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Establishing a framework methodology for covering micro-mobility in multi-modal public transport networks

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Abstract

Mobility as a Service (MaaS) is a recent innovative transport concept, anticipated to oblige significant changes in current transport practices. This study aimed to develop a methodology to justify the potential MaaS adoption. For this purpose, an innovative methodology is presented to identify four types of stations, including "Transit (servicing travelers by bus)", "Micro-mobility (servicing travelers by bike and scooter)", "MaaS (servicing travelers by bus, bike, scooter, and Uber)", and "None (no station)" for each node. The proposed methodology minimizes the total user and agency costs, including user travel time cost, out-of-pocket costs, agency construction costs for MaaS and agency MaaS operating costs. The methodology was tested with a 100 node transport network with existing bus routes. The following results were acquired: 1) Construction of micro-mobility station was not justified for 42 nodes and 37 nodes in 20-years and 30-years life cycles if only 20% of demand from shortest path demand select micro-mobility options 2) Over 20-years and 30-years life cycles, the operator benefits from daily savings amounting to \$18,520 and \$16,033, respectively, and 3) There are no consistent results to justify the MaaS construction and operation based on existence of the transit stations. In other words, the justification depends on users' shortest trip paths, amount of demand, and existing transit stations.

Keywords – Mobility-as-a-Service (MaaS), public transport, MaaS station, transport hub, travel cost, micro-mobility

1. Introduction

The growth of "new mobility services (NMS)" poses challenges for traditional public transport operators because they create an environment where travelers can demand "integrated mobility" from different transport modes and improve their accessibility. Traditional public transport systems are either over or underused since the demand for public transit is not efficiently covered by the current system. Hereupon, delay time is enhanced, crowdedness creates discomfort for public transport users, and the challenge of the provision of an adequate level of public transport infrastructures and service levels can be seen. A considerable percentage of current public transport routes do not have the desired performance. Accordingly, lines with high maintenance costs, lack of proper coverage, and low demand are seen in the traditional public transport systems. Mobility as a Service (MaaS) is a recent innovative transport concept, promising significant changes in current transport practices. The concept remains obscure, however, it is uncertain what the core characteristics of MaaS are and what ways they can be addressed [1]. MaaS aggregates different transport modes to offer a tailored mobility package for seamless travel. MaaS is often proposed as a tool for achieving sustainable mobility and, in particular, increasing the share of public transport trips in cities [2]. MaaS embodies a departure from conventional transportation planning by offering travelers the convenience of selecting and combining different modes of transportation through a single digital interface. This concept not only empowers individuals to make informed decisions about their journeys but also holds the potential to enhance urban sustainability, reduce congestion, and improve overall transportation efficiency. The integration of micro-mobility into multi-modal public transport networks holds immense promise for enhancing urban mobility and reducing congestion, environmental impact, and reliance on personal vehicles. However, this integration is not without its complexities. Micro-mobility services operate on a smaller scale compared to traditional public transit, and their inclusion requires careful consideration of factors such as infrastructure compatibility, user behavior, technological innovation, and regulatory frameworks. This research evaluates traditional public transport based on the MaaS concept, and redesigns traditional networks to apply sustainable transport principles. According to the results of this study, new public transport hubs such as MaaS stations are designed, and demand is distributed on the network in such a way so that micro-mobility transport modes like bicycle and scooter support traditional public transport systems and it is more convenient to choose sustainable travel options for public transport users.

The proposed methodology outlined in this research paper discusses how every node within a transportation network could be designated as a transit station, a micro-mobility station, a MaaS hub, or a walking access station to other nodes. The paper identifies stations with low passenger demand and examines their potential to accommodate alternative transportation modes like bicycles, scooters, and Uber. Four types of stations were investigated, including “Transit (#1; servicing travelers by bus)”, “Micro-mobility (#2; servicing travelers by bike and scooter)”, “MaaS (#3; servicing travelers by bus, bike, scooter, and Uber)”, and “None (#4; stations only accessible on foot)”. In order to specify the type of each node, a shortest path algorithm based on all possible combinations of transport modes (transit, bike, scooter, Uber, and walking) was developed in MATLAB software. The total cost, including user travel time cost, user out-of-pocket cost, and agency operating cost (e.g., fleet supplying cost and construction cost of MaaS stations) were analyzed. The shortest path algorithm was executed for a combination of transit+Uber+walking+bike+scooter (with micro-mobility) and a combination of transit+Uber+walking (without micro-mobility). The total savings and costs by Micro-mobility and MaaS for 100 stations were obtained and analyzed. Then, a sensitivity analysis of micro-mobility usage regarding 20%, 30%, 40%, 50% total demand (=the percentages are provided as the hypotheses of the research), and based on a binary-logit modal split model, was appraised. The paper aims to minimize user costs and agency costs simultaneously. Additionally, based on the shortest path algorithm, coverage area, and proximity to public transport stations, the stations' potential to transition into public transport hubs, micro-mobility stations, and MaaS stations is assessed.

The remainder of this paper is structured as follows: Section 2: Literature Review, Section 3: Research Methodology, Section 4: Examples, Section 5: Analysis & Discussion, Section 6: Summary and Conclusion, and References.

2. Literature review

MaaS enables the integration of public transport modes, commercial transport services such as ride-sourcing, bike- and car-sharing, and taxis into a comprehensive mobility offer [3]. Public MaaS considers the role taken by public transport operators or public transport authorities, which integrate supportive modes into a single public transport offering.

Previous studies highlight how the integration of MaaS and public transport networks can increase the sustainability of transport systems [4], become a solution for rural areas [5], change land use and travel patterns (by changing the location of transportation hubs, micro-mobility stations) [6], transform economies [7], address demographic changes [8] promote the emergence of new mobility as an alternative service model to reduce costs, and increase transportation equity [9]. MaaS could strengthen potentially complementary relationships between services, but could also threaten existing services that are potentially substitutive. Furthermore, MaaS could increase service use over time through subscription plans that offer customers bundled access to multiple transport services, and reduce operator costs by outsourcing particular functions, such as ticketing, and leveraging economies of scale by integrating these functions across multiple transport modes and services [10].

