Pooling for First and Last Mile

Ado Adamou Abba Ari*, Andrea Araldo*, André De Palma†, and Vincent Gauthier*

* Télécom SudParis
Institut Polytechnique de Paris, France
Email: {ado.ari, andrea.araldo, vincent.gauthier}@telecom-sudparis.eu

† CY Cergy Paris Université
CREST, France
Email: andre.de-palma@cyu.fr

Abstract—Carpooling is a system in which drivers accept to add some limited detours to their habitual journeys to pick-up and drop-off other riders. Most research and operating platforms present carpooling as an alternative to fixed schedule transit and only very little work has attempted to integrate it with fixed-schedule mass transit. The aim of this paper is to showcase the benefits of such integration, under the philosophy of Mobility as a Service (MaaS), in a daily commuting scenario.

We present an integrated mass transit plus carpooling system that, by design, constructs multimodal trips, including transit and carpooling legs. To this aim, the system generates vehicle detours in order to serve transit stations. We evaluate the performance of this system via simulation. We compare the “Current” System, where carpooling is an alternative to transit, to our “Integrated” System, where carpooling and transit are integrated in a single system. We show that, by doing this, the transportation accessibility greatly increases: about 40% less users remain without feasible travel options and the overall travel time decreases by about 10%. We achieve this by requiring relatively small driver detours, thanks to a better utilization vehicle routes, with drivers’ vehicles driving on average with more riders on board. The simulation code is available open source.1

Index Terms—Carpooling, Intelligent Transportation Systems, Mass Transit; Simulation

I. INTRODUCTION

Carpooling is recently becoming an important actor of urban mobility, creating an ecosystem of startups and public initiatives. On the other hand, the methods to design public transit have a long history. Unfortunately, transit and carpooling have mainly remained two separated worlds. In this paper, we show instead that carpooling has the potential to improve urban mobility when integrated with transit.

Indeed, the main limit of transit is its rigidity: routes are pre-determined and schedules are fixed. This is not an issue in areas with high demand density areas, in terms of passengers per Km² per hour, which can only be served by fixed mass transit [1], [2]. In such area, the cost to guarantee high station density is justified by the large amount of passengers each station serves. However, where the demand is more spread, e.g., suburbs, transit is inherently inefficient: to keep costs under reasonable levels, the density of stations is limited, which implies that riders may have to walk too much to access public transit.

On the other hand, despite its recent success, carpooling cannot alone solve mobility of suburban areas. Indeed, in traditional carpooling, riders are transported from their origin (or close by) to their destination (or close by). This limits the number of feasible driver-rider matching, as both needs to start and end in close location and at a close time.

We propose instead an Integrated System, where drivers make detours to pass by transit stations, where riders can be picked up or dropped off. This allows to consolidate driver and rider journeys and increases the possibility for riders to find a good driver matching to access transit. By doing so, we also relax the aforementioned rigidity of transit: carpooling takes a role of feeder service, collecting and consolidating sparse transportation demand in the First and Last Mile (close to riders origins and destinations, respectively), bringing riders to/from transit stations. The contribution of this paper can be summarized as follows:

• We design and formalize an integrated transportation system which includes in a single offer transit and carpooling (§III).
• We provide the algorithms with which such system can compute favorable travel options for riders and drivers’ detours (§III).
• We show in a simulation study the advantages of such system with respect to the dominant situation in suburban areas, where carpooling and transit are designed independently (§IV and §V). We show in particular the improvement of accessibility, i.e., the easiness for a traveler to move from any location to any location [3]: (i) reduction of unserted riders, i.e., riders who do not have a feasible way to perform their trip and would be forced to use their private cars, (ii) reduction of overall rider travel time and (iii) increase in the usage of carpooling, i.e., drivers can share their journey with more riders.
• We release the code of the simulation as open source, to allow for repeatability.

II. RELATED WORK

Policy makers around the world have placed transportation at the center of their sustainability agendas. The European
Commission goal [4] of “putting users first” and “providing more accessible alternatives to their current mobility habits” can be achieved by breaking the rigidity of classic mass transit and making it more adaptive to user demand.

One way to achieve the aforementioned objectives is to integrate flexible modes and traditional fixed schedule transit in a single transportation offer. Flexible modes can be ride sharing [5], provided by private companies often subsidized by transit authorities [6], demand-responsive buses [2] or semi-flexible buses. More extreme viewpoints have been advocated for a future complete replacement of fixed transit service with automated mobility on demand, which has been shown to be infeasible due to the incapacity of serving high demand density [1]. In other words, flexible modes alone and fixed schedule modes alone cannot entirely satisfy all urban transportation needs. Integrating both is the key to offer transportation at a reasonable monetary cost for the operator, low societal cost (pollution, congestion), affordable price and sufficient Quality of Service (QoS) for the users. Integration of different modes into a single transportation offer is called by some authors Mobility as a Service (MaaS) [7].

