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An Intermodal Dispatcher for the Assignment of Public Transport and Ride Pooling Services

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Abstract

This paper describes the components of an intermodal dispatcher of ride pooling requests to integrate these urban mobility systems with the public transport network in an urban area, thus making possible a new intermodal system. The intermodal dispatcher makes use of a prior dispatcher, developed exclusively for conventional ride pooling systems and a method that filters out the requests that have few possibilities of being served using the public transport system, leaving them to be served directly by ride pooling vehicles. The assignments of customers to vehicles of the ride pooling system are finally determined by an integer programming model of reduced dimensions, so that it can be solved efficiently by conventional solvers as shown in the preliminary computational results included in the paper.

Keywords: intermodal dispatching; ride pooling; public transport

1. Introduction

Currently some studies are being carried out showing that shared mobility services can be a new mode of transport with a very relevant role in large cities. Studies such as ITF (2020) show that their impact would improve and complement the public transport network instead of making public transport systems less appealing or even replacing them. Moreover, they could be feeders for the current public transport network in areas with inefficient or scarce coverage and consequently, there is a need to define intermodal methods for combining public transport and shared services and to adapt them for this new functionality.

Recently, some studies have been carried out on this line of research, although considering only the combination with one specific variant of shared service. In the case of a car sharing services, Friedrich and Noekel (2017) studied

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the intermodal combination applied in two types of scenarios: with a station-based car sharing service or freely located throughout the city, considering only the availability of individual-use vehicles and the space at the destination stations.

Other studies proposed by Delling et al. (2013) and Baum et al. (2019) discuss the variant of a bike sharing service and a non-shared taxi as an auxiliary transport mode that supports the public transport network, including them only as a first or last leg of the journey. Their approach consists of a transfer graph with the travel times between the available stops for transferring between the public transport and the auxiliary modes. However, their solution only covers the travel times to traverse the different distances and does not consider neither the availability of the fleet, nor the spaces at the destinations nor the waiting times for the taxi's arrival.

However, a ride pooling service is a more complex transport mode to model as they involve not only the availability of vehicles with the corresponding waiting times, but also the shareability of the vehicle en route, as well as always satisfying the time restrictions of all passengers. So it was not observed in the literature any optimal solution.

Consequently, our line of research focused on studying efficient methods for the combination of public transport systems and a ride pooling service. In the initial study, introduced in Lorente et al. (2021), it was presented the intermodal simulator which allows to evaluate the new use case. Hence, in this second part of the study the intermodal dispatcher, which actually compute the combined routes, is defined using the previous intermodal simulator.

The object of our paper will be then to define an intermodal assignment method that combines public transport and ride pooling services. The preliminary results are presented at the end of the paper. But more complete results for larger test models are expected at the time of the conference.

2. Intermodal system overview

The intermodal system proposed in this work, presented in Figure 1, consists of two main components. First, there is the intermodal dispatcher that computes the new combined routes and second the intermodal simulator which assesses the new intermodal use case based on simulation.

The initial research, presented in Lorente et al. (2021), introduced the architecture of the entire system and aimed to implement the intermodal simulator and the integration of all the components involved in the system, including the intermodal dispatcher. Although, it was left the study of a proper intermodal algorithm for further development and focused on the development of the base system of the computational experiments.

As introduced in this study, the intermodal simulator is based on a ride pooling simulator, the MaaS Simulator developed by PTV Group and available for internal developments only, the behaviour of which was expanded to cover the new intermodal use cases. It performs an agent-based simulation with two main agents (vehicles and customers). The which mimics the movement of the vehicle fleet of a ride pooling service according to the traffic network state at each step of the simulation. Moreover, it also simulates the generation of customer requests to the service and the progression of their journey. States and events which previously represented only ride pooling trips, now also apply to public transport ones or the intermodal combination of both modes of transport.