Recently, state-level projects in the U.S. [11] were arranged to increase the performance and the efficiency of public transport by relying on the MaaS concept. Transit agencies e.g., Indianapolis, Kansas City, MDOT MTA (Baltimore), Austin, Norfolk, and Oakland were mentioned as the pioneer agencies redesigning the current public transport networks based on the MaaS concept. In this report [11], for instance, improving service quality and reliability, maximizing accessibility to high frequency transit, strengthening connections between bus and rail routes, and aligning the network with existing and emerging job centers were taken into account to redesign the current transit network.

Predominantly, three categories have been suggested by researchers to redesign transit networks based on the MaaS concept: Interaction of public transport and MaaS studies e.g., [12-18], redesigning the public transport hubs [19-22], and relocating the bike and scooter sharing stations as supportive modes of public transport [23-29]. The first category (=interaction of public transport and MaaS studies) examines how traditional public transportation systems and emerging MaaS platforms can work together to provide efficient, seamless, and sustainable mobility options for individuals and communities. This interaction is crucial for addressing urban congestion, reducing carbon emissions, enhancing transportation equity, and improving overall transportation efficiency. The interaction between public transport and MaaS concept “enables travelers to plan and execute door-to-door journeys using multiple modes of transportation”, “provide solutions like ride-sharing or bike-sharing to bridge first-last mile connectivity and make public transport more accessible”, “personalize travel options based on individual preferences, such as cost, time, comfort, and environmental impact”, “generate valuable data about user behavior, travel patterns, and demand”, “contribute to reduced congestion, parking demand, and greenhouse gas emissions by offering a more convenient and flexible alternative to private car ownership”, and “consider challenges like data privacy, payment integration, interoperability between different transportation providers' systems, and ensuring equitable access to transportation options for all segments of the population”.

The second category (=redesigning the public transport hubs) involves integrating MaaS principles into the design and operations of public transport hubs, such as bus stations, train stations, subway stations, and transit centers. By combining the physical infrastructure of these hubs with the digital capabilities of MaaS platforms, cities can create more seamless, interconnected, and user-centric transportation ecosystems. The second category involves “integrating physical infrastructure (stations, terminals, platforms) with digital infrastructure (smartphone apps, online platforms) to provide a unified and comprehensive travel experience", "taking advantage of passengers to easily switch between modes, receive real-time updates, and access various transportation options from a single platform", "provide real-time information about arrivals, departures, delays, route changes, and service disruptions", "enable hubs offer integrated ticketing and payment systems that allow passengers to pay for their entire journey using a single payment method", "address the first-last mile challenge by suggesting and facilitating connections to and from the hub", "offer services tailored to the needs of different user groups, including those with disabilities or limited mobility", and "influence urban planning decisions, as it encourages people to use public transport and alternative modes over private cars".

The third category (=relocating the bike and scooter sharing stations as supportive modes of public transport) involves strategically placing these stations near existing public transportation hubs to create a seamless and integrated multi-modal transportation system. This concept aims to enhance the accessibility, convenience, and overall effectiveness of public transportation networks by providing last-mile solutions and alternative modes of travel. Relocating bike and scooter sharing stations near public transportation hubs, such as bus stops, train stations, and subway entrances, makes it easier for passengers to transition between modes. Travelers can pick up a bike or scooter after disembarking from a bus or train, and then complete the last leg of their journey. This approach contributes to creating more accessible, connected, and livable urban environments by placing sharing stations near transport hubs, these stations become accessible to a broader range of people who might not have access to a private vehicle can conveniently travel to and from the public transport hub using bikes or scooters.

As a consequence, previous studies have specified that redesigning a public transport network through an effective methodology in which all user and operator costs are fully included has not been studied yet. This study minimizes the total cost of the network, including travel time costs, which are converted from travel time to monetary costs, user's out-of-pocket costs, and agency costs in terms of the network operating and MaaS station construction costs. Furthermore, the paper aims to optimize the number of trips with extensive focus on the MaaS-including paths. Bikes and Scooters are also used as supportive micro-mobility transport modes in low demand areas.

3. Research methodology

The following methodology was pursued to find the type of each station.

Step #1: A shortest path algorithm based on five transport mode combinations was developed in MATLAB software. The algorithm is able to specify the shortest path in the least possible running time. The developed algorithm could find one hundred shortest paths in 2 minutes running time. The shortest path algorithm finds the shortest path between each origin and destination in a graph, including bus, bicycle, scooter, Uber, and walking modes of transportation. In other words, a graph including all possible links between nodes for different modes of transportation was developed. By providing the IDs of origin and destination nodes, the travel time and travel cost of each link, the algorithm can find the shortest path with the lowest total cost (including travel time costs, out-of-pocket costs, and agency operating costs (including fleet supply costs and MaaS station construction costs).

Step #2: The total cost ($) for each shortest path was analyzed, and the user and agency costs were accurately investigated. The shortest path algorithm for two combinations (with MaaS and without MaaS) was run and two 100*100 cost matrices were obtained. The obtained shortest paths and comparisons of the total costs between “with micro-mobility and without micro-mobility” combinations were utilized as two efficient criterions of micro-mobility and MaaS station locations. Additionally, other influential indicators e.g., “demand and capacity of each station, access and egress time of each station to transit stations, service areas (buffer zone) of each station, and probability of using transport modes in each station were propounded to identify the type of each station.

The “demand and capacity of each station” provides valuable insights by analyzing the existing usage patterns, passenger needs, and infrastructure capabilities. The factors such as passenger volume, origin-destination patterns, peak travel times, and types of trips serve as focal points for multi-modal travel and offer a substantial user base, the potential for passengers to shift between modes, stations with good accessibility and connectivity to other parts of the network, and stations located in areas with supportive local regulations and policies for alternative transportation modes and technology integration were nominated.

“Access and egress times” refer to the time it takes for passengers to travel between a station and their point of origin (access) or destination (egress), often involving walking, cycling, or using other modes of transportation. Analyzing access and egress times can provide insights into the feasibility and attractiveness of implementing MaaS services at specific stations. Stations with shorter access and egress times to key transit hubs, stations located farther away from transit hubs may require additional solutions for last-mile connectivity such as bike-sharing, scooter-sharing, or ride-sharing, stations with appropriate walking and cycling paths that connects them to transit stations, and stations with convenient access and egress options that cater to different user groups, including those with limited mobility or disabilities were specified.