Fueled by success of commercial carpooling services, like Bla Bla Car, Klaxit, Flink and others, carpooling has recently attract the interest of the research community. Most of the technical literature studies carpooling in isolation, without considering its integration with transit focusing on service design [8], user perception [9], driver incentives [10].

Our work is orthogonal to the aforementioned contributions, in that it focuses on the improvement of transportation accessibility when integrating carpooling with mass transit, as this integration has so far been more overlooked than the other flexible modes. Few exceptions are [11] and [12]. The former formalizes a matching problem to either maximize the number of rider-driver matches or minimize the total driver detours. Riders can be moved from their origin to a transit station. Their assumption is that riders obey to the system, which blindly maximizes or minimizes the aforementioned objectives. This is unrealistic in our opinion, as a rider would rather walk or use the transit, if these options are faster for her than carpooling. We therefore let riders choose the best mobility option for them. Moreover, in [11] riders can carpool only in the First Mile (origin to transit station) and not in the Last Mile (station to destination). In our preliminary simulation experiments, which we omit for lack of space, we noticed that this limits considerably the efficiency of the system. For this reason in our work riders can also carpool in the Last Mile (from a station toward a certain origin). Additionally, while in [11] drivers need to pickup and drop-off riders at their exact origin and destination, we instead create meeting points in which riders and drivers meet, which has been shown to improve vehicle routes [8], [13]. More importantly, our work has a completely different viewpoint. We want to understand how integrating carpooling and transit improves people mobility accessibility, rather than proposing a matching algorithm.

Authors of [12] also propose to integrate carpooling and transit. However, they impose drivers to pick up and drop off riders at their exact origin and destination and associate at most one rider per vehicle. However, they consider long trips (their average improvement is more than 80 minutes), while we are interested in assessing the benefits of integrating carpooling and transit in the First and Last Mile of an urban area during daily commuting.

Note that the aforementioned work did not release any code of their simulators. This is why we had to build our own, and we release it as open source.

III. System model

We consider a suburban area, as in Fig. 2, served by a commuter rail, whose schedule is exogenously pre-defined. Each train, visits a sequence of transit stations, where riders can alight and board. Two types of users participate join our system: drivers and riders. The former are available to pick-up and drop-off other riders. Each vehicle is characterized by a journey, which is a sequence of meeting points, each visited at a specific time instant. In a meeting point, drivers can let riders alight or board. Some of the meeting points correspond to (i.e., are co-located with) transit stations. Observe that our users are not representative of the entire population of the area. We consider only the users that joined our system.

A. Notation

The notation is summarized in Table I. The input to the system consists of a set of drivers $D = \{d_0, d_1, d_2, \ldots\}$ and of riders is $R = \{r_0, r_1, r_2, \ldots\}$. A user $u \in D \cup R$ is either a driver or a rider. Both drivers and riders have predefined origin and destination locations, indicated as $org_u, dst_u, \forall u \in U$. They also have a departure time, denoted with $t^+(u, org_u)$. The information above constitutes the Origin-Destination (OD) matrix. We assume the entire OD matrix is not known in advance, but reveals itself with time, since riders and drivers appear in the system at their departure times and are unknown before. We consider also a train line composed of a set of stations $S$.

It has been shown [8], [13] that limiting pick-ups and drop-offs to only occur in a finite set of meeting points allows to consolidate the demand, thus increasing the number of shared trips and the demand served. We thus assume there exists a predefined set of meeting points $M$, which are physical locations where drivers and riders can meet and carpool. Set $M$ includes stations ($S \subseteq M$) and other locations spread around the area.

Riders and drivers go from their origins to their destinations following a journey. A journey $J(u)$ for user $u$ is a sequence of locations, starting with her origin $org_u$, continuing with 0 or multiple meeting points and ending with her destination $dst_u$.

A user arrives at a location $z$ at time $t^-(u, z)$ and departs from it at $t^+(u, z)$. If for a driver $d$ we measure $t^+(d, z) - t^-(d, z) > 0$, it means it has stopped at $t$, to drop off or pick up some riders. If for a rider $r$ we measure $t^+(r, z) - t^-(r, z) > 0$, the rider has stayed in $z$ for the corresponding time, waiting for a driver or a train to depart.

