Preference-based Optimization for Multimodal Trip Planning with Public Transport and Shared Mobility

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Short summary

Multimodal trip planning has attracted attention from scholars because it can make use of the strengths of multiple transport modes. This study investigates preference-based optimization for multimodal trip planning with public transport and shared mobility. Both ride-pooling vehicles and shared micromobility are considered. A mixed integer programming model is developed. Preferences are incorporated into the objective function of the optimization model. The characteristics of different types of services are considered in constraints. Numerical studies are conducted using real transport network data in the Rotterdam area. The results show that considering preferences in multimodal trip planning can improve the service level.
Keywords: Shared Mobility; Public Transport; Preference; Multimodal Trip Planning; Optimization.

1 Introduction

While there have been pioneering investigations into the coordinated planning of public transport and ride-sharing services (Yu et al., 2021; Molenbruch et al., 2021), the integration of micromobility solutions into public transport remains largely unexplored (Stiglic et al., 2018). In recent years, there has been a notable increase in policy initiatives specifically designed to promote the widespread adoption of micromobility services as a means of achieving environmentally sustainable transportation (Abduljabbar et al., 2021). Furthermore, existing research predominantly concentrates on optimizing the supply aspect, such as finding the optimal assignment of vehicles (Ma, 2017), or delves into demand analysis, typically employing choice models (Vij et al., 2020; Ho et al., 2020). There is however a lack of knowledge on unifying both the supply and demand sides. Consequently, preferences are seldom incorporated into the framework of multimodal trip planning. Without preferences, trip planning may not prioritize the individual needs of users. This could result in inconvenient travel experiences, potentially discouraging users from adopting multimodal transport. The absence of preferences means that services may be designed as “one-size-fits-all", which can overlook variations in user behavior, potentially leading to reduced customer satisfaction. Moreover, failing to account for demand can lead to inefficient resource allocation. For example, vehicles may be dispatched without considering preferences and then be canceled by passengers, leading to wasted resources, increased operational costs, and underutilized or overburdened services.

The preference-based multimodal trip planning remains relatively unexplored, primarily due to its inherent complexities: (a) Modal Integration: It includes the planning of multiple transport modes, each requiring a distinct planning methodology as each mode has its unique set of variables, constraints, and optimization criteria. Coordinating these modes seamlessly is a challenging task, which involves synchronization of schedules and integration of services with specialized planning approaches. (b) Preference Integration: Integrating the preferences of passengers into the planning process amplifies the planning complexity. Passengers have diverse and often conflicting preferences. Some might prioritize speed and direct routes, while others may prefer more economical or environmentally friendly options. This heterogeneity requires the service provider to consider a wide range of preferences, making the planning process more intricate. To cater to individual preferences, the service provider needs to customize services and routes, leading to a multitude of potential permutations and combinations. This customization can result in a vast number of possibilities that must be evaluated, making the planning process computationally intensive. To handle these complexities, the service provider may need to develop sophisticated routing and scheduling

algorithms that can efficiently match passengers with their preferred services. This often involves solving complex optimization problems, which can be computationally demanding.
To bridge the existing gaps in the literature, we present optimization approaches for tailoring multimodal trip planning. Our focus extends to encompass public transport modes, such as the metro and train, alongside Shared Mobility (SM) options such as ridesharing and micro-mobility services. Our contributions include: (a) introducing a novel multimodal optimization approach, which seamlessly integrates public transport and SM services. (b) investigating different exogenous demand scenarios for different customer segments, including passengers with different genders, ages, incomes, education levels, etc., taking into account both homogeneous and heterogeneous preferences. (c) providing valuable managerial insights through extensive numerical experiments conducted on a real-world transport network and demand data set. These experiments compare scenarios with and without consideration of homogeneous or heterogeneous preferences, offering a comprehensive understanding of the model's performance.

Table 1: Notation.