Regarding the intermodal dispatcher, it is constituted by a set of independent components. The main component called the Outer Dispatcher, which is the object of this research, computes the intermodal routes aggregating the

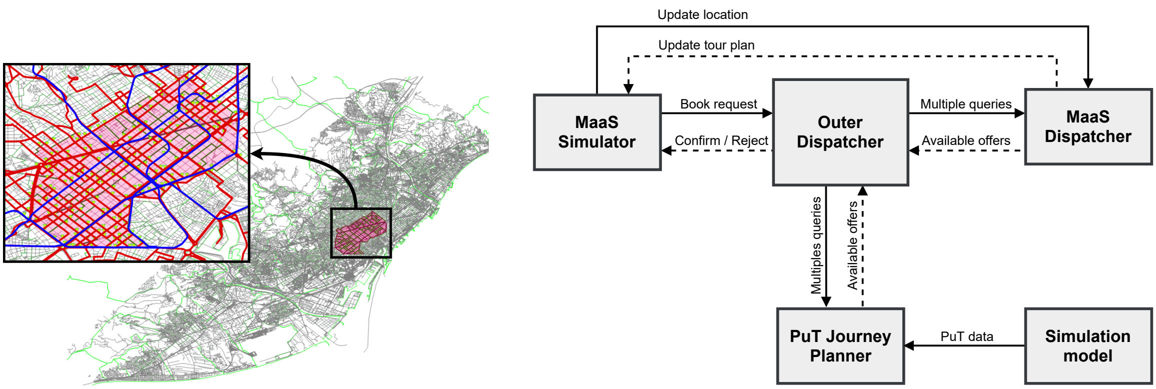

Fig. 1: (a) Barcelona's CBD, selected scenario from a simulation model (highlighted the subway and bus line routes in blue and red respectively); (b) Architecture diagram of the intermodal assignment system and the communication with the simulation model.

information provided by the other two components that address each mode to combine. First, there is the ancillary tool called MaaS Dispatcher which is an available resource oriented to the management of the ride pooling service that has been also developed by PTV Group, exclusively for internal developments. And second, there is the Public Transport Journey Planner, hereinafter referred to as PT Journey Planner, which computes the public transport routes.

As such, the focus of the research falls on the intermodal combination of a conventional ride pooling system with the existing public transport network. Accordingly, in this new context all booking requests are handled via the Outer Dispatcher, whereas the vehicle location updates and other related information are handled directly through the above mentioned MaaS Dispatcher, as this component manages the ride pooling vehicle fleet.

In this sense, the Outer Dispatcher combines the ride pooling routes with public transport routes computed by the PT Journey Planner. It is by means of this component that the appropriate routes are determined, based on the complete timetables for public transport (obtained from a simulation model) and the concrete time windows for the trips. The development of the PT Journey Planner has been done especifically for this study with the implementation of a time-expanded model of the public transport network as described in Bast et al. (2016) and in this preliminary implementation, conventional shortest path algorithms have been used as a basis to compute the adequate departure times at stops.

3. Outer Dispatcher

The considered intermodal routes are structured by now with a maximum of two legs, the first leg being covered by the ride pooling system and the possibility to interchange in a second one to the public transport network. In this schema the access points, or transfer points between both systems, are the transit stops (referred to in the following simply as *access points*).

The current research is only considering a preliminary simplified version of the problem in which neither the unimodal option with only public transport, nor intermodal combinations with ride pooling for egress are considered.

Furthermore, in a wide urban area, considering all the requests of service at a given moment and all the possible transit stops implies a very large number of possible combinations. Since each request to the ride pooling dispatcher implies a penalization in the total response time of the whole system, it is necessary to limit the number of combinations. Thus, the Outer Dispatcher is made up by a two-step algorithm. The first step consists of a candidate search method that excludes unlikely combinations of access points to ride pooling vehicles by means of a set of suitable rules and the second step consists of a module that resolves the requests made by the clients assigning them either to a combined trip in the new ride pooling-public transport mode, or to a pure ride pooling trip.