\footnote{In reality, the same individual could choose to be a driver or a rider, but we neglect this possibility and we assume each individual is by construction either one or the other.}
Symbols

- $r \in R, d \in D$: Riders and drivers.
- $u \in U = R \cup D$: Users (either drivers or riders).
- $s \in S, m \in M$: Stations and meeting points.
- $org_d, dst_d$: Origin and destination of user $u$.
- $m^{org}_d, m^{dst}_d$: The closest meeting points to the origin and destination of driver $d$.
- $s^{org}_d, s^{dst}_d$: The closest stations to the origin and destination of $u$.
- $t^+(u, z)$: Time at which user $u$ departs from location $z$.
- $t^-(r, z), t^-(u, z)$: Time at which user $u$ arrives at location $z$.
- $d(z, z')$: Distance between locations $z$ to location $z'$.
- $J(u)$: Journey of user $u$.
- $walk(z, z')$: Walking time to go from location $z$ to location $z'$.
- $drive(z, z')$: Time needed to drive from location $z$ to location $z'$.
- $c^-(d, z)$: Available seats in driver $d$’s vehicle immediately after she departs from location $z$.

Acronyms

- OT: Only Transit (transportation option).
- OC: Only Carpooling (transportation option).
- CT: Carpooling + Transit (transportation option).
- FM: First Mile.
- LM: Last Mile.

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TABLE I: Main notation

B. Transportation Systems

Users interact with our system by means of web or smartphone application, through which they declare their trip: origin, destination and departure time. We assume drivers’ declarations are done in advance (up to 1h from their departure). Riders’ declarations can instead be done on the fly (at the same time than the departure time) or in advance. All requests are processed by a Controller, then calculates drivers’ detours and feasible transportation options for riders. We compare three systems:

- **In the No Carpooling System** riders can just walk and/or use fixed schedule transit. This is the baseline. The controller does nothing and users do not need to declare their trips.

- **The Current System** corresponds to the current situation in many cities. Carpooling and transit both exist, but they are handled separately. The system is not able to propose multi-modal trips, including carpooling for a part of the trip and transit for the rest. Driver journeys are completely independent from transit.

- **We propose an Integrated System** in which the transit and carpooling routes are part of the same transportation service. Therefore, a rider can make a part of his trip by carpooling and the rest by transit. Furthermore, vehicle journeys are harmonized with transit via detours.

C. Driver journey

During her journey, driver $d$ may pass by a limited set of meeting points: $m^{org}_d, m^{dst}_d$ (i.e., the closest meeting points to $org_d$ and $dst_d$, respectively) and $s^{org}_d, s^{dst}_d$, i.e., the closest stations to $org_d$ and $dst_d$, respectively. The way journey $J(d)$ of driver $d \in D$ is constructed depends on the system.

In the **No Carpooling System**, $d$ just drives directly from her origin $org_d$ to her destination $dst_d$, starting at her departure time and following the shortest path, i.e., $J(d) = \{org_d, dst_d\}$.

In the **Current System**, if no riders carpool with $d$, her journey is the same as before. Otherwise, she picks riders up at $m^{org}_d$ and drops them off at $m^{dst}_d$. In this case her journey is $J(d) = \{org_d, m^{org}_d, m^{dst}_d, dst_d\}$.

In the reminder of this subsection, we will focus on the **Integrated System**. In addition to the previous situation, the Controller may decide to add a detour via either $s^{org}_d$ or $s^{dst}_d$ or both, which are the stations closest to $d$’s origin and destination, respectively. In this case, the journey is

$$J(d) = \{org_d, m^{org}_d, s^{org}_d, s^{dst}_d, m^{dst}_d, dst_d\}$$

where the parenthesis $[\ldots]$ denote optional stops. The detours proposed by the Controller to driver $d$ are such that the distance traveled by $d$ never exceeds the shortest distance between $m^{org}_d$ and $m^{dst}_d$ by more than 15%. Also note that a driver actually passes by a meeting point if there is some rider boarding or alighting there. Otherwise, that meeting point is skipped.

The Controller computes the journey of driver $d$ as in Alg. 1. With half probability the Controller starts by checking if it can add a detour passing by $s^{org}_d$, increasing the traveled distance no more than 15%. If yes, it then also checks if it is possible to an additional detour via $s^{dst}_d$. With the other half probability, the order in which the Controller tries to add detours by $s^{org}_d$ and $s^{dst}_d$ is inverted.

We assume the incentive provided to the driver to make the proposed detours (possibly coming from riders’ payments) is large enough for the driver to accept the detour. We will integrate compensation schemes, abundantly studied in the literature [10], in our formulation in future work.

D. Available Transportation Modes for a Rider

Let us assume the journeys $J(d)$ of all drivers $d \in D$ have been defined and consider any rider $r$ departing at an origin $org_r$, at a certain time instant $t^+(r, org_r)$ and willing to arrive to a destination $dst_r$, as soon as possible. The possible legs of a rider’s journey, with the different options available in the three systems of §III-B are depicted in Fig. 1. Before describing them, we specify that not all options are feasible.

**Definition 1. A transportation option is feasible for a rider only if it implies a total waiting time of at most 45 minutes and a total walking distance of 2.5 Km.**

As for the previous definition, if a rider’s journey is composed by several legs, and she has to wait for several vehicles (either trains or drivers), the total waiting time is the sum of all waiting times. Similarly, if the rider has multiple walking
legs in a single journey, the total walking distance is the sum of their distance.

