEL SHEETS

The calculations and ultimate results are saved in three excel files as part of the data set (DOI 10.4121/20418552) and each contains the following:

- business_count_rank.xlx
  - business count per TAZ
  - Count per Category
  - t_taz t_rank
  - Weight per Category calc
- rtm_base_model_validation.xlsx
  - Completed Trips per Run
  - Validation
- All_scenarios_emm_LostTime_stats.xlsx
  - VKT Comparison
  - aggr_emm
  - emm reduction comparison
  - base_run
  - alg1_run
  - alg2_run
  - alg2_nstp
  - all_timeLoss

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