Potential Impact of Car-Based Crowdshipping on Vehicle Mileage and Carbon Dioxide Emission:

An Agent-Based Modelling Study Case

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Abstract

The significant growth in B2C e-commerce in the last decade increased the traffic and volume of parcels in last-mile delivery significantly. To mitigate the impact of the last-mile delivery service such as the increased traffic and carbon dioxide (CO2) emission, crowdshipping emerged as an innovation that utilise the travelling crowd as occasional courier to deliver parcels. The goal of this study is to analyse the potential impact of crowdshipping performed by private cars to the local vehicle mileage and its result to the CO2 emission. This is done by simulating the passenger and parcel delivery transportation activities in agent-based modelling platform using MASS-GT and MATSim. An integration framework to bridge MASS-GT and MATSim was formulated in this study to model the interaction between the passenger and urban freight transport. Several scenarios are formulated to analyse the impact of crowdshipping. The results show that the CO2 and passenger-kilometres savings in parcel delivery vans transportation is exceeded heavily by the increase in passenger transportation performed by cars. This results in a slight increase in passenger-kilometres travelled and CO2 emission caused by car-based crowdshipping, although the value is very small that could be considered insignificant. It was found that car-based crowdshipping won't either improve or worsen the impact of the current last-mile delivery system. It could be concluded that crowdshipping will be better performed using a more sustainable transport mode instead.

Keywords: crowdshipping, agent-based, MASS-GT, MATSim, passenger-kilometres, CO2 emission

1. Introduction

In the last decade, B2C e-commerce has grown rapidly, with the expected income of 6.54 trillion US dollars by 2022 (Vakulenko et al., 2018; Lin et al., 2020). The COVID-19 pandemic also significantly increase the growth in e-commerce sector by 10% compared to the expected value (Nyrop et al., 2020). The increasing popularity of e-commerce market consequently increases the parcel delivery and return traffic in the last-mile delivery (LMD) sector, specifically home delivery service (Schewel & Schipper, 2012; Iwan et al., 2016; Faugere & Monstreuil, 2017; Vakulenko et al., 2018; Nahry & Vilardi, 2019). Therefore, it is urgent to improve the last-mile delivery (LMD) so that it could be faster, cheaper, and more reliable, because it could be accounted for 13-75% of the total logistics costs (Gevaers et al., 2011; Chen & Pan, 2016; Gdowska et al., 2018). This is further strengthened by the fact that cleaner transportation is one of the most important priorities of European Commission in The European Green Deal to achieve 90% reduction in emission produced by the transport sector by 2050 (European Commission, 2019).

One of the innovations to improve LMD is crowdshipping (CS). This innovation is based on the emerging sharing economy phenomenon, taking the advantage of the development in the app-based platform technologies and utilising the "crowd" or person-traveller as occasional couriers to deliver parcels (McKinnon, 2016 & Le et al., 2019). These occasional couriers will get a monetary compensation in return for their service (Simoni et al., 2020). This method is expected to promote sustainable urban freight transport by reducing the number of vehicles needed to deliver packages (Arslan et al., 2018).

The traditional urban freight deliveries using parcel vans can be accounted for approximately 0.6% of the local traffic yet their impact on the local emission and traffic could be considered troublesome (Aditjandra et al., 2016; Herold, 2019).

Crowdshipping will affect the dynamics between the traditional deliveries with the local passenger transportation since a few of the "crowd" traveller would act as occasional couriers. Furthermore, its impact on the local vehicle mileage and carbon dioxide (CO2) emission haven't been explored yet in the literatures. Moreover, while many studied crowdshipping using modes such as public transport and walking from various perspective, the car-based crowdshipping is rarely explored. Therefore, this study focuses on analysing the impact of car-based crowdshipping to the local vehicle mileage and CO2 emission.

Agent-based modelling (ABM) could be used as the method to analyse the interaction between the two and their impact to the externalities since it allows a modelling built from the bottom-up, considering the smallest component in the transportation sector, the travellers themselves (Tchervenkov et al., 2020). Two ABM frameworks are used in this study, MASS-GT (de Bok & Tavasszy, 2018), specifically LEAD parcel modules (Kourounioti and Tapia, 2021), to model the parcel delivery transport and MATSim (Horni et al., 2016) to model the passenger and van deliveries in a microscopic environment. The data of synthetic population are obtained from ALBATROSS (Arentze and Timmermans, 2004). Furthermore, there is a potential to use the output of MASS-GT and ALBATROSS as the input for MATSim. Therefore, these frameworks are integrated in this study by bridging the output of aforementioned platforms. The impact of both transport systems on the local vehicle mileage and CO2 emissions are measured based on the output of the simulations.

The remainder of this paper is structured as follows; first, the literature review on crowdshipping is discussed. Afterwards, both ABM frameworks and the integration process is described. Next, the scenarios used in the simulation are described, followed by the simulation results of the scenario. Finally, the conclusion and discussion is presented by the end of this paper.