In the **No Carpooling System**, the rider has two possible transportation options available:
- *Only walking*: Rider $r$ walks directly from $org_r$ to $dst_r$.
- *Only transit*: Rider $r$ walks from her origin $org_r$ to the closest station $s_{orgr} \in S$, waits for the next train, travels with that train to the station $s_{dstr} \in S$ closest to her destination $dst_r$, alights there and walks to $dst_r$. Note that the waiting time is the difference between the departure of the train and the arrival of the rider at the station.

In the **Current System**, in addition to the previous two options, the following is available:
- *Only carpooling*: Rider $r$ can carpool with a certain driver $d$ only if the meeting points closest to their respective origins and destinations correspond: $m_{org}^r = m_{org}^d$ and $m_{dst}^r = m_{dst}^d$. If they carpool, rider $r$ first walks from her origin $org_r$ to the origin meeting point $m_{orgr}$. Then, she waits for the driver to depart, carpools up to the destination meeting point $m_{dst}^r$ and, from there, she walks to her own final destination $dst_r$. Observe that carpooling with a certain driver may be infeasible, in the sense of Def. 1. Moreover, a rider can carpool with a driver only if the vehicle capacity (4 passengers) is not exceeded. The discipline to accept rider in a vehicle is first-come first-served. Infeasible carpooling and vehicles with no available seats are thus discarded. Among all the possible vehicles with which rider $r$ can carpool, the Controller proposes the one that brings her to her final destination the earliest. In order to do so, the Controller runs Alg. 3.

In the **Integrated System**, in addition to the previous 3 options, the following is available:
- *Carpooling + Transit*: Rider $r$ carpool with driver $d$ in the First Mile, i.e., from $org_r$ to $s_{orgr}^r$, or with a driver $d'$ in the Last Mile, i.e., from $s_{dstr}^r$ to $dst_r$, or with both $d$ in the First and $d'$ in the Last Mile. The Controller first computes the fastest way for rider $r$ to arrive to her closest station $s_{orgr}^r$. This can be either by only walking or by combining walking and carpooling. Then, rider $r$ takes the first train up to $s_{dstr}$, the station closest to her destination. The Controller finally computes the fastest way for rider $r$ to reach her final destination, which could be either by only walking or by carpooling with driver $d'$ and then walking. The details of this computation are in Alg. 4.

Fig. 1 summarizes the different transportation modes available for riders in the No Carpooling, Current and Integrated System. Observe that the trips depicted represent the most complex possible. For instance, if we consider a Carpooling + Transit trip, it may just include $t_1$, $t_2$, $t_3$, $t_4$, $t_1$, in case the rider only carpools in the First Mile.
Station 1 rider has carpooled in the First Mile with driver Last Mile with driver her own destination meeting point (the destination meeting point of rider Fig. 1).

3 walks to station to station 8 (point, which corresponds to her own origin meeting point point, which corresponds to her own origin meeting point m dst = m dst ', which corresponds to d org and from there she carpools with driver d' up to the destination meeting point of rider d', which corresponds to her own destination meeting point (m dst d = m dst'). From there, rider r walks up to her own destination. In this case, rider r has carpooled in the First Mile with driver d and in the Last Mile with driver d'. Let us now consider rider r'. She walks to station 3, travels by train up to station 1, carpools with driver d in the Last Mile up to the destination meeting point of d, which corresponds to her own destination meeting point (m dst d = m dst), and finally walks to her own destination. Note that the trips of riders r and r' are of type “Carpooling + Transit” and are only possible in the Integrated System (see Fig. 1).

IV. SIMULATION SCENARIO

We now describe the simulation scenario and in particular how we generate riders, drivers and meeting points.

A. Study Area

We consider a rectangular area of 30 Km x 16 Km, i.e., 480 Km2, which correspond to the surface of a small French department. A commuter rail serves this area, composed by a train route with 10 stations, with inter-station distance alternating between 2 and 3 Km. Train departures are every 5 minutes. All the distances mentioned in this paper are Manhattan distances.

B. Movement of Drivers, Riders and Trains

We assume a speed of 3, 30 and 60 Km/h for walking, driver car and train, respectively. The time needed to go from a location z to z', by walking, by car or by train, is a random variable with mean $d(z, z')/v$, where $v$ is either the walking, car or train speed, and standard deviation 1.5, 5 and 1 minutes, respectively. The random variables are normally distributed in case of walking and train, and a lognormal for the car.