Sets:	
W	Set of modes indexed by w.
R	Set of requests indexed by r. $R^t \subseteq R$ denotes the set of active requests at time t, which includes those that have not yet been scheduled or have not yet reached their intended destinations. $R_{\text{finish}} \subseteq R$ represents requests that already reached their destinations.
N	Set of locations indexed by i and j. $O \subseteq N$, set of depots. $P/D \subseteq N$, set of pickup/delivery locations. $C^t \subseteq N$, set of current locations of vehicles at time step t. $N_w \subseteq N$ represents the set of locations for mode w.
K	Set of vehicles indexed by k. $K_{\text{PT}} \subseteq K$, $K_{\text{ride}} \subseteq K$, and $K_{\text{micro}} \subseteq K$ represent sets of PT services, ride sharing vehicles, and micromobility vehicles, respectively. K_{private} and K^r_{private} are sets of private vehicles and private vehicles owned by passenger r, respectively.
A	Set of arcs. For $i, j \in N$, the arc from i to j is denoted by $(i, j) \in A$. $A_p/A_d \subseteq A$ represents the set of pickup/delivery arcs. For $(i, j) \in A_p$, $i \in P$. For $(i, j) \in A_d$, $j \in D$. $A_w \subseteq A$ represents the set of arcs for mode w.
H	Set of schedules of finished requests R_{finish}.
Parameters:	
u_k	Capacity of vehicle k.
q_r	Number of passengers associated with request r.
τ^k_{ij}	Travel time [minute] on the shortest path between locations i and j for vehicle k.
$[a_{p_r}, b_{d_r}]$	Earliest pickup time and latest delivery time for request r.
v_k	Speed [km/h] of vehicle k.
v_r	Walking speed [km/h] of request r.
d^k_{ij}	Distance [km] between locations i and j for vehicle k.
c^n_k	$c^1_k/c^{1'}_k$ are transport cost [euro] per min/km using vehicle $k \in K$. c^2_k is the cost per hour of waiting time.
M	A large enough positive number.
ASC_w	Alternative specific constant of using transport mode(s) m.
β	Parameters in travellers' utility functions.
$searching$	Time for searching parking space.
$parking$	Parking cost.
Variables:	
x^k_{ij}	Binary variable; 1 if vehicle k uses the arc (i, j), 0 otherwise.
y^{kr}_{ij}	Binary variable; 1 if request r transported by vehicle k uses arc (i, j), 0 otherwise.
s^{kl}_{ir}	Binary variable; 1 if request r is transferred from vehicle k to vehicle $l \neq k$ at location i, 0 otherwise.
ts_r	Binary variable; 1 if request r is transferred during transportation, 0 otherwise.
$t^{kr}_i/{t'}^{kr}_i/\bar{t}^{kr}_i$	The arrival time/service start time/service finish time of request r served by vehicle k at location i.
$t^k_i/{t'}^k_i/\bar{t}^k_i$	Arrival time/service start time/departure time of vehicle k at location i.
t^{wait}_{ki}	Waiting time of vehicle k at location i.
t^k	Micromobility vehicle k's last operation time.
l^k	Micromobility vehicle k's last location.

U_r	Utility value of request r.
U	Utility value of requests that have transfer operations during transportation.
U'	Utility value of requests that do not have transfer operations during transportation.
vt_w	In vehicle time of using transport mode(s) w.
$cost_w$	Cost of using transport mode(s) w.
$walk_w$	Walking time using transport mode w.
wt_w	Waiting time using transport mode w.

2 Methodology

The notations used in this paper are shown in Table 1. In the following, we envisaged a preference-based multimodal transport journey planner, which is designed to seamlessly provide PT and SM services to passengers. Walking to/from PT stations and SM vehicles is also considered. The objective of the service provider is to maximize the social welfare, which is the logsum function of utilities of all passengers who have not arrived their destinations (Objective Function 1). The cost function includes the fixed cost ($cost^k_{fixed}$), cost for travel time ($\tau^k_{ij} * cost^k_{time}$), and cost for travel distance ($d^k_{ij} * cost^k_{distance}$).

$$\max F = log \sum_{r \in R} exp(ts_r U + (1 - ts_r)U') \tag{1}$$

$$\begin{aligned} U = \sum_{k \in K} ASC_k {x'}^k_r + \sum_{(i,j) \in A} (\sum_{k \in K_{\text{public}}} (\beta_{PTwait} t^{\text{wait}}_{ki} + \beta_{\text{mainTime}} \tau^k_{ij} + y^{kr}_{ij} \beta_{\text{mainCost}} cost^k_{ij}) \\ + \sum_{k \in K \setminus K_{\text{public}}} (\beta_{\text{subTime}} (t^{\text{wait}}_{ki} + \tau^k_{ij}) + y^{kr}_{ij} \beta_{\text{subCost}} cost^k_{ij})) + \epsilon \end{aligned} \tag{2}$$

$$U' = \sum_{k \in K} ASC_k {x'}^k_r + \sum_{(i,j) \in A} (\sum_{k \in K_{\text{walk}}} \beta_{\text{walk}} \tau^k_{ij} + \sum_{k \in K \setminus K_{\text{walk}}} (\beta_{\text{mainTime}} \tau^k_{ij} + y^{kr}_{ij} \beta_{\text{mainCost}} cost^k_{ij})) + \epsilon \tag{3}$$

$$cost^k_{ij} = cost^k_{fixed} + \tau^k_{ij} * cost^k_{time} + d^k_{ij} * cost^k_{distance} \tag{4}$$