2. Crowdshipping: Literature review

Crowdshipping definition

Crowdshipping is built upon the idea of sharing economy and is expected to increase the efficiency and sustainability of urban freight transport (Marcucci et al., 2017). The occasional couriers that participate in crowdshipping are the people (or 'crowd') that already have an initial origin and destination and will take a detour along their route to pick up and drop off the parcel (Punel et al., 2018). Crowdshipping itself can be done using various modes of transport, from private motorized vehicles (i.e., cars, motorcycles), bicycles, public transport, and walking.

Today, most crowdsourced delivery services are exploring the market of food and groceries delivery, with more and more companies start to explore the potential of this method in other sectors such as retail logistics to offer same-day delivery service (Galkin et al., 2021). This innovative concept attracts the interest of logistics giants such as DHL and FedEx, which explore the possibility of utilising the crowd to deliver goods (Rogués and Montreuil, 2014).

Benefits and challenges

Crowdshipping relies on the travellers as the occasional couriers, hence, the number of trips can be reduced, which consequently would reduce the traffic congestions as well (Mckinnon et al., 2011). The delivery request in the crowdshipping is handled at an individual level, so, it could provide a more personalised delivery method (Punel and Stathopoulos, 2017). This method also has the potential to bring economic benefits for all parties involved, especially for the faster and cheaper same-day deliveries (Arslan et al., 2018). This is because occasional couriers could costs less compared to the professionals (Pakarti & Starita, 2019).

However, crowdshipping might bring negative impact as well, for instance, rebound effect in which the travellers generate more distance per vehicles instead of satisfying the shipping demand and consequently might negate the benefits of crowdshipping itself (Paloheimo et al., 2016; Gatta et al., 2019).

CS acceptance – study case in Rome

Considering the advantages and concerns of the crowdshipping, Marcucci et al. (2017) and Gatta et al. (2019) conducted studies on the potential of using crowdshipping in Rome. Marcucci et al. (2017) surveyed the students in Rome, Italy on the prerequisite requirements for crowdshipping to be successfully adopted in an urban area. It was found that the acceptance of the idea of crowdshipping is relatively high in Rome. 87% of the respondents are willing to act as crowdshippers if the parcel size is small (shoebox size), with monetary incentives of 5-10 euro per delivery, average maximum detour distance of 2.4 km (or 21% of the actual trip distance), and a proof that the crowdshipping is actually a sustainable method. However, this is relatively deviating from the real application of crowdshipping, in which the monetary incentives are averagely 2-4 euro per delivery and average urban crowdshipping distance varies from 8 to 30 km. They also found that 93% of the respondents would be willing to use the crowdshipping service if the crowdshipping company and the crowdshippers could be contacted and if the package tracking service is available. In contrast, the crowdshippers highly value their privacy and are unwilling to be traced (57% of respondents).

Supply and demand

Le et al. (2019) identified the crowdshipping from the supply and demand perspective. The supply means the actor that perform the crowdshipping activities, the crowdshippers. On the other hand, the demand is defined as the people that use the crowdshipping service, hence, the customers.

Since the majority of these couriers are participating in the crowdshipping market voluntarily, their availability and willingness-to-work (WTW) would heavily influence the *supply* side of the crowdshipping. The WTW is heavily dependent on monetary incentives, working environment, and platform operation (Buldeo Rai et al., 2018). Furthermore, the size of parcel, initial trip purpose of the crowdshipper, and and the detour also affects the WTW (Marcucci et al., 2017; Miller et al., 2017; Punel et al., 2018). The crowdshippers' attributes such as the couriers' age also affects the WTW of crowdshipper (Galkin et al., 2021).

The demand-side of crowdshipping is generated by the individuals in the crowd that act as the senders and the receiver of crowdshipped goods (Le et al., 2019). These individuals could be in the form of retailers, logistics businesses, or a person (Buldeo Rai et al., 2017). There are three types of crowdshipping based on the demand-side: business-to-business (B2B), business-to-customer (B2C), and peer-to-peer (person to person). Because the demand-side of crowdshipping is based on the crowd, the network flow of crowdshipping activity depends on the result of the crowdshipping matching procedure between the customer and the courier's planned route (McKinnon, 2016).

Potential market share

As the literatures have shown, crowdshipping will be best used as a complimentary means of delivery, instead of as the replacement to traditional van delivery. A study conducted in the Netherlands by Berendschot et al. (2021) shows that th\ere is a potential for crowdshipping to handle 6% of the total parcel volume in an urban area. Another study from Delft, the Netherlands, shows that bicycle-based crowdshipping could even reach 14-26% of the parcel deliveries market share (Wicaksono et al., 2021). No prior studies on potential market share of car-based crowdshipping is found. Although this study focus on car-based crowdshipping activities, to generalise, the potential number of 10-30% market share for car-based crowdshipping out of total logistics flow will be simulated and analysed in MATSim.