C. Generation of Riders and Drivers

We generate 8.3 riders/Km2/h and 4.8 vehicles/Km2/h, and thus riders are about double the drivers. Observe that that the ratio between car drivers and other travelers in urban and suburban areas varies a lot around the world. Therefore, our riders/drivers ratio is not representative of all the possible situations, but is anyways a realistic assumption, if compared with the values measured in reality. Also note that the drivers and riders we consider are the ones supposed to be subscribed to our system, and are not representative of the entire population.

For any rider, we generate an origin and a destination uniformly at random in the study area, as usually done in the literature [5].

We generate meeting points $M \setminus S$ as follows. First we generate meeting points uniformly at random in the study areas, with a mean of 1 meeting per 3.55 Km2. Then, we additionally generate 4 to 5 meeting points uniformly at random in a 300m radius circle around each station, to account for the higher population density close to transit stations. Finally, we also add the set $S$ of 10 stations to obtain the complete set of meeting points $M$. To generate origin and destination of another driver $d \in D$, we select two random meeting points from the set $M \setminus S$, which we set as $d'$s origin and destination meeting points $m_0^{org}$ and $m_0^{dst}$.

We also need to take into account the “boundary effects” present in all simulation studies: in a real situation, the time goes from $-\infty$ to $+\infty$, while in a simulation we need to measure the performance in a finite temporal window. Therefore, we may create riders toward the end of the simulation, which may finish before their trip completion. Such riders would be incorrectly classified as unserved. To prevent this, we generate a 3h scenario, but we only take into account the riders created within the 1st hour of simulation. To achieve this, we simulate driver departure times in the entire 3h interval, but we only measure our metrics on riders that depart in the 1st hour.

3https://en.wikipedia.org/wiki/List_of_French_departments_by_population
4https://en.wikipedia.org/wiki/Modal_share
V. PERFORMANCE EVALUATION

In this section we show that the benefits of carpooling are marginal if, as in real cities nowadays, it is operated independent from transit. Such benefits only emerge when carpooling is integrated with transit. By doing this, our proposed Integrated System greatly improves transportation accessibility, i.e., the easiness for a traveler to move from any location to any other location [3]. In particular, our Integrated System offers a feasible transportation option to 40% more travelers (which would otherwise remain unserved and would have no other choice apart from private car), with limited detours to drivers.

In the following results we contrast the No Carpooling and the Current systems with our Integrated System (§III-B). To allow for direct comparison, we provide the same input (i.e., the same set of rider origin-destination pairs and departure times and the same set of driver origin-destination pairs and departure times) to all the three systems. The acronyms used in this section are reported in Table I.

A. Rider metrics

1) Served Transportation Demand: In Fig. 3, we divide the riders based on the selected multimodal transportation option (§III-E). Observe that there is no much improvement in the demand served when carpooling is introduced separately from transit, since only very few riders find a driver whose origin and destination meeting points correspond to hers ($m^\text{org}_d = m^\text{org}_r$ and $m^\text{dst}_d = m^\text{dst}_r$) and whose departure time is compatible with hers. We see instead that carpooling is an excellent feeder for transit, with more than 40% of riders carpooling to reach a transit station in the First Mile or to go from a station to their destination in the Last Mile. In fact, transit stations take the role of aggregators, which are easily served by carpooling.

2) Travel Times: In Fig. 4, for each rider $r$, we plot her origin-destination distance $d(\text{org}_r, \text{dst}_r)$ against her travel time $t^-(r, \text{dst}_r) - t^+(r, \text{org}_r)$, in the three systems. As expected, almost all travelers manage to perform their trips for very short distances (less than 3Km). However, as the distance increases, only a smaller part of them can do it. In the No Carpooling System, no traveler can perform a trip of more than 20 Km. Introducing carpooling, as in the Current System, increases accessibility in that it provides a feasible option for longer trips. However, only few “lucky” riders have this option, as the others do not find any driver with compatible origin, destination and departure time. The Integrated System, instead, provides a feasible transportation option for much more travelers, and in particular for longer trips. In general, note that, for any distance, Fig. 4 shows much more feasible trips in the Integrated System than in the other systems. These are the riders that were unserved in the other systems (represented in cloud of points of the upper plots) and have instead feasible options in the Integrated System.

   To clearly visualize the travel time gains provided by our Integrated System, we plot in Fig. 5a, for each rider both served in the Current and Integrated systems, her travel time experienced in both systems. The points on the diagonal correspond to riders who experience the same travel time with both systems. They most likely have the same selected transportation option (only walking or only transit or carpooling only) in the Current as well as in the Integrated system. Observe that for short trips, up to 20 min, no difference exists between the two systems. The benefits of the Integrated System are evident instead after 20 min. Moreover, most riders’ travel times are between 20min and 60min in the Integrated System while almost all the travel times in the Current System are between 40min and 60min. This means that riders’ journeys in the Integrated System are shorter in terms of travel time than in the Current System. This is another proxy of improved accessibility.