The "service areas" or buffer zones around each station determines the vicinity of a station and influence the convenience, accessibility, and coverage of transportation options for passengers. The size and shape of the service areas can determine how effectively a station serves the surrounding population and destinations, service areas that include various transportation modes, such as walking, cycling, and micro-mobility options like scooters, buffer zones that include well-developed infrastructure like bike lanes, pedestrian paths, and shared mobility facilities, service areas with a diverse range of users, including various age groups, socio-economic backgrounds, and mobility needs, and stations with service areas that overlap with other mobility providers, such as bike-sharing or ride-sharing services were taken into account.

The "probability of using transport modes" refers to the likelihood that travelers will opt for different transportation modes when accessing or departing from a particular station. Understanding the most commonly chosen transportation modes in each station's vicinity, stations that exhibit multi-modal behavior, where users switch between different modes for different parts of their journey, stations with well-developed infrastructure for specific modes, such as bike lanes or ride-sharing pick-up areas, and stations with users who predominantly rely on private vehicles may have potential for mode shift to more sustainable options were taken into account.

According to traveler demand between each two stations, the total cost savings by MaaS matrix was obtained. As a logical hypothesis of this research and based on provided percentages in the state-of-the-art, it was assumed that 20% of the overall users opt for micro-mobility (bikes and scooters) for their daily commutes, while the remaining 80% opt for alternative modes of transportation. This assumption was provided so that certain users such as the elderly, individuals with disabilities, and young children might not be suitable candidates for micro-mobility usage. Also, a sensitivity analysis for 20%, 30%, 40%, and 50% (=the research hypotheses) of total demand was developed to compare the total cost savings by MaaS and micro-mobility.

In order to increase the accuracy of calculations, a binary-logit modal split model was developed to specify the traveler's travel choice between two modes (with micro-mobility and without micro-mobility). In the binary-logit model, the traveler associates some value for the utility of each mode, and if the utility of one mode is higher than the other, then that mode is chosen. It is worth mentioning that the cost of each shortest path was considered as disutility. Equation 1 shows the binary-logit model:

$$C_{OD} = b_1 * t_{OD}^{v} + b_2 * t_{OD}^{w} + b_3 * t_{OD}^{wt} + b_4 * F_{OD} + \phi \tag{1}$$

where C_{OD} is the travel cost from origin to destination, t_{OD}^{v} is the in-vehicle travel time between O and D, t_{OD}^{w} is the walking time to and from stops, t_{OD}^{wt} is the waiting time at stops, F_{OD} is the fare charged to travel between O and D, and ϕ is a parameter representing comfort and convenience. Finally, the probability of choosing MaaS paths and the probability of choosing paths without MaaS were identified, and the cost savings identified by the binary-logit modal split model was analyzed. The binary-logit model is a type of discrete choice model that focuses on modeling the binary (two-choice) decision-making process, where an individual chooses between two mutually exclusive alternatives. The binary-logit modal split model is taken into account to analyze and predict traveler choices, such as mode choice, route choice, or the decision to travel. The core concept of the binary logit model is the utility function. Each alternative (choice) is associated with a utility value that represents the perceived attractiveness or satisfaction a decision-maker derives from choosing that alternative. The choice probability of an alternative is calculated using the utility values of all available alternatives. Specifically, the probability that an individual will choose one alternative over another is determined by the relative utility difference between the two alternatives. The model includes parameters or coefficients associated with the attributes of the alternatives in the utility function. A key assumption of the binary logit model is the Independence of Irrelevant Alternatives (IIA) assumption. This assumption implies that the ratio of choice probabilities between two alternatives remains constant, regardless of the presence or absence of other alternatives.

Step #3: The daily travel cost savings by MaaS and cost spending by MaaS (MaaS station construction and operation) were calculated to justify the construction of MaaS stations at each node. Smart stop MaaS stations are equipped with physical and mental comfort improvement devices. MaaS stations are able to cover mobility and non-mobility related services, renewable energy sources, and intermodal facilities. Mobility related services include information provision services (e.g., real-time information, and warning services), ticketing (e.g., purchasing, validation, and control), and intermodal services (e.g., bike-sharing, scooter sharing, E-bike, E-scooter, and electric depots). Non-mobility related services include entertainment (e.g., phone charging, WiFi, and weather condition information provision), comfort (e.g., air-conditioning, and food/drink machine), and supplementary services (e.g., recycle waste, pick-pack point, and ATM). Based on the number of bike and scooter racks, bike and scooter locker systems, and charging depots in MaaS stations, the daily construction and operating costs for 20- and 30-years life cycles were analyzed. Furthermore, the marginal costs e.g., cost of awning the station and cost of installing ticket vending machines, were also considered.

In order to display the following methodology, Figure 1 shows the flowchart of proposed methodology to identify the location of Micro-mobility and MaaS stations on a multimodal transport network.