Impact of CS on Externalities

Crowdshipping relies on the road transport system on either side, passenger transport and traditional parcel delivery, and often, it will bring externalities impact. Externalities in road transport includes the traffic congestion and the environmental impact caused by the transport activities itself (Santos et al., 2010). The existence of crowdshipping could be a boomerang to the system itself, depends on the mode used, crowdshipping could either increase or reduce the traffic congestions and CO2 emission produced by transport system (Rai et al., 2017). The evidence from the literatures showed that if performed using a sustainable mode, crowdshipping will potentially reduce the congestion level and consequently, the CO2 emission could be decreases (Rouges and Montreuil, 2014; Rai et al., 2019). However, increasing supply and demand of crowdshipping can lead to an increasing transportation demand, and consequently, increasing the vehicle traffic in a city.

Alho et al. (2020) evaluates the last-mile impact of cargo-hitching, applied to mobility-on-demand (MOD) services, which is similar to crowdshipping, using simulation approach. One of their finding shows that by implementing the "crowdshipping" to the MOD vehicles, the VKT of both transport activities (MOD and freight transport) could be reduced by 2%. In other study conducted by Ballare and Lin (2020), it was found that the combination of crowdshipping with microhubs could significantly reduce the VKT of parcel vans in an urban area.

3. Integrated Agent-Based Modelling Framework

Agent-based modelling

ABM is characterised by the existence of autonomous agents, computational system that are situated in an environment that are capable of making their individual decision based on the predefined sets of goals (Maes, 1995; Jennings et al., 1998). ABM framework is built from the bottom up, meaning that it is a tool to understand a complex system by considering the behaviour of the smallest entities in the environment, in this case, agents themselves. (Chen, 2012). These agents have two key properties: autonomy and social ability (Chen, 2012). The autonomous characteristic means that the agents can operate, carry out the predefined instructions, and make decisions on their own (Hayes, 1999). The social ability means that the agents are able to interact with other agents in the environment to carry their tasks and involve in helping other agents' tasks (Jennings et al., 1998). With these characteristics, the ABM approach is deemed to be suitable for the application in socio-related studies, including urban transport studies (Chen, 2012).

Integrated model framework

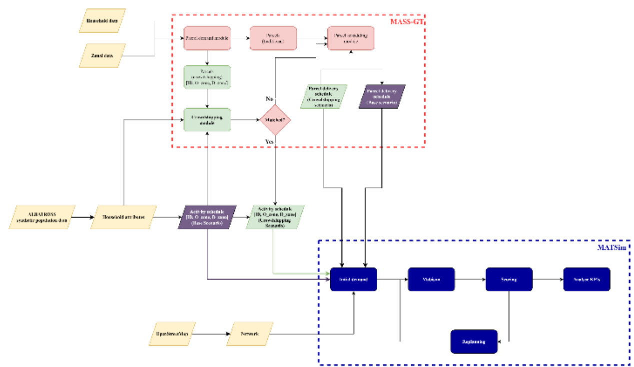

Figure 1Integrated model framework

The integrated model framework is presented in Figure 1. Generally, the integrated model could be distinguished into two parts: MASS-GT side and MATSim side. This section will discuss the integrated model framework.

MASS-GT

MASS GT is an agent-based logistics simulation model for freight transport in the Netherlands as was developed by de Bok and Tavasszy (2018) using large dataset with observed freight transport data in The Netherlands. MASS-GT can model the freight delivery in the shipping module and also parcel delivery in the parcel module. The parcel module of MASS-GT is being developed by LEAD project, a project on the sustainable urban mobility of the future funded by the European Union. This study use the latter module.

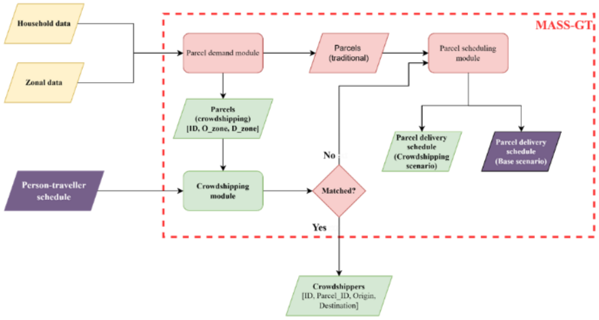

Figure 2 LEAD parcel modules (adapted from Kourounioti and Tapia, 2021)

The LEAD parcel modules are being used in this study to simulate the parcel-side of the model, before being implemented in MATSim. Generally, it consists of **parcel demand module** that generate the parcel demand, and **parcel scheduling module** that assign the synthetic parcel demand to tours and trips of parcel delivery vans. In addition, a special module extension, **crowdshipping module**, is used in this study. The main output of the LEAD parcel modules used in this study are **parcel delivery schedule** and **crowdshippers data.** Figure 1 visualises the workflow of LEAD parcel modules.