3.1. Batch dispatching

For the assignment of the requests, it is proposed a batch dispatching method which assigns multiple requests in a single batch executed periodically. That is, the requests are queued as they arrive and are left unanswered (hereinafter referred to as pending requests). At the end of each batch iteration, the dispatching method is executed which computes an assignment solution for each pending request that minimizes a predefined cost function. Such solution can be either a valid assignment of a pure ride pooling trip or a combined one, but also the impossibility of a feasible assignment which will leave the request unassigned.

For those requests for which no feasible assignment has been found, the dispatcher leaves them for a future service with a higher priority. If these unassigned requests from a previous batch iteration still do not achieved a valid assignment, then they are consequently left as unsatisfied.

3.2. Step 1 - Candidate Search Method

The first step of the dispatching method is the candidate search method which is the process that identifies the ride pooling vehicles and access points that may be the most suitable candidates for an intermodal combination.

As such, the proposed candidate search method applies a three-step filtering. First, restricting the potential access points within a certain radius to the origins and destinations of the clients. Second, estimating the access points that would have a proper connection to the access points at the destinations of the requests. And third, estimating the access points which could be served by the candidate ride pooling vehicles.

Thus, non-existent connections or those with an excessive travel time using the public transport would be filtered. Also combinations with an excessive travel time to the access points would also be discarded. In this way, most of the unnecessary calls to the service in the second step of the Outer Dispatcher will be avoided. To solve this process in a more efficient way, this procedure uses the public transport skim matrices which provide the approximated travel times between transit stops through the public transport system.

3.3. Step 2 - Assignment of vehicles-to-clients (V2C module)

A key component of the Outer Dispatcher is the decision module that assigns client requests made to the system, up to a given time instant t_0, to the available vehicles that have been selected by means of the Candidate Search Method. This module will be referred to in this paper as V2C module. This decision module is executed periodically by the Outer Dispatcher trying to accommodate new requests with pending requests from previous periods. Decisions made by the V2C module should ideally be as close as possible to the results of an mathematical programming problem that will be described in this section.

Assume that, in one of the periods, at time instant t_0, there is a set N of clients with pending requests and a set J of vehicles that may potentially satisfy these requests. Besides, there is a set of S candidate transit stops, or access points, where clients may be dropped off in order to continue the trip to their destination using the public transport system. For convenience, vehicle 0 represents the ”null-taxi” that will be used for indicating clients left as pending for a next time period. Then, the set of vehicles J_0 will denote to $J_0 = J \cup \{0\}$. Also, stop 0 represents the ”null-stop”, meaning that an intermodal combination will not be formed or, equivalently, that the vehicle will not visit any transit stop, whether it serves or not the client. Also for convenience, S_0 will denote to $S_0 = S \cup \{0\}$.

Possible decisions taken for each client $i \in N$ can be illustrated by means of the graph depicted in Figure 2. Thus, for each client $i \in N$, each route that originates at i and ends at the final isolated node to the right (labeled as e_0), corresponds to a possible decision. Each route will be described by a sequence (i, j, k, e_0), if $j \neq 0$ and by a sequence $(i, 0, e_0)$, if $j = 0$ (client i will be left for the next period). Here, $i \in N$, $j \in J$ and $k \in S_0$.

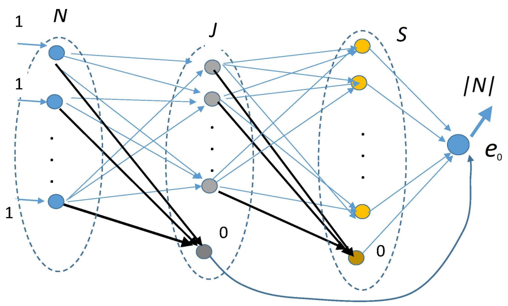

Fig. 2: A graph representation for the possible decisions that the V2C module may adopt for assigning clients (set N) to the set of available vehicles J and dropping them off at an appropriate transit stop (set S). Constraints (c1)-(c1”) for variables x_{ij}, y_{jk} can be interpreted as binary flows on a graph with this structure.

