Quantifying the Efficiency of Ride Sharing

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***Abstract*— In unit-capacity mobility-on-demand systems, the vehicles transport only one travel party at a time, whereas in ride-sharing mobility-on-demand systems, a vehicle may transport different travel parties at the same time, e.g., if paths are partially overlapping. One potential benefit of ride sharing is increased system efficiency. However, it is not clear what the trade-offs are between the efficiency gains and the reduction in quality of service. To quantify those trade-offs, an open-source simulation environment is introduced, which is capable of evaluating a large class of operational policies for ride-sharing mobility-on-demand systems. The impact of ride sharing on efficiency and service level is assessed for several benchmark operational policies from the literature and for different transportation scenarios: first a dense urban scenario, then a line-shaped, rural one. Based on the results of these case studies, we find that the efficiency gains in ride sharing are relatively small and potentially hard to justify against quality of service concerns such as reduced convenience, loss of privacy, and higher total travel and drive times. Furthermore, in the assessed scenarios, the relatively low occupancy of the vehicles suggests that smaller vehicles with 4–6 seats, able to handle occasional ride sharing, may be preferable to larger and more expensive vehicles such as minibuses.**

***Index Terms*— Ride sharing, mobility on demand, operational policies.**

I. Introduction

MOBILITY-ON-DEMAND (MoD) transportation systems promise to combine the convenience of motorized individual transport with the environmental friendliness and price of conventional public transit [1]. In this work, we consider coordinated MoD systems, in which there are no autonomous decisions at the vehicle level, thereby ruling out uncooperative behavior; this corresponds to the category of "dynamic real-time ridesharing" systems described in [2] with the additional condition that the vehicles belong to an operator, not the users. Such systems have the potential to improve existing transportation systems in many ways, e.g., by increasing accessibility [3], improving public transportation in rural areas [4], and lowering cost for users [5].

The percentage of trips done using MoD systems, i.e., their mode share, is expected to increase significantly with the forthcoming introduction of fully autonomous vehicles, which may resolve important shortcomings such as system imbalance [6], lack of system-wide coordination [7], and driver availability. MoD systems with autonomous vehicles are called autonomous mobility-on-demand (AMoD) systems.

In the most commonly described operating concept for large-scale coordinated mobility-on-demand systems, a fleet of vehicles, each with enough capacity for **one** travel party is used, e.g., 4 seats. These vehicles serve one travel party at a time by transporting them from their origin directly to their travel destination. After drop-off, the vehicle may be dispatched to the next customer or relocated. In this work, such systems are referred to as *unit-capacity mobility-on-demand systems* (1MoD). In contrast to this, the vehicles in *ride-sharing mobility-on-demand systems* (RMoD) may have larger capacity and might transport **several** travel parties at the same time. This is efficient for certain cases, e.g., if two travel parties have nearby origins and are traveling in a similar direction (see Fig. 1).

Serving requests together can reduce the system's total vehicle miles traveled (VMT), and fewer vehicles might be needed to provide a given service level; in other words, the benefit of ride sharing could be increased system *efficiency*. The associated gains could potentially be passed on to users in the form of reduced fares. The drawbacks of the method are that drive times for passengers are necessarily increased; even at potentially reduced total travel times, this might be perceived as a nuisance. Furthermore, the loss of privacy inherent to ride sharing may be a concern, e.g., from a safety viewpoint [8], [9]. Although the operator can potentially decrease the fleet size by taking advantage of ride sharing, larger vehicles have higher costs and emissions.

Quantitative comparison of gains in operational efficiency and losses in service level allows determining if the gains are sufficiently large to outweigh the losses. However, the current state of the literature does not conclusively answer how these variables are related. Several shortcomings exist: operational policies guiding the behavior of the fleets have been shown to be an important factor [5]; many existing studies do not take this into account, as they are based on simplified assumptions or heuristic fleet operational policies. In addition, artificially generated demand profiles are often used instead of realistic demand distributions. Any spatial or temporal aggregation in the demand profiles used favors the application of ride sharing and thus alters the results. Finally, road networks with comparatively low resolution may introduce an artificial spatial aggregation of demands in some cases.