Parcel demand module use the household and zonal data to generate synthetic parcel demand. Each parcel generated has their own ID, origin, and destination. The origin and destination variables used in MASS-GT are on the zonal level, specifically, the V-MRDH (*Verkeersmodel Metropoolregio Rotterdam Den Haag)* zones.

The crowdshipping module assigns some percentages of the generated parcels to travelling crowd. The number of crowdshipable parcels and number of travellers allowed to be crowdshipper are bounded by two factors that represents the crowdshipping adoption rate: "CS_eligible" and "CS_willingness", respectively. Then, this module will assign the parcels to the travelling crowds that have their own origin and destination. The matching process is based on the least detour distance, calculated on zonal level using the zonal skim matrix data. The output of this modules is the data of the crowdshipper (traveller ID, origin, destination, parcel origin, and parcel destination).

This data then will be used to create scenarios, discussed on the next section (4. Scenarios). In case there are parcels that were not matched with traveller, the data will be brought back to the demand data and being used as input to parcel scheduling module. This module is the key for integrating MASS-GT with MATSim in this study because it connects all frameworks (MASS-GT, MATSim, and ALBATROSS), along with MATSim's initial demand module.

Finally, parcel scheduling module process the generated synthetic parcel demand that were not assigned for crowdshipping to tours and trips of parcel van deliveries. Each vehicle departs from their own depot, and they have a limit of 180 parcels/vehicle. The main output of this module is the parcel delivery schedule, including the tour ID, trip ID, CEP (parcel and express company), departure and arrival time, and origin and destination of each trips.

MATSim

One of the most popular microscopic traffic simulations platforms is MATSim (Multi-Agent Transportation Simulation), due to its high computing speed and excels in modelling the behaviour in the trip planning (Maciejewski & Nagel, 2013). MATSim is an open-source disaggregate activity-based multi-agent transport simulation software, designed to handle large-scale scenarios (Horni et al., 2016). Horni et al. (2016), the developers of MATSim, described the software in their paper, elaborately. MATSim enables a single-day modelling of an activity-based transportation. MATSim is built based on co-evolutionary principle, in which the agents' objective is to optimise their daily activity while competing for space-time slots amongst others in the transport infrastructure. While being relatively similar to the route assignment cycle, MATSim also incorporates time choice, mode choice, or destination choice into the iterative cycle, along with the route assignment.

MATSim iterative loop consists of several modules, namely: initial demand, mobsim, scoring, replanning, and analyses as presented on Figure 3.

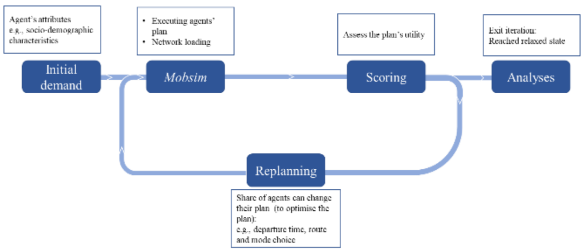

Figure 3 MATSim iterative cycle (adapted from Horni et al., 2016)

Initial demand will be formulated from the observation area populations' daily activities. The populations are consisted of agents, representing a person in real life. Each agent has the socio-demographic characteristics, representing that of real person, for instance, age, gender, occupation, home location, and private vehicle ownerships (Ciari et al., 2016). These agents have a memory, consisted of fixed number of day plans, and each plan is constructed of a daily activity chain (locations, times, and the activities agents will conduct) along with its respective score.

The second step is *mobsim* or mobility simulation. Prior to this step, each agent will select a plan form its memory, depends on the score of the plan, computed after each *mobsim* run, considering the executed plans' performances. The selected plan then will be executed using queue-based traffic flow simulator (Maciejewski & Nagel, 2013). The queue-based model is based on the principle that a vehicle will spend time on a link that is equal to time moving end-to-end of the link and added with waiting time in a queue (Zilske et al., 2012). The links are represented in first-in-first-out (FIFO) manners with sets of parameters, for instance, the length of the link, free-flow speed, flow capacity, and storage capacity. Having the network loaded, this module will give a documentation of changes in the state of any object in the system.

Few agents (often 10%) can clone the chosen plan and modify the clone in replanning modules. The factors that are considered in this step are departure time (and activity duration), route, mode, and destination. This step is done in order for the agents to achieve a more optimal plan with higher utility score. The changes that can be made are among others, change their departure time, mode choice, and their routes (Ciari et al., 2016). In this study, the replanning method that are used are *ChangeExpBeta* and *ReRoute*. *ChangeExpBeta* allows the agent to choose the best plan possible by switching between plans so that it finally converges into the best plan. On the other hand, *ReRoute* strategy allows a few of the agents to change their route based on the information obtained in the previous iteration.

The iteration then will be completed by assessing the agents' experiences within the selected day plans. This step is called scoring. The solutions that generate a high score will be selected by the agents and won't be removed during the replanning step. The iteration between plan generation and *mobsim* is repeated until the system achieve a relaxed equilibrium state (Ciari et al., 2016). The simulation in MATSim is generated stochastically, it means that the convergence criteria is not suitable in this case.