The utility functions outlined in Montes et al. (2023) are used in this study. Montes et al. (2023) study the multimodal transportation in Rotterdam, focusing on the preferences and choices associated with both metro usage and the subsequent egress modes, which encompass bus/tram, shared bicycles, shared e-mopeds, and walking. Montes et al. (2023) do not consider ride pooling and ingress trip and we extend the applicability of the parameters initially established for private cars and egress trips to encompass ride pooling and ingress trips. These utility functions are listed in Equations 5 to 11.

$$\begin{aligned} U_{PT\&sb} =& \text{ASC}_{PT} + \text{ASC}_{sb} + \beta_{PTwait} * wt_{\text{PT}} + \beta_{\text{mainTime}} * vt_{\text{PT}} + \\ & \beta_{\text{mainCost}} * cost_{\text{PT}} + \beta_{\text{subTime}} * vt_{sb} + \beta_{\text{subCost}} * cost_{sb} + \epsilon \end{aligned} \tag{5}$$

$$\begin{aligned} U_{public\&sm} =& \text{ASC}_{PT} + \text{ASC}_{smE} + \beta_{PTwait} * wt_{\text{PT}} + \beta_{\text{mainTime}} * vt_{\text{PT}} + \\ & \beta_{\text{mainCost}} * cost_{\text{PT}} + \beta_{\text{subTime}} * vt_{sm} + \beta_{\text{subCost}} * cost_{sm} + \epsilon \end{aligned} \tag{6}$$

$$\begin{aligned} U_{public\&ride} =& \text{ASC}_{PT} + \text{ASC}_{rideE} + \beta_{PTwait} * wt_{\text{PT}} + \beta_{\text{mainTime}} * vt_{\text{PT}} + \\ & \beta_{\text{mainCost}} * cost_{\text{PT}} + \beta_{\text{subTime}} * (vt_{\text{ride}} + wt_{\text{ride}}) + \beta_{\text{subCost}} * cost_{rideE} + \epsilon \end{aligned} \tag{7}$$

$$\begin{aligned} U_{PT} =& \text{ASC}_{PT} + \beta_{PTwait} * wt_{\text{PT}} + \beta_{\text{mainTime}} * vt_{\text{PT}} + \\ & \beta_{\text{mainCost}} * cost_{\text{PT}} + \beta_{walk} * walk_{PT} + \epsilon \end{aligned} \tag{8}$$

$$U_{sm} = \text{ASC}_{sm} + \beta_{walk} * walk_{sm} + \beta_{\text{mainTime}} * vt_{\text{sm}} + \beta_{\text{mainCost}} * cost_{\text{sm}} + \epsilon \tag{9}$$

$$U_{car} = \text{ASC}_{car} + \beta_{\text{mainTime}} * (vt_{\text{car}} + searching) + \beta_{\text{mainCost}} * (cost_{\text{car}} + parking) + \epsilon \tag{10}$$

$$U_{bike} = \text{ASC}_{bike} + \beta_{\text{mainTime}} * vt_{\text{bike}} + \epsilon \tag{11}$$

Constraints (12) to (35) are constraints for all transport modes.

Constraints (12) and (13) ensure that passengers for each request starts and ends at its origination and destination, respectively.

$$\sum_{k\in K}\sum_{j\in N} y^{kr}_{p_r j} \leqslant 1 \quad \forall r \in R \tag{12}$$

$$\sum_{k\in K}\sum_{j\in N} y^{kr}_{j d_r} \leqslant 1 \quad \forall r \in R \tag{13}$$

Constraints (14) enforce that each vehicle may initiate at most one route from its initial location; Constraints (15) ensure that if a vehicle is used, it ends the route at its ending location, except for micromobility and walking. Constraints (16) represent vehicle flow conservation. Constraints (17) link y^{kr}_{ij} and x^{k}_{ij} variables in order to guarantee that for a request to be transported by a vehicle, that vehicle needs to traverse the associated arc.

$$\sum_{j\in N} x^{k}_{o(k)j} \leqslant 1 \quad \forall k \in K \setminus K_{\text{walk}} \tag{14}$$

$$\sum_{j\in N} x^{k}_{o(k)j} = \sum_{j\in N} x^{k}_{jo'(k)} \quad \forall k \in K \setminus K_{\text{walk\&micro}} \tag{15}$$

$$\sum_{j\in N} x^{k}_{ij} - \sum_{j\in N} x^{k}_{ji} = 0 \quad \forall k \in K \setminus K_{\text{walk}},\ \forall i \in N \setminus o(k), o'(k) \tag{16}$$

$$y^{kr}_{ij} \leqslant x^{k}_{ij} \quad \forall (i,j) \in A,\ \forall k \in K,\ \forall r \in R \tag{17}$$