This suggests the use of a model using binary variables x_{ij} and y_{jk}, $i \in N$, $j \in J_0$, $k \in S_0$, which admit a representation as binary network flows on the graph in Figure 2. If $x_{ij} = 1$ then client i is assigned to vehicle j and 0 otherwise. If $y_{jk} = 1$ then vehicle j visits stop k and 0 otherwise. Variable $x_{i0} = 1$ indicates whether client i has not been assigned to any vehicle. Likewise, if variable $y_{j0} = 1$ then vehicle j will not visit any transit stop for dropping off a client. It is assumed that unlikely or illogical connections (i, j), (j, k) will be previously purged by the Candidate Search Method.

3.3.1. A mathematical programming model for the decisions of the V2C module

As a consequence of being binary network flow variables on the graph of Figure 2, decision variables x_{ij} and y_{ik} will verify constraints (c1) of the following mathematical programming problem (c1) to (c5).

Additionally to variables x_{ij} and y_{jk}, variables z_{ijk} defined namely as the product $z_{ijk} = x_{ij} \cdot y_{jk}$ are required. If $z_{ijk} = 1$, then client i is assigned to vehicle j and visits stop k. Otherwise, $z_{ijk} = 0$. In order to express the product $x_{ij} \cdot y_{jk}$ in terms of linear constraints, constraints (c2) to (c2”) must be added to the model.

There follows a description of the aim of program (c1) to (c5) as well as of its parameters and additional variables. Variable T_i denotes the expected travel time of client i to its destination taking into account that current time instant is t_0. Variable T_i must be a consequence of the resulting decisions. The latest arrival time for client i is $\hat{t}_i$. If client i is assigned to some vehicle $j \in J$, then the upper bound, $\hat{t}_i$, on T_i must be taken into account by the mathematical programming problem (c1)-(c5) (i.e., when $x_{i0} = 0$), whereas a non binding, large enough bound $\hat{s}_i$, must apply on T_i, if client i will not be assigned to any vehicle in the current period (i.e. $x_{i0} = 1$). Constraint (c3) enforces these requirements.

$$\text{Min}_{x,y,z,T} \sum_{i\in N}\sum_{j\in J}\sum_{p\in P(j)}\sum_{k\in S_0} z_{ijk}\,\tilde{\theta}_{ipk} + M_1\sum_{i\in N_1} x_{i0} + M_2\sum_{i\in N_2} x_{i0}$$

$$\sum_{j\in J_0} x_{ij} = 1 \qquad i\in N \qquad (c1)$$

$$\sum_{i\in N} x_{ij} \le 1 \qquad j\in J \qquad (c1')$$

$$\sum_{i\in N} x_{ij} = \sum_{k\in S_0} y_{jk} \qquad j\in J \qquad (c1'')$$

$$z_{ijk} \ge x_{ij} + y_{jk} - 1 \qquad i\in N,\, j\in J_0,\, k\in S_0 \qquad (c2)$$

$$z_{ijk} \le x_{ij} \qquad i\in N,\, j\in J_0,\, k\in S_0 \qquad (c2')$$

$$z_{ijk} \le y_{jk} \qquad i\in N,\, j\in J_0,\, k\in S_0 \qquad (c2'')$$

$$t_0 + T_i \le \hat{t}_i + (t_0 + \hat{s}_i - \hat{t}_i)x_{i0} \qquad i\in N \qquad (c3)$$

$$t_0 + \tilde{v}_p + \tilde{\theta}_{ipk}\, z_{ijk} \le t_0 + \hat{v}_p + M_0(1 - z_{ijk}) \qquad j\in J,\ p\in P(j),\ i\in N,\ k\in S_0 \qquad (c4)$$