The main input of MATSim are **plan file, network file,** and **config file**. The plan file is the activity schedule of the agents in the simulation. In this study, the plan file of the parcel delivery is obtained from the output of MASS-GT, while the passenger's plan file is obtained from ALBATROSS data. However, MATSim needs the plan file to be set on the operational level, using coordinates to define the location variables. Therefore, pre-processing steps were done to convert the output of MASS-GT (in V-MRDH zones) and ALBATROSS (postcode number) into coordinates. This were done by overlapping both location variables in GIS software, then get all coordinates of buildings inside of it. Afterwards, the agents in the schedule file are assigned randomly to a location if they are located inside of the study area. If a location is outside of the study area, then it will be assigned to the centroid's coordinates of the zone/postcode. The study area is discussed further in the next section (4. Scenarios).

The network file defines the geo-spatial boundary of the simulation and is obtained from OpenStreetMap, processed with JOSM's MATSim module. By doing so, the network file of OSM is converted into XML format that is compatible with MATSim.

The config file contains all configurations used to run the MATSim simulation. Besides the directory details, this file also controls the simulation, for instance, the number of iterations, which mobsim module is going to be used, etc. The weights and utility function used in the logit model that influence agents' behaviour is also defined in this file.

4. Scenarios

The scenarios are needed to run and analyse the output of MATSim. Two kind of scenarios is formulated in this study: the base scenario and crowdshipping scenarios. Base scenario represents the existing condition, without the existence of crowdshipping. On the other hand, crowdshipping scenarios represents the condition in which crowdshipping exists in the simulation.

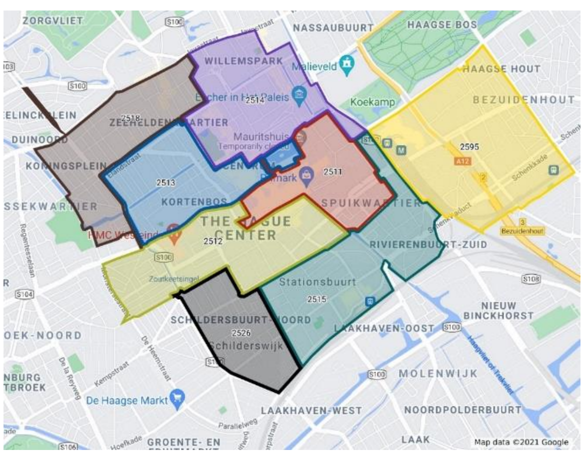

Figure 4 Study area

Study area

This study focuses on the city centre of The Hague. Since the term "city centre" have no specific boundary, a study area is introduced to set the spatial limit of the simulation. Furthermore, the data needed, and computational time of the simulation can be significantly cut down. The study area that is being used in this thesis consists of eight 4-digits Dutch postcode zones that are located in the heart of The Hague, The Netherlands. Figure 4 pictures the study area used in this study. The trips that are considered in this study are only the trips with at least one leg inside of the study area, which means only trips **to, from,** and **within** the study area are considered.

General assumptions

Several assumptions were made in this study. This simulation study aims to analyse the externalities impact of car-based crowdshipping, which means the movement of the vehicles are more interesting compared to the static vehicles, such as parking problem. Both passenger's transportation mode, car and carPassenger, have the same parameters defined in the config file. The only difference is that the agents that are using carPassenger as the transport mode can't be a crowdshipper. Furthermore, this study will focus on the value of VKT, which is based on the number of vehicles instead of passenger. For the van mode, it is also assumed that a van is consisted of one driver.

While assigning the agents to buildings inside the study area, no distinctions between the buildings were made. This means that the function of the building is not considered in this study, for instance, this study doesn't consider which building is school, office, home, etc.

Base scenario

The base scenario was formulated based on the data from ALBATROSS and MASS-GT. The base scenario is the (synthetic) existing condition of the population in The Hague, without the existence of crowdshipping. In this scenario, all parcels are distributed by the parcel vans and person-agents execute their activities throughout the day. After the data have been processed, they could be run in MATSim to set the base of comparison, to be compared with the crowdshipping scenario.

In this scenario, the parcel vans' activities are independent of the passengers' activities. The number of parcels delivered are not considered in the base scenario, since there will be no exchange between the parcel vans and the person-agents. The interaction between the two is only that they are sharing the very same transport infrastructure.

Crowdshipping scenarios

Three crowdshipping scenarios, each with different value of crowdshipping adoption rate are formulated in this study. In this scenario, parcels are partially delivered by crowdshipping activity, in addition to the traditional van delivery.

Not all person-travellers could be chosen as crowdshipper. They have to fulfil the crowdshippers' eligibility criteria that were derived from the literatures. The crowdshippers' criteria used in this study are summarised in Table 1 below.