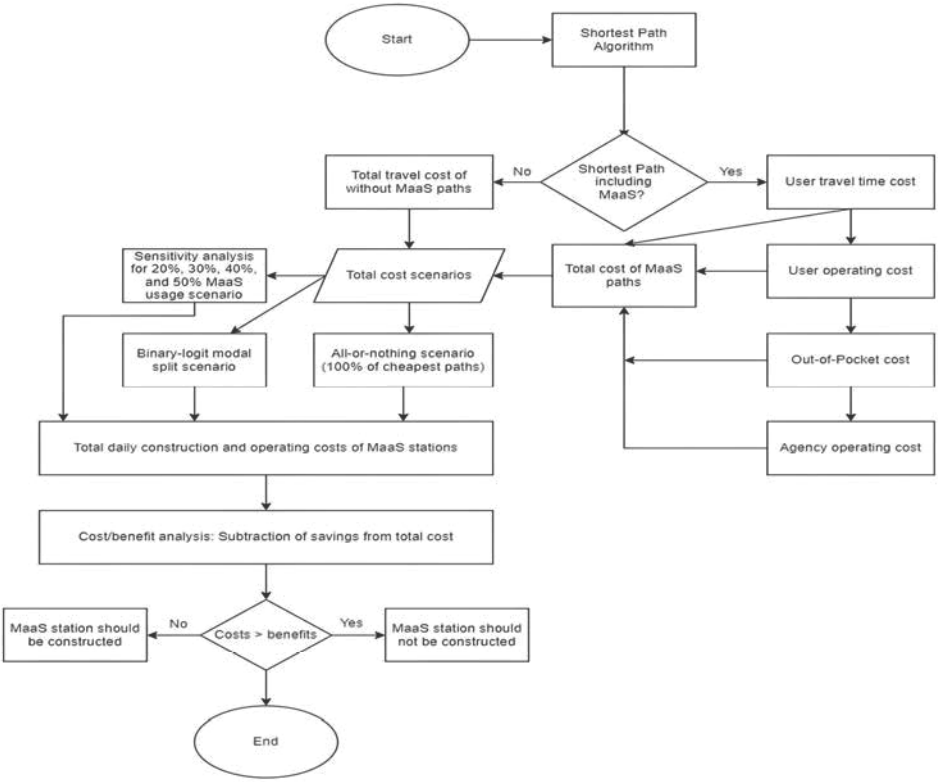

Fig. 1 - MaaS stations location identifying methodology flowchart

As shown in Equation 1, the shortest path algorithm finds the shortest path between each origin and destination in a graph, including bus, bicycle, scooter, Uber, and walking modes of transportation. In other words, a graph including all possible links between nodes for different modes of transportation was developed. By providing the IDs of origin and destination nodes, the algorithm can find the shortest path with the lowest total cost (including travel time costs, out-of-pocket costs, and agency operating costs including fleet supply costs and MaaS station construction costs). After identifying the most efficient route (the shortest path) between every origin and destination, a distinct color is employed in the output graph to emphasize the specific mode that the traveler should employ for the journey. As can be seen in Figure 1, user travel time cost is the cost which refers to the value that individuals or users assign to the time spent traveling. It represents the opportunity cost of the time that individuals spend while they are in transit, and it reflects the idea that time spent traveling could have been used for other productive or leisure activities. The amount of money that individuals are willing to pay to save a certain amount of travel time, and non-monetary aspects such as the inconvenience, stress, and reduced quality of life associated with longer travel times are considered in “user travel time cost”. The user travel time cost is entered as an input to user operating cost which refers to the costs that individuals or users incur when using a particular mode of transportation. It encompasses the expenses associated with the operation and maintenance of a vehicle, as well as the costs incurred during travel, such as fuel, maintenance, tolls, parking fees, and any other expenses directly related to using a transportation mode. The summation of “user travel time cost” and “user operating cost” is entered as a term in “out-of-pocket cost” which it refers the actual monetary payments made by users for transportation-related services and activities. Out-of-pocket costs can include various expenses associated with travel, vehicle ownership, and use e.g., fuel costs, toll fees, parking fees, public transit fare, vehicle maintenance and repairs, insurance costs, licensing and registration fees, and depreciation. Finally, the “user travel time cost”, “user operating cost”, and “out-of-pocket cost” are merged inside the “agency operating cost” which refers to the costs incurred by transportation agencies or organizations responsible for operating and maintaining transportation infrastructure and services. These costs encompass the expenses required to manage and provide various modes of transportation, ensure their safety and functionality, and deliver reliable services to the public. Finally, in order to calculate the total cost, all four costs are combined for MaaS paths including transit+bike+scooter+Uber as shown in **Figure 1**.

4. Transport network

A symmetrical network including 100 nodes (Figure 2) was developed. The bus lines and their characteristics (including headway, transfer time, and in-vehicle time), total demand, distance between each two nodes, and the charging cost paid by travelers for each mode were assumed. As shown in Figure 2, two transit lines from nodes 1 to 100 and from nodes 83 to 38 were assumed. Furthermore, node 15 is specified as a transfer hub between two transit lines. It is worth mentioning that the general configuration of the network follows a part of Downton of Baltimore City transport network. The hypotheses for symmetrical network are summarized as below:

1. Five transport modes consisting of k=1 (bike), k=2 (scooter), k=3 (Uber), k=4 (bus transit), k=5 (walking) were defined.
   a. Fixed operation costs for users ($/day) were analyzed below: Bike: $1 to unlock and $0.05 for every additional minute [30]
   b. Scooter: $1 to unlock and $0.15 per minute of riding [31]. Users are required to pay a fee of $1 to unlock the scooter, followed by an additional charge of $0.15 per minute of active riding time.
   c. Uber: $2.55 as a base fare and $1.75 per km [32]. A fundamental fare of $2.55 is applied, and an additional charge of $1.75 per kilometer traveled is incurred.
   d. Transit: The traveler pays $2 for one-way trip [33]. The traveler incurs a fee of $2 for a single journey.
2. Fixed operation costs for operator (agency) ($/day). In other words, these costs remain consistent regardless of the number of users or trips. The agency encompasses a variety of expenditures essential for the functioning of the system, such as administrative salaries, vehicle maintenance, infrastructure upkeep, insurance premiums, and administrative overheads. These costs contribute to the overall financial landscape of the service and play a crucial role in determining its economic viability and sustainability.
   a. Bike: there is limited published literature addressing the fleet allocation problem of bike-sharing systems [34]. Totally, the annual operating cost of a bike-share system may cost $100-200 [35]
   b. Scooter: Based on a fleet size, the upfront costs would be different — this is taking into consideration hardware (roughly $650/scooter), insurance, city permits and scooter software ($50,000 for a fleet size of 50 scooters) [36]
   c. Uber: The operating cost hypothesized as 8700 $/year [37]
   d. Transit: Various operation costs have been suggested, for instance, $215 per hour in New York City; $195 per hour in San Francisco; $110 per hour in Dallas; $90 per hour in San Diego [38]
3. In order to find the operating daily cost for each transport mode, Table 1 was prepared.