   We compute an empirical cumulative distribution function of the riders’ travel times in Fig. 5b. It is completed, in its right part, by the fraction of unserved users (which also corresponds to Fig.3). The travel time is within 75 minutes in most cases in the Integrated System, while in the other systems 80% of users are unserved (§V-A1) While all the results shown in this paper regard one scenario only, we ran the same scenario several times and observed no change in the general trend. We also point out that, by taking riders served in both Current and Integrated system, and computing the average travel time improvement across them, we obtain values around 10% in all such different runs.

3) Waiting and Walking Times: Fig. 6a shows the average waiting time and walking time of the riders whose selected transportation options are Only Transit (OT), Only Carpooling (OC) and Carpooling + Transit (CT). Since the train frequency is 5 minutes, the waiting time is low in OT. It increases in OC, as riders may wait more time for a rider to depart. In CT, the waiting time for trains and riders sum up, but this increase is not too high. Note however, that in any case the rider is better off waiting more in OC and CT (otherwise she would have selected OT): (i) either the overall travel time is less in OT or (ii) just OT would be an infeasible option (Def. 1). As for the walking time, OC reduces it considerably, as the rider walks to one of the meeting points, which are distributed in the entire area, instead of going to stations, whose number is limited. Also observes that CT further reduces walking time, as riders can now go either to a station or a meeting point.

4) Number of mode changes: In Fig. 6b, we represent, for any rider, the number of mode changes against the origin-destination distance of their selected transportation option: -1 means that the rider just walks, 0 that she just uses one vehicle (either carpooling or boarding a train), 1 that she carpools and then boards a train or vice-versa and 2 that she carpools in the
Fig. 4: Travel time against origin-destination distance for the selected rider options. Each point represents a rider. The cloud of points in the upper plots are the unserved riders, for whom we can only represent the origin-destination distance and not the travel time, as they did not travel (in real life they would be forced to take their private car). To ease the visualization, we represent such points with a random vertical displacement.

Fig. 5: On the left, the overall travel time of riders served both in the Current and Integrated System. On the right, empirical cumulative distribution function of travel times for riders.

Fig. 6: Breakdown of riders’ walking and waiting time for each transportation option (left). Number of mode changes (right).

First Mile, then boards a train, then carpool again in the Last Mile. Observe that in the Carpooling+Transit option, riders mostly carpool both in the First and Last Mile.

B. Driver metrics

1) Vehicle Occupancy: The number of occupied seats in a driver car changes with time, as riders board and alight. In this section, we focus on the maximum occupancy $M$, i.e., the maximum number of riders that have simultaneously been a driver’s vehicle. For instance, if driver $d$ picks up one rider at her origin meeting point $m_{org}^d$, then other two riders at a station, and all riders alight at the meeting point $m_{dst}^d$, the maximum occupancy of driver $d$’s vehicle is $M = 3$.

In Fig. 7a, we represent the percentage of vehicles having maximum occupancy $M = 0, 1, 2, 3, 4$. Observe that the Integrated System allows to more efficiently exploit the capacity offered by carpooling. Indeed, in the Current System only very “lucky” riders $r$ find a feasible rider $d$ matching, i.e., with corresponding origin and destination meeting points ($m_{org}^d = m_{org}^r$ and $m_{dst}^d = m_{dst}^r$) and compatible departure times (neither too late nor too early). In the Integrated system, instead, transit stations are consolidation points, and the probability to find a driver passing by a station at the “right” time is relatively high. Observe also that this increase in rider-vehicle matching is also boosted by the fact that we purposely construct vehicle detours in order to preferentially pass through transit stations, around which we consolidate demand (riders) and offer (drivers), who can thus more easily be associated.

2) Detours: As explained in §III-C, the Controller constructs drivers’ journeys in order to add detours via stations, if they are not too long. Therefore, either the driver makes no detours, or she passes by the station closest to her origin (we call such detour a First Mile (FM) detour), or by the station closest to her destination (Last Mile (LM) detour), either by both (FM & LM). This detour mechanism introduced in our approach enhance the overall accessibility and increases the
probability for a rider to find a vehicle at a meeting points or stations, which match with the rider’s origin, destination and departure time.

Fig. 7b shows how many drivers perform FM, LM, FM & LM detours or no detours. Note that some drivers do not perform any detour, simply because the Controller has not matched any rider to them. Note that most drivers do not perform any detour and very few of them perform FM & LM detours. This indicates that the Integrated System does not impose a high dis-utility to drivers. On the contrary, by just requiring relatively few driver detours, we are able to achieve high accessibility improvements for riders. This successful result is due to the demand consolidation operated around few meeting points and, more importantly, transit stations.

VI. CONCLUSION AND FUTURE WORK

We have devised an Integrated System in which carpooling and transit are offered as a unified mobility service. By requiring relatively small detours to drivers, our system greatly increases accessibility, in terms of reduced travel time and, more importantly, richer feasible travel options, which would allow to reduce the need for using private cars.