Table 1 Crowdshippers' eligibility criteria

Criteria	Findings	Sources	Implementation
Age	22 to 55 years old	*Galkin et al., 2021; OECD, 2021*	"<35" and "35-55"
Trip purpose	More flexible activity	*Miller et al., 2017*	Not **Work**
Compensation	Lower than traditional van, 1.5 – 3.35 euros	*Autoriteit Consument & Markt, 2020; Berendschot et al., 2021*	$compensation = \ln(distance + 2)$ (Implemented in LEAD modules)
Acceptable detour	2 to 2.5 kilometres	*Marcucci et al., 2017; Neudoerfer et al., 2021*	Considered
Mode	Car, bicycle, PT, walk	*Binetti et al., 2019; Gatta et al., 2019; Wicaksono et al., 2021*	Car
Household Income	-	*Assumed*	"low", "average", "aboveAverage"

If a traveller is chosen to be a crowdshipper, they have to deliver the parcels directly. This means their route should be from their origin → parcel origin → parcel destination → their destination, as visualised by Figure 5.

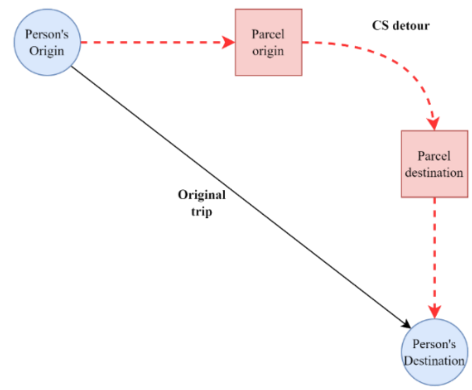

Figure 5 Illustration of crowdshipping trip

Three different crowdshipping adoption rates are used in three different crowdshipping scenarios. The adoption rates used in each scenarios are presented in Table 2.

Table 2 Crowdshipping adoption rate

Parameter	CS - reference	CS B – increased	CS C – reduced
CS_willingness	0.2	0.3	0,1
CS_cust_willingness	0.1	0.2	0.05

5. Results

The scenarios formulated are simulated using the constructed modelling framework. The results of each scenario run are compared based on the defined KPIs.

Calibration, verification, and validation

To ensure the model is working correctly, the model is calibrated, verified, and validated first. The calibration process is done by fine-tuning the network capacity factor (*flowCapacityFactor* and *storageCapacityFactor*) until the simulation results represents the input schedule file. The integrated model is conceptually validated by doing an expert review. The verification process is done by running the simulation with different random seeds to see if the model shows consistency. Finally, the model is validated by doing a behaviour prediction test. This is done by formulating multiple hypotheses while changing several variables of the model and to see if the model behaves accordingly.

KPIs

Two KPIs are defined to assess the externalities impact of car-based crowdshipping in the study area, based on the simulation results. The first KPI is **Vehicle kilometres travelled (VKT)**. One of the MATSim output is the data of passenger-kilometres (pkm) travelled, which represents the distance through by each passenger. Since in this study each vehicle is assumed to be occupied with one passenger, 1 VKT is considered as 1 pkm.

The other KPI is the carbon dioxide (CO2) emission. This is calculated by multiplying the transport activity (VKT) with the CO2 emission factor per mode, measured in gCO2/km. The passenger cars in this study are assumed to be uniform and are using petrol fuel. The same goes for parcel vans, they are considered as uniform and are using diesel fuel. The value of CO2 emission factor per mode are presented in Table 3.

Table 3 CO2 emission factor

Mode	α_{mode} $(gCO2/km)$	Source
Passenger cars	127.6	*European Environment Agency, 2021*
Parcel vans	245	*PostNL, 2020*

Simulation results

All the necessary files that have been developed are simulated in MATSim environment. The simulation was run for 100 iterations, and it took 6 hours of run time using a computer with Intel i7 and 8GB of RAM.

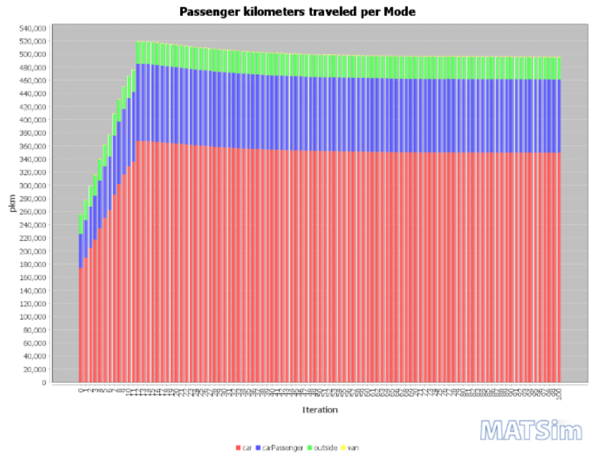

Figure 6 pkm per mode (base scenario)

Figure 6 is the value of pkm travelled per mode in the base scenario over iterations. It can be seen that after number of iterations, the value of pkm stabilises. This implies that the "relaxed state" or the Stochastic User Equilibrium (SUE) condition has been reached by the simulation. The same goes for all scenarios simulated in this study, the SUE condition already has been reached in each scenario.