$$-M_0 x_{i0} \le T_i - \sum_{j\in J}\sum_{k\in S_0} z_{ijk}(\tilde{\mu}_{ijk} + \tilde{u}_{ki}) \le M_0 x_{i0} \qquad i\in N \qquad (c5)$$

$$x_{ij}\in\{0,1\},\ y_{jk}\in\{0,1\},\ z_{ijk}\in\{0,1\} \qquad i\in N,\ j\in J_0,\ k\in S_0$$

$$T_i \ge 0 \qquad i\in N$$

It is assumed that available vehicles $j \in J$ are already servicing passengers and by $P(j)$ it is denoted the set of passengers on board of vehicle j. Their estimated and latest arrival times to destination, given by $t_0 + \tilde{v}_p$ and $t_0 + \hat{v}_p$, $p \in P(j)$, must be taken into account. To this end, parameter $\tilde{\theta}_{ipk}$ is the detour time that will experience passenger $p \in P(j)$ of vehicle j if this vehicle deviates to pick up client i to transit stop k. Constraint (c4) imposes that the latest arrival restriction of the passengers en-route given by $t_0 + \hat{v}_p$ is satisfied whenever the vehicle detours to pick up a new client which increases the passengers' arrival time by $\tilde{\theta}_{ipk}$.

Likewise, parameter $\tilde{\mu}_{ijk}$ is the detour time that vehicle j, from its current position, needs to pick up client i plus the time from the position of client i to the public transport access point k ($\neq 0$). Trip times in the public transport system, $\tilde{u}_{ki}$, from stop k to the destination of client i are evaluated by the Candidate Search Method, taking into account that the current time instant is t_0 as well as access times from drop-off points to the platforms or stops, in-vehicle times and times from the final stop in the public transport system to the final destination of the client. Notice that, since M_0 is assumed to be a large number, constraint (c5) imposes no condition on the expected trip time T_i if client i is not served in the current period (i.e., $x_{i0} = 1$). On the contrary, if the client i is assigned to car j to reach a public transport access point k (i.e., $x_{i0} = 0$), then its travel time will be given by $\tilde{\mu}_{ijk} + \tilde{u}_{ki}$. Constant M_0, also used in constraints (c4), must be taken greater than the summation of all the trip times, $\sum_{j\in J}\sum_{k\in S_0}(\tilde{\mu}_{ijk} + \tilde{u}_{ki})$, and the largest $|\tilde{v}_p - \hat{v}_p|$, $p \in P(j)$, $j \in J$.

Since the previous mathematical programming problem is run periodically by the V2C module, all the clients in set N that are under consideration may have been non-served during previous periods and left pending for future service. This subset of clients will be denoted by N_2, whereas those clients that have just sent a request previously to the current period will make up the set N_1. This is taken into account in the objective function of the mathematical programming problem. Constants M_1 and M_2 appearing in the second and third term of the objective function have the purpose of penalizing the clients left pending for a future period, which correspond to the penalty coefficients for the current period and those of a previous period respectively. The first term prioritizes those assignments, clients-to-vehicles-to-transit stops, indicated by the binary variables z_{ijk}, which minimize the total detour time of the passengers that are already in service by the set of vehicles in J. Also, the constants should verify the following inequalities

$$M_2 > |N|M_1, \quad M_1 > \sum_{i\in N}\sum_{j\in J}\sum_{p\in P(j)}\sum_{k\in S_0}\tilde{\theta}_{ipk}$$

and in this way, clients $i \in N_2$ gain priority in service over clients $i \in N_1$ and secondly in as much as possible, all the requests considered (i.e., all clients $i \in N$) are served. In addition, notice that in the current implementation of the model the shareability between pending requests is not contemplated for now and only considers the shareability with passengers already served from previous periods, enforced by constraint (c1').