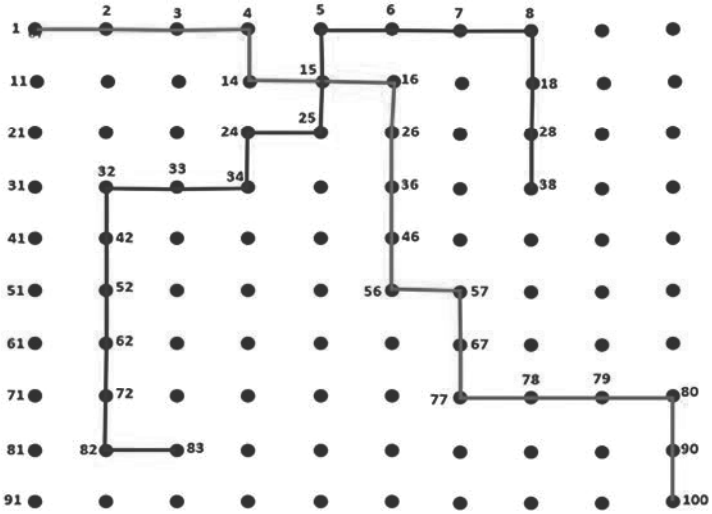

Fig. 2 - The symmetrical transport network

Tab. 1 - Daily depreciation cost of each transport mode

Transport mode	Total purchasing price of each vehicle ($)	Life cycle (year)	Depreciation cost ($/day)	Reference(s)
Bike sharing	4,000	5	2.2	[35], [39]
Scooter sharing	650	3	0.6	[36], [40]
Uber	34,000	15	6.2	[37]
Transit (Diesel bus)	550,000	12	126	[38], [41]

4. Layout of the transit route is given and transit vehicles may skip those stops where there is no boarding or alighting passengers.
5. For the sake of simplicity, it was assumed that the average speed of a bike is 25 km/hour, scooter is 27 km/hour, Uber is 55 km/hour, transit is 45 km/hour, and pedestrians are 5 km/hour [42].
6. The maximum access distance from any point in the service area to the transit stop is $s/2$ in the longitudinal direction and $w/2$ in the transversal direction, respectively. Passengers are assumed to board and alight from buses at given stops. It is worth notifying that s and w are the total length and width of the network [43-44].
7. With the current technology, users know the arrival time of vehicles at each stop or location. It was assumed the waiting time is a coefficient of the average time headway and the variance of headways.
8. In accordance with previous studies [35-40] and in order to specify the total cost of MaaS stations construction, Table 2 was obtained. As shown in Table 2, the daily construction and operating of MaaS stations for a 20- and a 30- years life cycles were investigated. The cost of bike and scooter locker systems (technology and installation), the cost of bike and scooter fleet supply, the cost of awning the station, and the cost of ticket vending machines installation were taken into account after reviewing the previous studies [35-40]. The results of Table 2 were utilized for cost/benefit analysis of MaaS station construction.
9. The distance matrix between nodes are presented in Table 3.

Tab. 2 - Daily construction and operating costs of MaaS stations

Number of Bike and Scooter racks	Daily construction cost ($)		Daily operating cost ($)		Total daily cost ($)	
	Life Cycle 20 years old	**Life Cycle 30 years old**	**Life Cycle 20 years old**	**Life Cycle 30 years old**	**Life Cycle 20 years old**	**Life Cycle 30 years old**
20	20	14	350	350	370	364
30	30	20	385	385	415	405
40	40	27	420	420	460	447
50	50	33	455	455	505	488

Tab. 3 - The distance (mile) between origin-destination nodes

Origin node	**Destination node**	**Distance**	**Origin node**	**Destination node**	**Distance**	**Origin node**	**Destination node**	**Distance**
1	**2**	0.4	**3**	**14**	0.671	**7**	**18**	1.166
2	**3**	0.5	**13**	**24**	0.424	**17**	**28**	1.044
3	**4**	0.3	**23**	**34**	0.583	**27**	**38**	1.118
4	**5**	0.6	**33**	**44**	0.671	**37**	**48**	1.166
5	**6**	0.7	**43**	**54**	0.500	**47**	**58**	1.077
6	**7**	0.6	**53**	**64**	0.583	**57**	**68**	1.118
7	**8**	1	**63**	**74**	0.762	**67**	**78**	1.221
8	**9**	0.9	**73**	**84**	0.873	**77**	**88**	1.293
9	**10**	1.1	**83**	**94**	0.734	**87**	**98**	1.204
1	**11**	0.6	**4**	**15**	0.849	**8**	**19**	1.082
11	**21**	0.3	**14**	**25**	0.671	**18**	**29**	0.949
21	**31**	0.5	**24**	**35**	0.781	**28**	**39**	1.030
31	**41**	0.6	**34**	**45**	0.849	**38**	**49**	1.082
41	**51**	0.4	**44**	**55**	0.721	**48**	**59**	0.985
51	**61**	0.5	**54**	**65**	0.781	**58**	**69**	1.030
61	**71**	0.7	**64**	**75**	0.922	**68**	**79**	1.140
71	**81**	0.82	**74**	**85**	1.016	**78**	**89**	1.218
81	**91**	0.67	**84**	**95**	0.899	**88**	**99**	1.122
1	**12**	0.721	**5**	**16**	0.922	**9**	**20**	1.253
11	**22**	0.500	**15**	**26**	0.762	**19**	**30**	1.140
21	**32**	0.640	**25**	**36**	0.860	**29**	**40**	1.208
31	**42**	0.721	**35**	**46**	0.922	**39**	**50**	1.253
41	**52**	0.566	**45**	**56**	0.806	**49**	**60**	1.170
51	**62**	0.640	**55**	**66**	0.860	**59**	**70**	1.208
61	**72**	0.806	**65**	**76**	0.990	**69**	**80**	1.304
71	**82**	0.912	**75**	**86**	1.078	**79**	**90**	1.372
81	**92**	0.780	**85**	**96**	0.969	**89**	**100**	1.288
2	**13**	0.781	**6**	**17**	0.849			
12	**23**	0.583	**16**	**27**	0.671			
22	**33**	0.707	**26**	**37**	0.781			
32	**43**	0.781	**36**	**47**	0.849			
42	**53**	0.640	**46**	**57**	0.721			
52	**63**	0.707	**56**	**67**	0.781			
62	**73**	0.860	**66**	**77**	0.922			
72	**83**	0.960	**76**	**87**	1.016			
82	**93**	0.836	**86**	**97**	0.899			

5. Analysis & discussion

Considering the described methodology to specify the location of MaaS stations, the daily travel cost savings by MaaS and cost spending by MaaS were assessed. Paths including micro-mobility options (combination of bike and scooter) are always cheaper (or at least same as paths without micro-mobility options). Therefore, the daily travel cost savings by micro-mobility may increase since the increased demand of each station increase the amount of savings. Three scenarios, including an all-or-nothing scenario with choosing 100% of the cheapest paths, all-or-nothing assuming that 20% of network users choose the micro-mobility paths, and a binary-logit modal split model, were developed to specify the cost savings in each station. Meanwhile, an OD demand matrix assumed that the journey from the origin to the destination station is based on a transit or non-transit station. 5 people/day, 10 people/day, and 30 people/day were assumed for traveling from non-transit to non-transit stations, from non-transit to transit or transit to non-transit stations, and from transit to transit stations, respectively. The three developed scenarios are described:

Scenario #1: All-or-nothing with choosing 100% of the cheapest paths

The first scenario describes that the users permanently opt the cheapest paths. Regardless of the presence of Micro-mobility trip legs, 100% of users opt the cheapest paths. Hereupon, this method demonstrates the peak of cost savings.