Scenario comparison

All scenarios simulated are compared based on the KPIs that have been defined: pkm value and the CO2 emission produced. The simulation results of all scenarios are presented in the Table 4. It can be observed that car-based crowdshipping slightly increased the vehicle mileage and CO2 emission. However, the increase in all scenarios are very small, ranging from 0.07% increase (CS-C) to 0.27% increase (CS-B) on both KPIs. This is mainly caused by the fact that the traditional van delivery service offers a more established and efficient method in delivering parcels due to its capabilities of parcels consolidation and delivering multiple parcels on a single trip. Car-based crowdshipping, on the other hand, can only deliver a single parcel on a single trip and it has to take two extra trips to deliver each parcel, one to pick-up the parcel and another to deliver the parcel.

Table 4 Scenario comparison

Mode	Base		CS-C		CS-Reference		CS-B	
	pkm (km)	**CO2 (gCO2)**	**pkm (km)**	**CO2 (gCO2)**	**pkm (km)**	**CO2 (gCO2)**	**pkm (km)**	**CO2 (gCO2)**
car	349,846	44,640,350	350120	44675312	350,619	44,738,984	351,074	44,797,042
van	951	232,995	941	230300	932	228,340	823	201,635
Total	350,797	44,873,345	351,061	44,905,612	351,551	44,967,324	351,897	44,998,677

All crowdshipping activities involve a detour from the agent's original route. The detour is calculated by the differences in total driven distance of car in the base scenario and crowdshipping scenarios. From the comparison between the two scenario, it is found that the average detour distance caused by crowdshipping in all crowdshipping scenarios ranging from **2.28 to 2.76 km per parcel**. This result is in-line with the findings of Marcucci et al. (2017) and Neudoerfer et al. (2021), stating that the maximum detour of crowdshipper is around 2 – 2.5 km. The parcel delivery efficiency comparison between the CS scenario reference with the base scenario is presented in Table 5.

Table 5 Parcel delivery efficiency (CS scenario reference)

	CS-C: reduced		**CS-reference**		**CS-B: increased**	
	van	car	van	car	van	car
Avg. distance/parcel (km/parcel)	0.790	2.28	0.799	2.523	0.84	2.76
Avg. emission/parcel (gCO2/parcel)	193.73	290.93	195.75	321.93	205.8	352.18

Results implication

The results of all scenarios imply that the adoption of car-based crowdshipping will not have a significant impact to the total vehicle mileage and CO2 emission produced by the transport activities in the study area. Although the simulation results show that all crowdshipping scenarios will lead to increase in both KPIs, the differences are very small, ranging from 0.07% to 0.28% increase. However, a pattern on the correlation between car-based crowdshipping with the total mileage and CO2 emission can be discerned. With the increasing value of crowdshipping adoption rate, the total CO2 emission produced will also increase. This could be explained by the better efficiency of traditional van in delivering parcels due to its capability of delivering multiple parcels in a single trip and the ability of consolidating parcels before dispatching delivery fleets from the depot. The crowdshipper, on the other hand, have to dedicate two extra trips, detouring from their initial route to pick-up and deliver one parcel. Consequently, the increase in car mode due to crowdshipping activity exceeds the savings in the traditional van in every scenario.

The simulation shows that even 5% of crowdshipping adoption rate will increase the CO2 emission and vehicle mileage, although the addition in both KPIs are very small. However, if the car-based crowdshipping adoption become more successful, the increase in both KPIs will potentially increase. To prevent further increase in CO2 emission, crowdshipping would be better performed using a more sustainable transport mode such as bicycle or public transport. Electric car could also be a sustainable option to perform car-based crowdshipping, as the emission produced by its entire life cycle are approximately 17-30% less than the emission produced by the traditional cars and it emits zero gas emission on the operational level (EEA, 2018). However, electric cars operates in the same transport network as the regular cars, hence, the impact on vehicle mileage will still be similar with that of the regular cars. It is also interesting to execute an experiment with even lower value of market adoption rate than crowdshipping scenario C to find the threshold in which car-based crowdshipping exists while also reducing the CO2 emission and mileage.

To even reduce the detour distance, innovations in last-mile deliveries such as pick-up points or parcel lockers could be combined with crowdshipping. If pick-up points exist across the city in a frequently busy area such as metro or train stations, supermarkets, and business area, the detour of the crowdshipper could be potentially decreased. Furthermore, if public transport mode is also considered in the simulation, this should be more environmentally beneficial. However, it would possess its own challenges for the crowdshipping service providers since they have to formulate a more comprehensive matching algorithm.

Added value of the integrated model

The integrated model developed in this study offers a microscopic simulation of both transport spectrum, the passenger and parcel delivery transport, in an activity-based agent-based modelling framework. The added value that the integrated model could provide are presented in Table 6. The input to the integrated model is simulated in zonal level, and MATSim simulates them in a more microscopical way, on the coordinate level. This offers a higher level of detail in modelling a scenario.