Constraints (18) ensure that there is only one transfer for one request at a transfer location. Constraints (19), Constraints (20), and Constraints (21) forbid transfers without PT services and walking, transfers between micromobility vehicles, and transfers between the same vehicle k, respectively.

$$\sum_{j\in N} y^{kr}_{ji} + \sum_{j\in N} y^{lr}_{ij} \leqslant s^{kl}_{ir} + 1 \quad \forall r \in R,\ \forall i \in T,\ \forall k, l \in K \tag{18}$$

$$s^{kl}_{ir} = 0 \quad \forall r \in R,\ \forall i \in T,\ \forall k, l \in K \setminus K_{\text{public\&walk}} \tag{19}$$

$$s^{kl}_{ir} = 0 \quad \forall r \in R,\ \forall i \in T,\ \forall k \in K_{\text{micro}},\ \forall l \in K_{\text{micro}} \tag{20}$$

$$s^{kk}_{ir} = 0 \quad \forall r \in R,\ \forall i \in T,\ \forall k \in K \tag{21}$$

Constraints (22) are the capacity constraints.

$$\sum_{r\in R} q_r y^{kr}_{ij} \leqslant u_k x^{k}_{ij} \quad \forall (i,j) \in A,\ \forall k \in K \tag{22}$$

Constraints (23) ensure the transfer occurs in the PT stations that have the available facilities for transfers, such as SM hubs.

$$s^{kl}_{ir} = 0 \quad \forall k \in K_{w_1},\ \forall l \in K_{w_2},\ \forall i \in T \setminus T^{w_2}_{w_1},\ \forall r \in R,\ \forall w_1, w_2 \in W \tag{23}$$

Constraints (24) guarantee that service start time is later than the arrival time of passengers. Constraints (25) ensure that the service finishing time equals service starting time plus time t''^{kr}_{i}. The time t''^{kr}_{i} varies according to the specific transport mode. In the context of public transport, it means dwelling time, whereas in the case of micromobility, it means the time required for unlocking and locking the vehicle. Constraints (26) ensure that departures occur only after all passengers have boarded or disembarked from the vehicle. Constraints (27) ensure that the request's arrival time is the same as the vehicle's arrival time. Constraints (28) define the vehicle's service starting time.

$$t^{kr}_{i} \leqslant t'^{kr}_{i} \quad \forall i \in N,\ \forall k \in K,\ \forall r \in R \tag{24}$$

$$t'^{kr}_{i} + t''^{kr}_{i} \sum_{j\in N} y^{kr}_{ij} \leqslant \bar{t}^{kr}_{i} \quad \forall i \in N,\ \forall k \in K,\ \forall r \in R \tag{25}$$

$$\bar{t}^{k}_{i} \geqslant \bar{t}^{kr}_{i} \quad \forall i \in N,\ \forall k \in K,\ \forall r \in R \tag{26}$$

$$t^{k}_{i} \leqslant t^{kr}_{i} \quad \forall i \in N,\ \forall k \in K,\ \forall r \in R \tag{27}$$

$$t'^{k}_{i} \geqslant t'^{kr}_{i} \quad \forall i \in N,\ \forall k \in K,\ \forall r \in R \tag{28}$$

Constraints (29) and (30) ensure that the time on route is consistent with the distance travelled and speed. Various modes of transportation have distinct speeds (Medical News Today, 2023; VerkeersNet, 2023; Pulse, 2023). Constraints (31) take care of the time window for origination and destination.

$$\bar{t}_i^k + \tau_{ij}^k - t_j^k \leqslant M(1 - x_{ij}^k) \quad \forall (i,j) \in A,\ \forall k \in K \setminus K_{\text{fix}} \tag{29}$$

$$\bar{t}_i^k + \tau_{ij}^k - t_j^k \geqslant -M(1 - x_{ij}^k) \quad \forall (i,j) \in A,\ \forall k \in K \setminus K_{\text{fix}} \tag{30}$$

$$t'^{kr}_{p_r} \geqslant a_{p_r} y_{ij}^{kr},\ \bar{t}_{d_r}^{kr} \leqslant b_{d_r}) \quad \forall (i,j) \in A, \forall r \in R,\ \forall k \in K \tag{31}$$

Constraints (32) are time constraints for transfers. If there is a transfer from vehicle k to vehicle l at transfer location i, the boarding time t'^{lr}_i for vehicle l must occur after the alighting time $\bar{t}_i^{kr}$ from vehicle k. Constraints (33) calculate waiting time.