Much remain to do, on the basis of this first building block. In this work, we have not considered congestion on the road and in transit, which would instead impact and be impacted by our system. Moreover, we have assumed each user is either rider or driver, while in reality they can change from a day to another. Endogenous use of car and endogenous number of trips (e.g. due to teleworking, teleshopping) are likely also to affect congestion patterns. Finally, a future cost-benefit analysis can guide the design of incentive strategies for drivers, such as privileged parking, special transit fares, and possibly High-Occupancy Toll (HOT) or High-Occupancy Vehicle (HOV) Express Lanes.

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VII. APPENDIX

We report now Alg. 1, 2, 3 and 4 run by the Controller.

Algorithm 1: Generation of driver $d$’s journey in the Integrated System.

Input:
- $m_d^m$, $m_d^s$: the meeting points closest to the origin and destination of $d$, respectively.
- $s_d^m$, $s_d^s$: the stations closest to the origin and destination of $d$, respectively.
- $l^d(d, org_d)$: Time instant at which the driver starts.

Output: $J(d)$

1. Initialize $J(d) := \{org_d, m_d^m, m_d^s, dst_d\}$
2. Throw $r$ uniformly at random in $[0, 1]$
3. if $r \leq 0.5$ then
   - Try to add a detour close to the origin
4. if $d(m_d^m, s_d^m) + d(s_d^m, m_d^s) \leq 1.15 \cdot d(m_d^m, m_d^s)$ then
   - Add a detour through station $s_d^m$
   - $J(d) := \{org_d, m_d^m, s_d^m, m_d^s, dst_d\}$
5. if $d(m_d^m, s_d^m) + d(s_d^m, s_d^s) \leq 1.15 \cdot d(m_d^m, m_d^s)$ then
   - Also add a detour through the station close to the driver destination.
6. $J(d) := \{org_d, m_d^m, s_d^m, s_d^s, m_d^s, dst_d\}$
7. else
8. if $d(m_d^m, s_d^m) + d(s_d^m, m_d^s) \leq 1.15 \cdot d(m_d^m, m_d^s)$ then
9. if $d(m_d^m, s_d^m) + d(s_d^m, dst_d) \leq 1.15 \cdot d(m_d^m, m_d^s)$ then
10. $J(d) := \{org_d, m_d^m, s_d^m, s_d^s, dst_d\}$
11. else
12. $J(d) := \{org_d, m_d^m, s_d^m, s_d^s, m_d^s, dst_d\}$
13. $J(d) := \{org_d, m_d^m, s_d^m, s_d^s, dst_d\}$
14. $t^d(d, z_i) := t^d(d, z_{i-1}) + \text{travel}(z_{i-1}, z_i)$, for $i = 1, \ldots, k$
15. $t^d(d, z_i) := t^d(d, z_{i-1}) + \text{travel}(z_{i-1}, z_i)$, for $i = 1, \ldots, k$
Algorithm 2: Computation of the arrival time of rider $r$, if she carpools with driver $d$.

**Input:**
- $z$: Location from which rider $r$ starts
- $z'$: Location that rider $r$ wishes to reach
- $t$: Time at which the rider starts from $z$
- $d$: Driver with which rider $r$ carpools
- $m$: Meeting point in which rider $r$ boards $d$'s vehicle.
- $m'$: Meeting point at which rider $r$ alights.

**Output:**
- $t'$: Arrival time of rider $r$ in $z'$ (if $t' = \infty$, it means that $r$ cannot be matched with $d$)
- $wt$: Waiting time experienced by $r$
- $wd$: Distance rider $r$ has to walk.

1. Initialize $t' := wt := wd := \infty$
2. // Check if there is a seat available
3. foreach meeting point $m''$ in driver $d$'s journey from $m$ to $m'$
4. if $c'(d, m'') \leq 0$ then
5. return
6. $t' := t + \text{walk}(z, m)$ // First, rider $r$ needs to walk to $m$
7. $wd := d(z, m)$
8. if $t' > \text{t}'(d, m)$ then
9. // The rider would arrive after the driver has departed
10. return
11. else
12. $wt := t'(d, m) - t'$ // The rider waits for driver $d$'s departure
13. $t' := t'(d, m'')$ // The rider carpools up to $m''$
14. $wd := wd + d(m', m'')$ // Then she finally walks to $z'$
15. $t' := t' + \text{walk}(m', z')$

Algorithm 3: Driver selection for rider $r$ in the Only Carpooling option.