Scenario #2: All-or-nothing with choosing 20% of micro-mobility paths

Whereas a relatively significant percentage of users may not be able to benefit from micro-mobility paths, such as the elderly, people with disabilities, or little children, it was assumed that 20% of users prefer to choose micro-mobility. In order to realize the best percentage of micro-mobility usage, a sensitivity analysis including 30%, 40%, and 50% of total demand were assessed and the findings were compared with 20% demand.

Scenario #3: Binary-logit modal split model

The third scenario ascertains the total demand by relying on the probability of choosing routes with or without micro-mobility paths. Accordingly, the probability of the two options is specified, then the number of trips are distributed based on the probabilities.

Table 4 shows the station-based cost/benefit justification of Micro-mobility stations including reduced travel time and out-of-pocket travel costs for 20- and 30-years life cycles. Except 20% of total demand for the micro-mobility, all other cases, for all stations, micro-mobility construction and operation is justified. The results specified that by assuming 20% of total users opt to use micro-mobility paths, the subtraction of savings from costs show negative values at some stations. This means that the construction of micro-mobility stations in these nodes is not justified, if 20% of total demand for the shortest paths decided to choose micro-mobility. On the other hand, a positive cost/benefit value shows the construction of a micro-mobility station is justified. It is worth noting that the values of cost/benefit justification for all scenarios used 30-year life cycles in Table 4 and the last two columns in the Table 4 is the comparison between daily cost/benefit for 30-year life cycle and 20-year life cycle with micro-mobility savings from 20% of total demand. As expected, there are some extra stations that could not be justified if life cycle becomes 20 years (node #61, #71, #77, #78 and #81).

Tab. 4 - Cost/benefit justification of micro-mobility stations location (continued to next page)

Station #	**All-or-nothing (100% of total demand)**	**All-or-nothing (20% of total demand)**	**All-or-nothing (30% of total demand)**	**All-or-nothing (40% of total demand)**	**All-or-nothing (50% of total demand)**	**Binary-logit modal split model**	**Daily Cost/Benefit for 30-year Life Cycle Based on 20% of MaaS users**	**Daily Cost/Benefit for 20-year Life Cycle Based on 20% of MaaS users**
1	1490	-59	134	328	522	1392	-59	-73
2	1480	-61	131	324	517	1382	-61	-75
3	1480	-61	131	324	517	1382	-61	-75
4	1471	-63	129	320	512	1374	-63	-77
5	1475	-62	130	322	514	1377	-62	-76
6	1495	-58	136	330	524	1398	-58	-72
7	1518	-54	143	339	536	1422	-54	-67
8	1536	-50	148	346	545	1441	-50	-64
9	2422	194	472	751	1029	2351	194	187
10	4445	598	1079	1560	2041	4436	598	591
11	2374	184	458	732	1005	2297	184	177
12	2205	150	407	664	921	2119	150	143
13	1024	-86	53	192	330	911	-86	-93
14	1465	-64	127	318	509	1367	-64	-78
15	1465	-64	127	318	509	1367	-64	-78
16	1464	-65	126	318	509	1366	-65	-78
17	2200	149	405	662	918	2113	149	142
18	1564	-45	156	358	559	1470	-45	-58
19	2362	182	454	727	999	2290	182	175
20	4437	597	1077	1557	2037	4427	597	590
21	2562	222	514	807	1099	2497	222	215
22	1931	95	325	554	784	1827	95	89
23	1045	-82	59	200	341	933	-82	-89
24	1475	-62	130	322	514	1378	-62	-76
25	1475	-62	130	322	514	1378	-62	-76
26	1489	-60	134	328	521	1393	-60	-73
27	2241	157	418	678	939	2157	157	151
28	1601	-37	168	372	577	1509	-37	-51
29	2388	187	462	737	1012	2318	187	180
30	4616	632	1130	1628	2126	4606	632	626
31	1414	-8	170	348	525	1285	-8	-15
32	1511	-55	141	336	532	1414	-55	-69
33	1512	-55	141	337	533	1415	-55	-68
34	1493	-59	135	329	523	1397	-59	-72
35	2123	134	382	631	880	2030	134	127
36	1552	-47	153	353	553	1459	-47	-60
37	2260	161	423	686	948	2174	161	154
38	1631	-31	177	384	592	1540	-31	-45
39	2587	227	522	817	1112	2523	227	220
40	4638	637	1137	1637	2137	4629	637	630
41	1429	-5	174	354	533	1301	-5	-12
42	1523	-53	144	341	538	1427	-53	-66
43	2069	123	366	610	853	1975	123	116
44	2349	179	450	722	993	2271	179	172
45	2530	215	505	794	1083	2461	215	208
46	1620	-33	173	380	587	1531	-33	-47
47	1850	79	301	522	743	1738	79	72