$$\bar{t}_i^{kr} - t'^{lr}_i \leqslant M(1 - s_{ir}^{kl}) \quad \forall r \in R,\ \forall i \in T,\ \forall k,l \in K,\ k \neq l \tag{32}$$

$$t_{ki}^{\text{wait}} \geqslant t'^k_i - t_i^k \quad \forall i \in N,\ \forall k \in K \tag{33}$$

Constraints (34) and (35) set variables x and y as binary variables.

$$x_{ij}^k \in \{0,1\} \quad \forall (i,j) \in A,\ \forall k \in K \tag{34}$$

$$y_{ij}^{kr} \in \{0,1\} \quad \forall (i,j) \in A,\ \forall k \in K,\ \forall r \in R \tag{35}$$

The constraints represented by (36) guarantee the continuous operation of public transportation (PT) vehicles, even in the absence of passengers.

$$x_{ij}^k = 1 \quad \forall (i,j,k) \in PT \tag{36}$$

Constraints (37)-(40) are for PT and ride pooling. Constraints (37)-(40) represent request flow conservation. Constraints (37) and (38) are for regular and transfer locations, respectively. If request r is not transferred at location $i \in T$ but vehicle k passes location i for other requests, Constraints (37) do not work on request r. Therefore, additional flow conservation of requests (Constraints (39) and (40)) are added.

$$\sum_{j \in N_{\text{ride\&public}}} y_{ij}^{kr} - \sum_{j \in N_{\text{ride\&public}}} y_{ji}^{kr} = 0 \quad \forall k \in K_{\text{ride\&public}},\ \forall r \in R,\ \forall i \in N_{\text{ride\&public}} \setminus T, p_r, d_r \tag{37}$$

$$\sum_{k \in K_{\text{ride\&public}}} \sum_{j \in N_{\text{ride\&public}}} y_{ij}^{kr} - \sum_{k \in K_{\text{ride\&public}}} \sum_{j \in N_{\text{ride\&public}}} y_{ji}^{kr} = 0 \quad \forall k \in K_{\text{ride\&public}},\ \forall r \in R,\ \forall i \in T \setminus p_r, d_r \tag{38}$$

$$\sum_{j \in N_{\text{ride\&public}}} y_{ij}^{kr} - \sum_{j \in N_{\text{ride\&public}}} y_{ji}^{kr} \leqslant \sum_{l \in K_{\text{ride\&public}}} s_{ir}^{lk} \quad \forall k,l \in K_{\text{ride\&public}},\ \forall r \in R,\ \forall i \in T \setminus p_r, d_r \tag{39}$$

$$\sum_{j \in N_{\text{ride\&public}}} y_{ji}^{kr} - \sum_{j \in N_{\text{ride\&public}}} y_{ij}^{kr} \leqslant \sum_{l \in K_{\text{ride\&public}}} s_{ir}^{kl} \quad \forall k,l \in K_{\text{ride\&public}},\ \forall r \in R,\ \forall i \in T \setminus p_r, d_r \tag{40}$$

Constraints (41) ensure vehicles running on predefined routes. Routes of PT are predefined, and ride-pooling vehicles may also operate along predetermined routes. Dock-based micromobility vehicles can only be parked in predefined locations, therefore Constraints (41) also apply to these vehicles. Constraints (42) take care of the time windows for predefined stations, and they are not applied to micromobility vehicles.

$$x_{ij}^k = 0 \quad \forall k \in K_{\text{fix}},\ \forall (i,j) \in A \setminus A_{\text{fix}}^k \tag{41}$$

$$t_i^{kr} \geqslant a_i^k y_{ij}^{kr},\ \bar{t}_i^{kr} \leqslant b_i^k + M(1 - y_{ij}^{kr}) \quad \forall (i,j) \in A,\ \forall r \in R,\ \forall k \in K_{\text{fix}} \setminus K_{\text{micro}} \tag{42}$$

Constraints (43) ensure that a micromobility vehicle is incapable of independent movement, as it is only allowed to be relocated by a passenger.

$$x_{ij}^k \leqslant y_{ij}^{kr} \quad \forall (i,j) \in A_{\text{micro}},\ \forall k \in K_{\text{micro}},\ \forall r \in R \tag{43}$$

Constraints (44) are designed to preserve the records of completed requests, ensuring that their schedules are maintained.

$$y_{ij}^{kr} = 1 \quad \forall (i,j,k,r) \in H \tag{44}$$

Since a passenger can be transferred more than once, Constraints (45) and (46) set a new variable ts_r, which determines whether request r is transferred or not.