**Output:** Arrival time of rider $r$ in $z'$ (if $t' = \infty$, it means that $r$ cannot be matched with any driver).

1. Initialize $t' := wt := wd := \infty$
2. foreach driver $d \in D$ do
3. // In the Only Carpooling option, a rider and a driver can carpool only if they have the same origin and destination meeting points
4. if $m''_d = m''_r$ and $m''_d = m''_r$ then
5. // Compute the arrival time of rider $r$ if she carpools with $d$, by calling Alg. 2
6. $t', wt, wd := \text{Alg. 2}(z = \text{org}_r, z' = \text{dst}_r, d = d, m = m''_d, m' = m''_r)$
7. if $wd \leq 2.5\text{ Km and wt} \leq 45\text{ min and } t' < t'$ then
8. $t' := t'; wd := wd; wt := wt;$

Algorithm 4: Driver selection for rider $r$ in the Carpooling+Transit option.

**Output:** $t'$: Arrival time of rider $r$ in $\text{dst}_r$ (if $t' = \infty$, it means that Carpooling+Transit is infeasible for the rider).

1. Initialize $t' := t'(r, \text{org}_r)$
2. // Walking distance and waiting time accumulated by the rider.
3. Initialize $wd := wt := 0$
4. //FIRST MILE (to reach $s''_r$)
5. Initialize $t_f := \infty$ // Instant in which the rider arrives at $s''_r$
6. foreach $d \in D$ do
7. if $m''_d = m''_r$ and $d$ passes by $s''_r$ then
8. $t, wt, wd := \text{Alg. 2}(z = \text{org}_r, z' = s''_r, t' = t'; d = d, m = m''_d, m' = m''_r)$
9. if $wd + wt \leq 2.5\text{ Km and wt} + wt \leq 45\text{ min and } t < t_f$ then
10. $t_f := t; wd := wd + wt; wt := wt + wt;$
11. if $t_f = \infty$ then
12. // It is not possible to bring $r$ directly to the station. Let $m'$ be the meeting point closest to $s''_r$. Find a driver that can bring the rider in $m'$ and let the rider walk from there to the station.
13. foreach $d \in D$ do
14. if $m''_d = m''_r$ then
15. $t, wt, wd := \text{Alg. 2}(z = \text{org}_r, z' = s''_r, t' = t'; d = d, m = m''_d, m' = m''_r)$
16. if $wd + wt \leq 2.5\text{ Km and wt} + wt \leq 45\text{ min and } t < t_f$, then
17. $t_f := t; wd := wd + wt; wt := wt + wt;$
18. if $t_f = \infty$ then
19. // The last resort for the rider is to walk from the station to her destination.
20. $wd := d(\text{org}_r, s''_r)$
21. $t_f := t + \text{walk}(\text{org}_r, s''_r); wd := wd$
22. if $t_f = \infty$ then
23. // The rider cannot reach the origin station $s''_r$
24. $t' := \infty$; return
25. // TRAIN
26. $t' = t + 1\text{ min}$ // After reaching the station, we assume 1 minute is needed to reach the platform
27. Increment $wt$ by the time the rider waits for the next train after $t'$
28. $t' := \text{instant in which the train arrives at station } s''_r$, i.e., the closest to the destination
29. //LAST MILE (from $s''_r$ to $\text{dst}_r$)
30. Initialize $t_{\text{last}} := \infty$ // Instant in which the rider arrives at $\text{dst}_r$
31. Get $D''_t$: // Drivers passing by $s''_r$
32. foreach $d \in D''_t$ do
33. $t, wt, wd := \text{Alg. 2}(z = s''_r, z' = \text{dst}_r, t = t'; d = d, m = s''_r, m' = m''_r)$
34. if $wd + wt \leq 2.5\text{ Km and wt} + wt \leq 45\text{ min and } t < t_{\text{last}}$ then
35. $t_{\text{last}} := t; wd := wd + wt; wt := wt + wt;$
36. if $t_{\text{last}} = \infty$ then
37. // It is not possible to carpool starting from $s''_r$. Let $m'$ the stop point closest to $s''_r$. Find a driver that starts from there.
38. foreach $d \in D''_t$ do
39. if $d$ passes by $s''_r$ and $m''_d = m''_r$ then
40. if $m''_d = m''_r$ then
41. $t, wt, wd := \text{Alg. 2}(z = s''_r, z' = \text{dst}_r, t = t'; m = m''_d, m' = m''_r)$
42. if $wd + wt \leq 2.5\text{ Km and wt} + wt \leq 45\text{ min and } t < t_{\text{last}}$ then
43. $t_{\text{last}} := t; wd := wd + wt; wt := wt + wt;$
44. if $t_{\text{last}} = \infty$ then
45. // The last resort for the rider is to walk from the station to her destination.
46. $wd := d(s''_r, \text{dst}_r)$
47. $t_{\text{last}} := t' + \text{walk}(s''_r, \text{dst}_r); wd := wd + wd$
48. if $t_{\text{last}} = \infty$ then
49. // The rider cannot reach her final destination
50. $t' := t_{\text{last}}$