48	2509	211	498	785	1073	2437	211	204
49	3980	505	940	1374	1808	3965	505	498
50	4489	607	1092	1578	2063	4479	607	600
51	1440	-3	177	358	538	1312	-3	-10
52	1536	-50	148	346	545	1440	-50	-64
53	2185	146	401	656	911	2094	146	139
54	2955	300	632	964	1296	2906	300	293
55	2506	210	497	784	1071	2434	210	204
56	1660	-25	185	396	607	1572	-25	-39
57	1701	-17	198	412	627	1614	-17	-31
58	2619	233	531	829	1128	2555	233	226
59	3865	482	905	1328	1751	3847	482	475
60	3647	439	840	1241	1642	3624	439	432
61	1454	0	182	363	545	1327	0	-7
62	1563	-45	156	357	558	1469	-45	-58
63	2046	118	359	600	841	1948	118	112
64	2992	308	643	979	1314	2930	308	301
65	3526	414	803	1192	1581	3502	414	408
66	2077	125	369	613	857	1978	125	118
67	1765	-4	217	438	659	1679	-4	-18
68	2731	255	565	874	1184	2668	255	249
69	2432	196	475	755	1034	2352	196	189
70	2381	185	460	734	1009	2299	185	179
71	1471	3	187	370	554	1344	3	-3
72	1593	-39	165	369	573	1500	-39	-52
73	2214	152	410	668	925	2123	152	145
74	2995	308	644	980	1316	2931	308	301
75	3677	445	849	1253	1657	3657	445	438
76	2421	193	472	750	1029	2343	193	187
77	1815	6	232	458	684	1732	6	-8
78	1837	10	238	467	695	1754	10	-3
79	1870	17	248	480	712	1788	17	3
80	1890	21	254	488	722	1808	21	7
81	1468	3	186	369	552	1340	3	-4
82	1617	-34	172	379	585	1525	-34	-47
83	1673	-23	189	401	613	1583	-23	-36
84	1248	-41	120	281	442	1143	-41	-48
85	3187	347	702	1057	1412	3137	347	340
86	3868	483	906	1329	1752	3851	483	476
87	2615	232	530	828	1126	2547	232	225
88	2533	216	505	795	1085	2461	216	209
89	2597	229	525	821	1117	2526	229	222
90	1895	22	256	490	724	1813	22	8
91	3086	326	671	1016	1361	3046	326	320
92	2287	167	432	697	962	2203	167	160
93	2286	166	431	696	961	2203	166	160
94	2817	273	591	909	1227	2761	273	266
95	4706	650	1157	1664	2171	4694	650	644
96	5386	786	1361	1936	2511	5381	786	780
97	4164	542	995	1448	1900	4151	542	535
98	4156	540	992	1444	1896	4142	540	534
99	2925	294	623	952	1281	2872	294	287
100	1903	23	258	493	728	1822	23	10

Tab. 5 - Title of stations after cost/benefit analysis

Station #	**Title**	**Station #**	**Title**	**Station #**	**Title**	**Station #**	**Title**
1	Transit	26	Transit	51	None	76	Micro-mobility
2	Transit	27	Micro-mobility	52	Transit	77	MaaS
3	Transit	28	Transit	53	Micro-mobility	78	MaaS
4	Transit	29	Micro-mobility	54	Micro-mobility	79	MaaS
5	Transit	30	Micro-mobility	55	Micro-mobility	80	MaaS
6	Transit	31	None	56	Transit	81	Micro-mobility
7	Transit	32	Transit	57	Transit	82	Transit
8	Transit	33	Transit	58	Micro-mobility	83	Transit
9	Micro-mobility	34	Transit	59	Micro-mobility	84	None
10	Micro-mobility	35	Micro-mobility	60	Micro-mobility	85	Micro-mobility
11	Micro-mobility	36	Transit	61	Micro-mobility	86	Micro-mobility
12	Micro-mobility	37	Micro-mobility	62	Transit	87	Micro-mobility
13	None	38	Transit	63	Micro-mobility	88	Micro-mobility
14	Transit	39	Micro-mobility	64	Micro-mobility	89	Micro-mobility
15	Transit	40	Micro-mobility	65	Micro-mobility	90	MaaS
16	Transit	41	None	66	Micro-mobility	91	Micro-mobility
17	Micro-mobility	42	Transit	67	Transit	92	Micro-mobility
18	Transit	43	Micro-mobility	68	Micro-mobility	93	Micro-mobility
19	Micro-mobility	44	Micro-mobility	69	Micro-mobility	94	Micro-mobility
20	Micro-mobility	45	Micro-mobility	70	Micro-mobility	95	Micro-mobility
21	Micro-mobility	46	Transit	71	Micro-mobility	96	Micro-mobility
22	Micro-mobility	47	Micro-mobility	72	Transit	97	Micro-mobility
23	None	48	Micro-mobility	73	Micro-mobility	98	Micro-mobility
24	Transit	49	Micro-mobility	74	Micro-mobility	99	Micro-mobility
25	Transit	50	Micro-mobility	75	Micro-mobility	100	MaaS

Table 4 represents that construction of Micro-mobility station assuming a 30-years life cycle in stations #1, #2, #3, #4, #5, #6, #7, #8, #13, #14, #15, #16, #18, #23, #24, #25, #26, #28, #31, #32, #33, #34, #36, #38, #41, #42, #46, #51, #52, #56, #57, #62, #67, #72, #82, #83, and #84 is not justified. Additionally, the construction of stations #61, #71, #77, #78, and #81 is not justified with a 20-year life cycle. If it is assumed that the mentioned stations are not constructed by the operator, the daily operator's savings in 20- and 30-year life cycles will be $18520 and $16033, respectively. Given the findings, Table 5 shows the title of each station after cost/benefit analysis.

As shown in Table 5, Some transit stations could not justify the micro-mobility or MaaS stations, and it is assumed that users for those stations can access by walking easily because those station are not very far from the near nodes, while the stations (#77, #78, #79, #80, #90, #100) were justified as MaaS stations, because they are located in less dense areas, users must use micro-mobility services to access those stations. Table 5 shows the result of cost/benefit analysis provided in Table 4, highlighted that the transformation into micro-mobility or MaaS stations for stations 1 to 8 is not feasible. As shown in Figure 1, the stations 1 to 4 and the stations 5 to 8 are the transit stations of red and blue transit routes. The cost/benefit analysis as can be seen in Table 4 highlighted that these eight stations should serve transit users.

Considering the obtained results from Table 4, there are 57 nodes that became Micro-mobility stations, and six transit stations that became MaaS stations. The new title of each station is shown in Figure 3. As can be seen in Figure 3, in "before cost/benefit analysis", *T* describes transit stations (=stations where buses are the only mode of transportation), and *N* describes the stations without any title (=stations where walking is the only mode of transportation).