$$ts_r \leqslant s_{ir}^{kl} \quad \forall k,l \in K \setminus K_{\text{walk}},\ \forall r \in R,\ \forall i \in T \tag{45}$$

$$ts_r M \geqslant s_{ir}^{kl} \quad \forall k,l \in K \setminus K_{\text{walk}},\ \forall r \in R,\ \forall i \in T \tag{46}$$

$$x'^{k}_{r} \geqslant x_{ij}^{k} \quad \forall k \in K,\ \forall r \in R,\ \forall (i,j) \in A \tag{47}$$

3 Results and discussion

The distances between locations are obtained from OpenStreetMap (OpenStreetMap, 2023). PT service schedules are obtained from GTFS data (MobilityData, 2023). The capacity of PT is assumed to be unlimited. According to a commonly used Hexagonal Hierarchical Geospatial Indexing System (H3, 2023), the studied area is divided into hexagonal grid cells. The requests are generated based on these grid cells. First, an origin-destination grid cell pair is selected, and the locations of the origin and destination are randomly generated within each cell. The start and latest ending times are also generated with random durations. Requests can be generated according to specific distributions. When designing instances, the time of passengers follows a Poisson distribution that considers peak hours in a day. The origination and destination follow a uniform distribution. At each time step, the solutions considering all passengers are generated and recorded. The best solution will be considered as the initial state in next time step. The specific solution for each individual passenger is also recorded, which includes travel cost, time, utility, transport mode, route, and schedule. The profiles and heterogeneous preferences of passengers are considered using parameters in Montes Rojas (2021). We conduct a case study in the Maassluis city, which is a suburban area in The Netherlands. Figure 1 shows the Maassluis area with grid cells.

Figure 1: Grid cells in Maassluis area.

Figures 2-5 show the OD pairs of passengers, depots of ride-pooling vehicles, depots of sharing scooters, and hubs of sharing bikes, respectively. The origins of passengers are randomly generated, and the destinations of passengers are generated based on Gamma distributions, as outlined in the illustrations referenced in Soza-Parra et al. (2022). The centers of destinations are two metro stations and one church. The stations of dock-based vehicles are fixed in these three centers. The departure and latest arrival times are generated using Poisson distributions, considering peak hours.

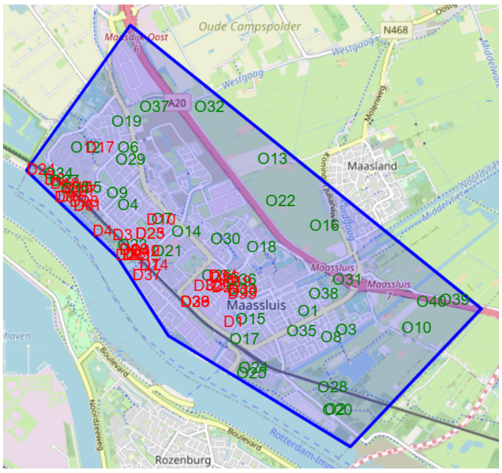

Figure 2: Originations (green color) and destinations (red color) of passengers in Maassluis area.

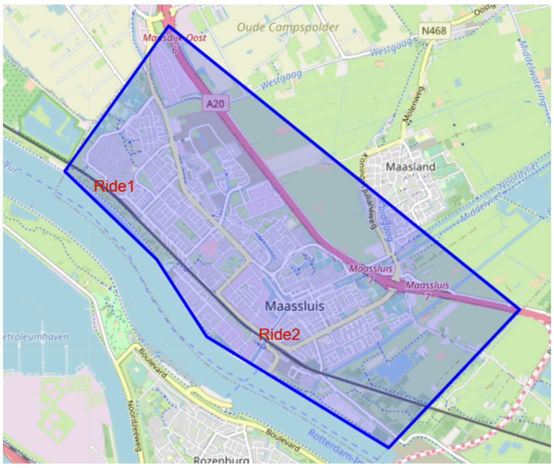

Figure 3: Depots of ride-pooling vehicles in Maassluis area.

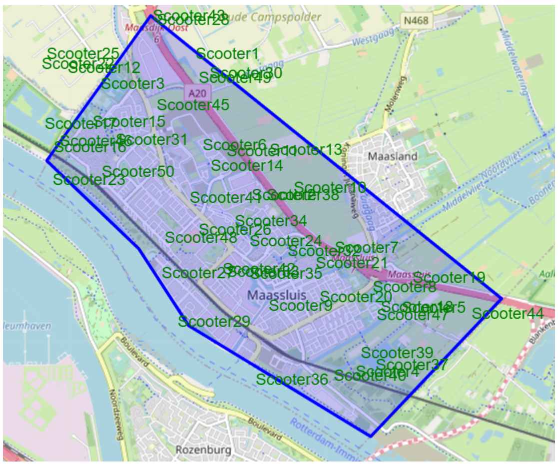

Figure 4: Beginning depot (green color) and ending depot (red color) of scooters in Maassluis area.