Table 6 Added value of the integrated model

	MASS-GT	**Integrated MATSim**
Passenger transport simulation	No	Yes
Parcel transport simulation	Yes	Yes
Travel time and distance calculation	Zonal level	Coordinate level
Network congestion and background traffic	No	Yes
Route choice	Static network assignment	Stochastic, based on the initial demand and replanning module
Input data	Zonal data, household data, network	Activity schedule, network
Contribs and extension modules	Do not exist yet	Yes

MASS-GT can simulate parcels with an ABM framework, as was explained in Chapter 3.2. The parcels are simulated thoroughly, from the parcel demand generation process, the parcel distribution among the firms, parcel distribution along the network, until it reached a parcel schedule, consisted of tours and trips. The MASS-GT parcel modules also has the potential to be expanded, for instance, the inclusion of other methods in last-mile delivery such as parcel lockers, pick-up points, etc.

The integrated model provides a framework to convert the output of MASS-GT's parcel module to be simulated in MATSim. Since MASS-GT by itself offers an in-depth simulation for freight transport, by simulating the model in MATSim, the output provided would be in even more detailed. Moreover, simulating in MATSim allows the inclusion of congestions and background traffic because it can simulate all transport mode that are configured, including public transport, passenger cars, etc. MATSim simulates the route choice stochastically, meaning, it captures the uncertainties that might occur in the environment. Moreover, MATSim has numerous modules that could be used to expand the model and it could help in solving future research. For instance, the MATSim's emission module could be used to measure the hot and cold emission produced by the agents in the simulation.

6. Conclusion

The presented results indicates that car-based crowdshipping would not have a significant impact to the vehicle mileage and the carbon dioxide emission. The increase in the local vehicle mileage and CO2 emission are insignificant, ranging from 0.07% to 0.28% increase. This slight increase is due to the distance savings in traditional delivery vans are greatly exceeded by the increased travel distance covered by the private cars in the simulation.

In all crowdshipping scenarios, the average detour distance of the courier ranges from 2.52 km to 2.8 km per parcel, which are in line with the findings of Marcucci et al. (2017) and Neudoerfer et al. (2021) that found the average maximum detour distance accepted by the crowdshippers ranges from 2 to 2.5 km. The more successful a car-based crowdshipping, indicated by the increasing adoption rate of crowdshipping, could lead to more CO2 emission produced by the transport activities. However, no business was made to be unsuccessful, therefore, this study could be an evident that if car-based crowdshipping succeeds heavily, it could lead to more CO2 emission in last-mile delivery. This is in-line with the findings of Pourrahmani and Jaller (2021) which found that crowdshipping will be environmentally beneficial if performed mainly by sustainable transport modes.

The inefficiency of car-based crowdshipping simulated in this study is mainly underlined by two factors: the (still) inefficient parcel delivery system in crowdshipping and the mode choice to deliver a parcel on crowdshipper. For each crowdshipper, two extra trips are made, which means that it would require more trips to deliver parcel demand compared to the van delivery service, which can consolidate the parcels in an urban consolidation centre (UCC) before dispatching the vans. These extra trips will slightly increase the CO2 emission produced and the total mileage, as long as they are performed using regular private cars.

A more sustainable transport mode could be a better option to perform crowdshipping, on the other hand. This is because of the difference in the CO2 emission produced per distance travelled of the other mode. For instance, electric vehicle and bicycle emit less or even no (local) CO2 emission while traveling. This is in-line with the finding of Rouges and Montreuil (2014) and Rai et al. (2019) that discussed if crowdshipping is performed using a sustainable transport mode, the CO2 emission could be reduced.

7. Discussion

Sets of assumptions and simplifications are formulated in order to construct the model and simulate the scenarios in this study. These generalisation might cause some imperfection to the results of the model. This study model all buildings iniside of the study area in the city centre of The Hague, however, no distinctions between the building's function, for instance, schools, offices, grocery stores, etc. This could cause the model's transportation pattern to be different with the real-life situation. The study area set in this study is relatively small, therefore, the ratio between the number of parcel and its trips with the travellers might be inaccurate. The enormous differences in the number of trips between parcel vans and private cars causes the model to be relatively unresponsive to the changes in both KPIs. A study conducted in Vienna shows that passenger cars could be accounted for 86.5% of the traffic while the parcel delivery trips are around 0.6%, while in this study, the value of parcel vans' pkm is accounted for 0.3% of total pkm. Moreover, no references on car-based crowdshipping adoption rate could be found in the literatures, and therefore, the value used in this study are assumed. This could hinder the results since the number of supply and demand of crowdshipping in this study might be over or underestimate the real life case. Other sets of assumptions on the crowdshippers side are made, for instance, they have to deliver the parcel directly and can only take one parcel at a time. The demand-side of crowdshipping also represented rather minimally in this study.

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