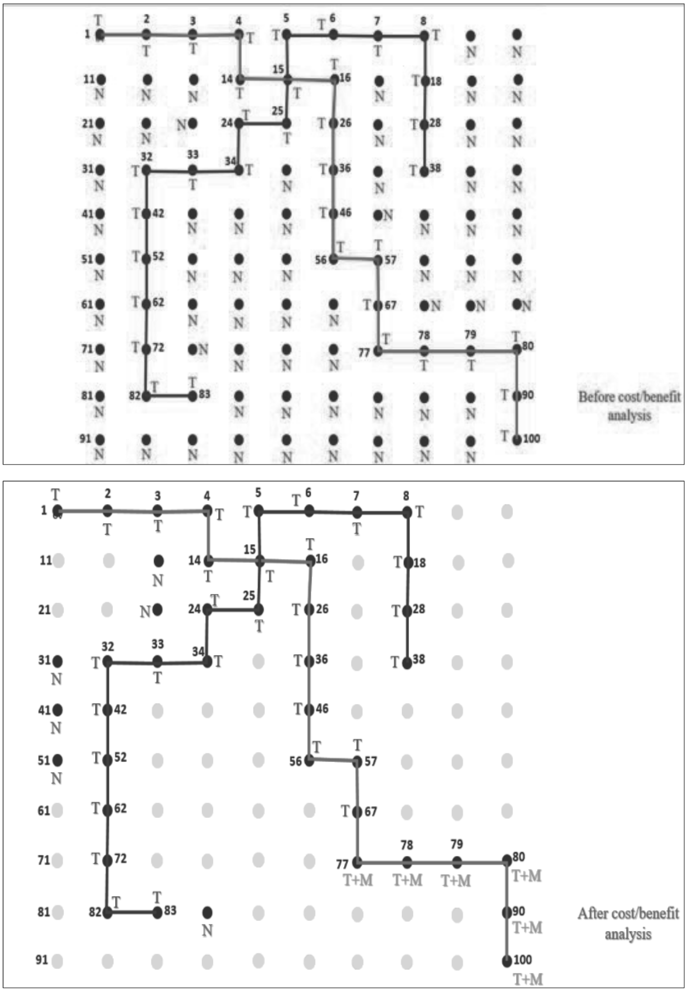

Fig. 3 - The location of micro-mobility and MaaS stations after cost/benefit analysis

In “after cost/benefit analysis”, the stations are shown with title of transit (*T*), the stations with no title (*N*), the micro-mobility stations (yellow color dots), and MaaS stations (*T+M* - the stations encompassed by both transit and micro-mobility transport modes).

6. Summary and conclusion

Mobility-as-a-Service (MaaS) enables the integration of public and private transport modes into a comprehensive mobility option for transport users. Integration of Micro-mobility and public transport can increase the sustainability of transport systems and strengthen complementary relationships between transport services. Furthermore, MaaS could increase service use over time through subscription plans that offer travelers bundled access to multiple transport services. This study aimed to concentrate on MaaS roles in minimizing the total costs to users and agencies. The literature highlighted that user travel time costs, user operating costs, user out-of-pocket costs, agency operating costs, and infrastructure construction costs were not investigated as an integrated total cost function in previous studies. Hence, the first achievement of the paper was developing a comprehensive total cost function. Thereupon, a shortest path algorithm was developed in MATLAB software to identify the shortest paths between each origin and destination node depending on user's lowest travel time and cost. The shortest path algorithm was applied for a transport network including 100 nodes that developed from downtown of public transport network of Baltimore City. In order to identify the location of Micro-mobility and MaaS stations, the total cost function was imported to the shortest path algorithm.

The shortest path algorithm was executed in two cycles with each cycle executed 10,000 times for two transport mode combinations, including one with micro-mobility (combination of transit+Uber+bike+scooter+walking) and one without micro-mobility (combination of transit+Uber+walking). Other effective parameters e.g., demand and capacity of each station, access and egress time of each station to transit stations, service area (buffer zone) of each station, and the probability of using transport modes in each station were propounded to identify the ideal type of each station. Hence, three scenarios, including all-or-nothing with choosing 100% of the cheapest paths, all-or-nothing assuming that 20% of network users opt to use micro-mobility paths, and a binary-logit modal split model were developed to specify the cost savings created by micro-mobility construction in each station. Meanwhile, in order to identify the best percentage of micro-mobility -including paths usage by travelers, a sensitivity analysis including 20%, 30%, 40%, and 50% of total demand was provided. Eventually, the daily savings costs of micro- mobility station's construction and operation were ascertained, and the construction of micro-mobility station in each node was justified.

As shown in Table 4, the value of the savings by micro-mobility include reduced travel time and out-of-pocket travel costs. In order to increase the accuracy of findings, a cost/benefit analysis was appraised for two life cycles consisting of 20-years and 30-years. The results demonstrated that construction of micro-mobility stations was not justified for 42 nodes and 37 nodes in 20-year and 30-year life cycles, respectively. Additionally, excluding the construction of these stations during these two time intervals benefits daily operator savings by $18520 and $16033, respectively. Given the cost/benefit analysis of each station, the title of each station was distinguished as shown in Table 5 and Figure 3. The findings demonstrated that changing the performance of stations #77, #78, #79, #80, #90, and #100 to MaaS can turn these stations into transport hubs. Meanwhile, Uber and micro-mobility services are served around these stations simultaneously. Stations like #23, #31, #41, #51, and #84 as "None" stations benefit from the transportation services available in their neighboring stations. "Transit" stations serve users as transit or transfer stops.

From the results, there are no consistent results to justify the micro-mobility and MaaS construction and operation based on existing transit stations. The justification depended on users' shortest trip paths, amount of demand, existing transit stations, etc. Eventually, "MaaS" stations' benefit users through micro-mobility services e.g., bicycles and scooters, and boost the sustainability of the network. The findings from this research provide insight into the impacts of gradual deployment of MaaS station construction, which helps planners develop public policies to redesign the performance of traditional public stations. Some limitations of the study worth mentioning are its network, and traffic composition and O-D matrix. The proposed methodology can be utilized efficiently on actual networks. Taking into account factors such as the configuration of the transportation network, passenger demand, the distribution of public transport routes, and the possible modes between origin-destination pairs, it is conceivable that the results could be changed.

In the next step of this research, the priority and location of MaaS stations will be specified through a bi-level optimization model. Additionally, heuristic or metaheuristic methods are applied to analyze the optimization model.

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Disclosure of information and conflicts of interest

The author declares no conflict of interest.

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