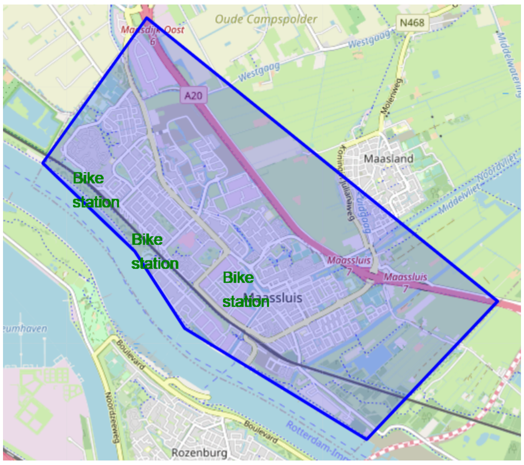

Figure 5: Hubs of bikes in Maassluis area.

Compared to general passengers, female passengers prefer bikes and private vehicles over the combination of PT and bike/ride-pooling vehicles when scooters are not available, as shown in Figure 6. When scooters are available, the results for female and general passengers are the same.

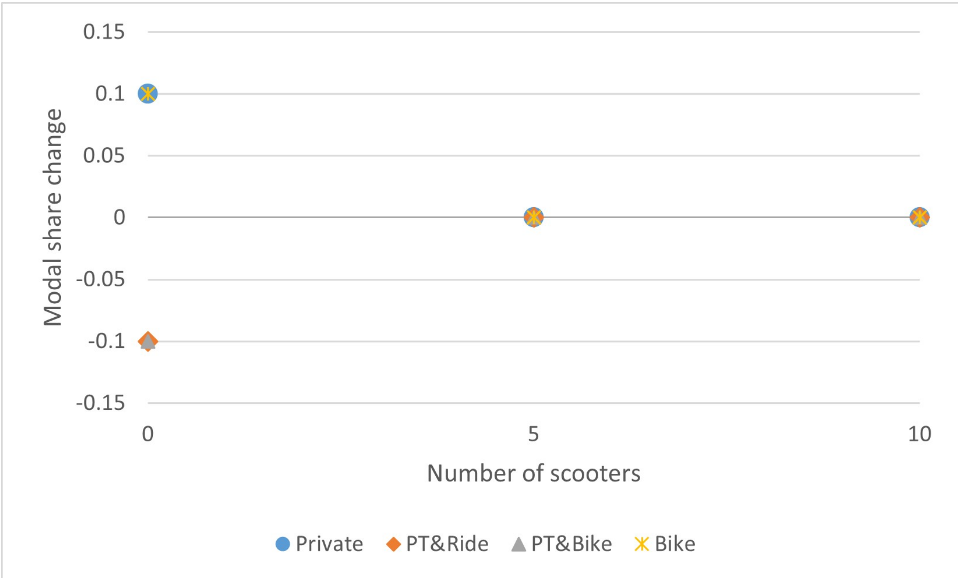

Figure 6: Modal share changes of female passengers compared to general passengers

We also check that the modal share changes when the price of scooters changes, as shown in Figure 7. The results are unaffected by the number of shared bikes, as the modal share changes for 0, 5, and 10 shared bikes are identical. The results show that when the price of scooters is reduced from 4 euros to 1 euro, the modal share of scooters is decreased, while the modal share of using a combination of public transport and scooters is increased. As the price of scooters decreases, the overall cost of using multimodal transport becomes more appealing. The multimodal service provides faster transport compared to using only scooters. Therefore, when the price of scooters decreases, multimodal transport services instead of standalone scooter services are chosen.