3.3.2. *Model parameters calculation*

All these parameters, $\tilde{u}_{ki}$, $\tilde{\mu}_{ijk}$, $\tilde{\theta}_{ipk}$, considered in the previous problem (c1) to (c5), are evaluated previously by the PT Journey Planner and the MaaS Dispatcher at each iteration. The first one calculates the departure choices at an origin stop to a set of destination stops taking into account the concrete departures and arrivals in the timetable. And the second one calculates the candidate vehicles with the best expected pick-up and drop-off times, considering the congestion of the network in that precise time window.

The Outer Dispatcher then aggregates these intermediate results to estimate the feasible assignments for each pending request with its subset of candidate stops. For the considered two-leg intermodal assignments, the appropriate departures within the request's time windows are firstly estimated. Next, the proper candidate vehicles are chosen for serving the requests from its origin (client's location) to the transit stop drop-off point, in advance to the departure of the transit transport unit. Finally, the ride pooling-only assignments are determined by estimating the candidate vehicles that could serve the request from its origin to its destination within the original time window.

4. Design of experiments

The case-study city considered in this paper is the Barcelona metropolitan area in Spain whose required data was obtained from the Barcelona Virtual Mobility Lab model (Montero et al. (2018)). For the demonstration and debugging of the Outer Dispatcher, only a small subarea is selected. Accordingly, the selected subarea is the Eixample (Barcelona CBD's), extracted from the whole Barcelona model, which is highlighted in Figure 1.

This model provides an updated road network version for private vehicles and the entire public transport network, along with their operating timetables, which is an essential information for the estimation of trip travel times of the public transport system. In this case, it is selected all the route lines crossing the Eixample subarea, which is served by the subway and bus transport modes (marked in blue and red, respectively, in Figure 1). Overall, within the area there are more than 350 public transport access points with approximately 9,500 vehicle journeys covering all the routes during working days (1,600 at peak hour from 6 to 9 a.m. - the morning peak hour in Barcelona and almost 1,500 at non-peak hour from 9 a.m to 12 p.m.).

For the computational experiments, three different scenarios are proposed: a first one with a small number of trip requests to test easily the correctness of the system and a second and a third one with a higher number of trip requests to perform a higher stress test. The generation of these tests have been previously conducted using PTV Visum's simulator, by generating the specific trip volumes in both time periods (peak and non-peak hour).

The proposed experimental instances are then reported in Table 1. In which the fleet size and capacity are specified, factors of which may impact the performance of a ride pooling dispatcher but they are out of scope of the current study. Thus, some proportional values are taken from the literature of ride pooling research articles such as Alonso-Mora et al. (2017).

Table 1: Experimental instances summary.

	Trip requests	**Fleet size (cars)**	**Vehicle capacity (seats)**
Eix (TR-100)	101	8	4
Eix (TR-1750)	1,771	126	4
Eix (TR-5000)	4,990	360	4

Additionally, for the batch dispatching procedure, a batch iteration time of 30 s is defined. Whose value is also taken from the Alonso-Mora et al. (2017) research.

5. Preliminary results

The aim of these preliminary results is to evaluate the initial implementation of the Outer Dispatcher and check the correct interaction of the components involved. The results that have been obtained show that an intermodal dispatcher designed using an already-implemented ride pooling dispatcher is indeed feasible. In addition this is a confirmation that the intermodal MaaS Simulator, operates correctly with scenarios of higher complexity and congestion, which was also the object of the previous study introduced in Lorente et al. (2021).

The results are shown in tables 2 to 5 below, illustrating the performance for the two intermodal types considered in the study (*RP* for ride pooling only and *RP+PT* for the combination of ride pooling and public transport) in both situations (non-peak and peak hour).

Tables 2 and 3 analyze the demand served and the experienced travel times. Columns *#* and *Total travel time* indicate the demand served by each intermodal type and their mean experienced total travel time. Also shown for the combined routes the mean total experienced travel times with each mode of transport separately in columns *RP travel time* and *PT travel time*. Note that the difference between these individual travel times to the total one is the experienced waiting and accessing the stops and walking to their destination from the last stop. In addition, columns *Demand served* and *Seat occup.* indicate the percentage of total demand served and the mean seat occupancy of the ride pooling fleet.

Tables 4 and 5 analyze the experienced trip distances variation. Column *Direct distance* indicates the distance of the direct trip from the origin to the destination without any detour in between. While columns *Expected distance* and *Experienc. distance* indicate the initial distance estimated by the system (given the saturation at the moment of the booking) and the one that would actually experience due to future detours of new passengers. In addition, column *Detour factor* indicate the detour factor between the experienced and the expected distances.

Table 2: Results at non-peak hour from 9 a.m. to 12 p.m..

	RP trips		**RP+PT trips**					
	#	**Total travel time**	**#**	**Total travel time**	**RP travel time**	**PT travel time**	**Demand served**	**Seat occup.**
Eix (TR-100)	17	10.04 min	81	18.98 min	4.09 min	6.38 min	97.03%	0.68
Eix (TR-1750)	419	12.39 min	1,302	17.90 min	4.44 min	5.12 min	97.18%	1.02
Eix (TR-5000)	1,843	11.50 min	2,993	17.80 min	4.38 min	5.23 min	96.91%	1.18

Table 3: Results at peak hour from 6 to 9 a.m..

	RP trips		**RP+PT trips**					
	#	**Total travel time**	**#**	**Total travel time**	**RP travel time**	**PT travel time**	**Demand served**	**Seat occup.**
Eix (TR-100)	54	19.81 min	33	26.37 min	5.88 min	10.55 min	86.14%	1.61
Eix (TR-1750)	900	16.57 min	731	25.63 min	6.23 min	10.39 min	92.09%	1.59
Eix (TR-5000)	2,141	15.55 min	2,608	25.50 min	6.29 min	10.37 min	95.17%	1.45

Table 4: Distance results at non-peak hour from 9 a.m. to 12 p.m..

	RP trips				**RP+PT trips**			
	Direct distance	**Expected distance**	**Experienc. distance**	**Detour factor**	**Direct distance**	**Expected distance**	**Experienc. distance**	**Detour factor**
Eix (TR-100)	2.42 km	3.21 km	3.73 km	1.16	2.00 km	2.86 km	2.86 km	1.00
Eix (TR-1750)	2.33 km	3.37 km	4.37 km	1.39	1.94 km	2.60 km	2.65 km	1.02
Eix (TR-5000)	2.06 km	2.79 km	3.71 km	1.33	2.03 km	2.60 km	2.64 km	1.02

According to these results, a combined trip is more attractive at non-peak hours, whereas at peak hours it is the pure ride pooling trip. Overall, a combined trip taking between 30 to 80% longer than the pure ride pooling choice.

This difference in the total number of trips on each intermodal type between peak and non-peak hours could be explained for the following reasons. First, at peak hour the combined trips take too long and the total duration is

Table 5: Distance results at peak hour from 6 to 9 a.m..

	RP trips				RP+PT trips			
	Direct distance	**Expected distance**	**Experienc. distance**	**Detour factor**	**Direct distance**	**Expected distance**	**Experienc. distance**	**Detour factor**
Eix (TR-100)	2.00 km	3.29 km	5.09 km	1.55	2.29 km	3.41 km	3.52 km	1.03
Eix (TR-1750)	1.92 km	2.80 km	3.72 km	1.41	2.18 km	3.40 km	3.50 km	1.03
Eix (TR-5000)	1.84 km	2.61 km	3.35 km	1.35	2.20 km	3.33 km	3.40 km	1.02

limited by a maximum latest arrival time at the destination. And second, because the chosen departure time in public transport results in slightly restrictive margins for the latest drop off in the ride pooling leg. A trade-off between waiting times and a reasonable margin for riding the next coming transit unit must be considered carefully. Another reason is because monetary costs are not considered in the study for now.

Overall, the demand served is generally high. At non-peak hour the ride pooling travel times are obviously shorter and therefore the fleet is able to pick up more passengers. In contrast, at peak hours the trips take longer because the city is congested and therefore the demand served is slightly lower than in the previous situation.