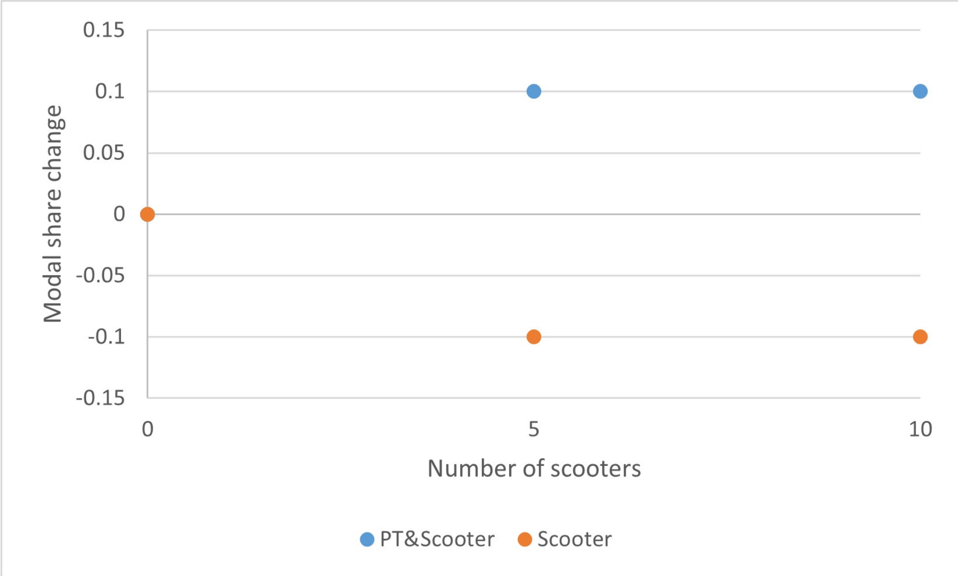

Figure 7: Modal share changes when scooter price is reduced from 4 euros to 1 euro

4 Conclusions

This study has delved into preference-based optimization for multimodal trip planning, encompassing public transport and shared mobility. By integrating preferences into the objective function of the optimization model, our research contributes to improving the efficiency of multimodal transportation solutions. The results under different groups of passengers and prices of vehicles are also analyzed. Our findings indicate that the demand side is influenced by factors such as the number of vehicles and service prices on the supply side, which should be taken into account when delivering multimodal trip services. The proposed approach can be used by the multimodal trip planner or incorporated into a Mobility as a Service (MaaS) platform.

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References

Abduljabbar, R. L., Liyanage, S., & Dia, H. (2021). The role of micro-mobility in shaping sustainable cities: A systematic literature review. *Transportation research part D: transport and environment*, *92*, 102734.

H3. (2023). *Hexagonal Hierarchical Geospatial Indexing System.* `https://h3geo.org/`. ([Online; accessed 6-September-2023])

Ho, C. Q., Mulley, C., & Hensher, D. A. (2020). Public preferences for mobility as a service: Insights from stated preference surveys. *Transportation Research Part A: Policy and Practice*, *131*, 70–90.

Ma, T.-Y. (2017). On-demand dynamic bi-/multi-modal ride-sharing using optimal passenger-vehicle assignments. In *2017 ieee international conference on environment and electrical engineering and 2017 ieee industrial and commercial power systems europe (eeeic/i&cps europe)* (pp. 1–5).

Medical News Today. (2023). *What is the average walking speed?* https://www.medicalnewstoday.com/articles/average-walking-speed. ([Online; accessed 30-December-2023])

MobilityData. (2023). *General Transit Feed Specification.* https://gtfs.org/. ([Online; accessed 6-September-2023])

Molenbruch, Y., Braekers, K., Hirsch, P., & Oberscheider, M. (2021). Analyzing the benefits of an integrated mobility system using a matheuristic routing algorithm. *European Journal of Operational Research*, *290*(1), 81–98.

Montes, A., Geržinic, N., Veeneman, W., van Oort, N., & Hoogendoorn, S. (2023). Shared micromobility and public transport integration-a mode choice study using stated preference data. *Research in Transportation Economics*, *99*, 101302.

Montes Rojas, A. (2021). Studying mode choice in multimodal networks including shared modes: A case study for the city of rotterdam.

OpenStreetMap. (2023). *OpenStreetMap.* https://www.openstreetmap.org/#map=7/52.154/5.295. ([Online; accessed 6-September-2023])

Pulse. (2023). *How fast do electric scooter go?* https://www.linkedin.com/pulse/how-fast-do-electric-scooter-gowhat-max-speed-scooter-holy-he/. ([Online; accessed 6-September-2023])

Soza-Parra, J., Kucharski, R., & Cats, O. (2022). The shareability potential of ride-pooling under alternative spatial demand patterns. *Transportmetrica A: Transport Science*, 1–23.

Stiglic, M., Agatz, N., Savelsbergh, M., & Gradisar, M. (2018). Enhancing urban mobility: Integrating ride-sharing and public transit. *Computers & Operations Research*, *90*, 12–21.

VerkeersNet. (2023). *We cycle more often and further.* https://www.verkeersnet.nl/fiets/20584/we-fietsen-vaker-en-verder/?gdpr=accept. ([Online; accessed 6-September-2023])

Vij, A., Ryan, S., Sampson, S., & Harris, S. (2020). Consumer preferences for mobility-as-a-service (maas) in australia. *Transportation Research Part C: Emerging Technologies*, *117*, 102699.

Yu, X., Miao, H., Bayram, A., Yu, M., & Chen, X. (2021). Optimal routing of multimodal mobility systems with ride-sharing. *International Transactions in Operational Research*, *28*(3), 1164–1189.