With respect to the demand served with combined trips, it can be appreciated that in a normal situation combined trips represent between 62 to 83% of the total trips served while at peak hour only represent between the 38 and 55%. The expected results however, would have been that at peak hour there would be more combined trips to avoid such longs travel times in ride pooling only trips as the roads are congested. But ride pooling only trips increase while the combined trips decrease by almost a half compared to a non-peak situation. That could be caused by a low detour factor in combined trips and the non-consideration of monetary costs for now, as mentioned above.

Moreover, it can be observed in the distances that effectively the combined trips do not leave a large margin for detours and therefore the expected and experienced distances are almost the same. In contrast, in ride pooling only trips, the trips experience detours between a 16 and 55% above what was initially expected.

Nevertheless, the results obtained are satisfactory. Since the correctness of the Outer Dispatcher is proved and it dispatches satisfactorily the large majority of the demand. These objectives were the aim of the current study.

And finally, the execution times of the proposed assignment method of the Outer Dispatcher are also analyzed. The results obtained are also satisfactory, since it takes a short amount of time between 0.7 to 1.5 s for solving each request in the smallest instances. Although with some observed peaks of 4 s in the largest scenario when many requests are accumulated at the same time. These are still consistent results as with large queue sizes, the set of variables of the optimization model increase significantly and therefore also its execution time. Results which suggests the necessity of also limiting the batches by a maximum number of requests (not only by a batch frequency of 30 s) in order to avoid these peaks. However, this should be further analyzed in larger networks to really test the performance.

6. Conclusions and future work

This paper reports a novel approach for a key component, called Outer Dispatcher, of a MaaS application integrating ride pooling and public transport as components of intermodal trips. It first performs a pre-selection of ride pooling vehicles and public transport access nodes, to then determine the assignment of requests by means of a graph flow model translated in terms of a linear integer programming problem.

A preliminary version has been tested in a real subnetwork of limited dimensions of a real large network (Figure 1) at two distinct time periods (peak and non-peak hours). The results reflect a consistent performance and prove the correct operation of the entire intermodal system.

Although the objectives of the paper were achieved, there are some factors outside the scope of the paper that could be done. First, the optimization model considers only assigning at each instant the requests that minimize the total detour times of the passengers already en-route without considering those to come at a latter iteration. Thus, it does not consider that by dispatching combined trips will leave more space for picking up additional passengers. And second, although the monetary cost is a decisive factor between the two types of intermodal trips, it has not been considered in this study. The results, show that in combined mode total trip times may be longer, especially if the area under consideration is of small size, suggesting that an extension to be included in the system should be to take into account a fare system consistent with this. It should be noted that the object of the work is not to investigate what the customer's choice would be (RP or RP + PT), what information should be given, or how a consistent fare system should be designed and implemented.

As a result, the system assigns a lot of ride pooling only trips during peak hours, which leads to high experienced travel times with the ride pooling service and therefore its cost would be very high for most. Consequently, the fare system should also depend on the saturation also referred to as surge pricing. Strategy that would encourage clients to shift for ride pooling only to combined, which would shorten trips and free up the fleet to serve more passengers. Thus, a refinement of the model is necessary which definition will be the objective of a forthcoming paper.

Furthermore, the initial implementation of the PT Journey Planner only considers timetables for computing the shortest paths. While this is not an issue for an scenario such as the Eixample, the subarea of Barcelona tested in the study, in which all this data is available, for more complex scenarios it may occur that certain line routes operate based on the frequency of the service. Thus, such implementation is contemplated for the improvement of the public transport component.

Finally, other variants of this intermodal system should also be considered, such as the inclusion of intermodal routes with three-legs, allowing ride pooling also for egress, in addition to an unimodal option with only public transport. In this way, the system would be enriched and extended providing a better service to the demand at areas where the public transport network does not have a sufficient coverage.

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