Contributions: We assess whether, for coordinated mobility-on-demand systems, large gains in system efficiency can be generally obtained with ride sharing with only minor impact on the service level. In a series of simulations, we use state-of-the-art operational policies for ride sharing from the literature and apply them to different transportation scenarios that are created with high-resolution, realistic demand patterns and evaluated on a high-resolution road network. We assess both urban and rural scenarios; in the first, the case for ride sharing is driven by the large number of requests per time, and in the second, by the spatial alignment of the requests. In order to perform the study, we extended the AMoDeus framework [10] with ride-sharing policies. All of the new code and scenario data developed for this article are available open source in the latest version of AMoDeus, thus providing a tool for the community to conveniently evaluate and benchmark additional policies and scenarios.

Organization: We first provide an overview of related research in Section II. Then, we present the simulation environment,

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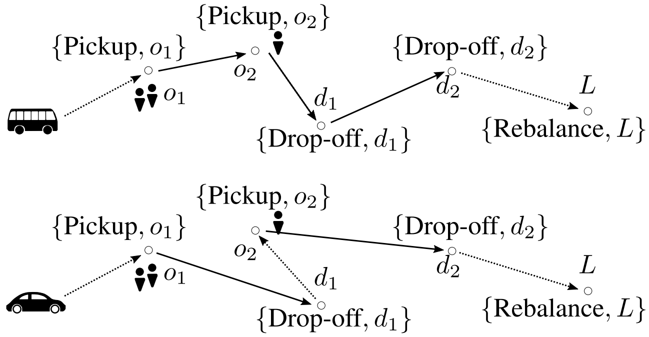

Fig. 1. Ride-sharing and unit-capacity coordinated MoD.

the ride-sharing interface, and the simulation setup in Section III. The urban and rural case studies are presented in Sections IV and V, respectively. Finally, a conclusion is drawn in Section VI. This short paper is written with a focus on brevity and conciseness; additional information is provided in the complementary materials and referred to in this text.

II. Related Work

A. Efficiency Gains of Ride Sharing

Many results from the literature suggest that efficiency gains from ride sharing for coordinated mobility-on-demand systems are substantial and can be realized in most cases. One example is the results provided in [11]; based on a model with macroscopic parameters, almost 100% of trips are estimated to be shareable; e.g., for San Francisco, the study estimates that approximately 97% of trips can be shared with a delay of no more than 5 minutes at an arrival rate of 1200 trips per hour. Generalizing the results to other cities, the study shows a potential to share almost 100% of trips in Amsterdam, Newcastle, Paris, Prague, Rome, and Santiago with an arrival rate of 8.5 trips per hour and square kilometer. In [12], a 23% reduction of vehicle miles traveled is attributed to ride sharing based on a survey of 30 000 carpool commuters in the 1970s. Ride sharing is predicted to reduce cumulative trip length by 40% in New York [13] and by 65% in Prague [14]; a more conservative estimate of 13% savings in vehicle miles traveled at 25% more trips served is made in [15]. The positive impact of ride sharing on mobility on demand is also the subject of other studies, e.g., [16], [17], and [18]. Successful real-world implementations can be interpreted as a proof of the validity of these estimates. For example, jitneys or dollar vans are small buses that (often informally) operate in larger cities and transport passengers on temporarily fixed routes which are adjusted as needed. The New York City jitney system serves about 120 000 riders daily [19]. Since the more widespread availability of internet-enabled technologies [20], large ride-hailing companies have also experimented with ride-sharing schemes, e.g., UberPool; however, in most cases it is not known what percentage of ride-sharing trips was actually matched to a second passenger [21].

These mostly positive assessments drawn in the literature are contrasted by a number of other studies and a history of discontinued implementation attempts. A simulation study for Austin, Texas, revealed that at a mode share of 11% in a small central and dense area of the city, only 4.83% of vehicle miles traveled were ride-shared, vehicle miles traveled were reduced by just 4.5 to 8.7% [22]. There is currently no consensus regarding whether ride-sharing services are complementing public transit schemes, e.g., bus lines, or if they are unfair competition that only serves the profitable fraction of trips at the public transit's expense; competing mechanisms have, for instance, been studied in [23]. Low utilization and sharing rates have been reported for several of the ride-sharing mobility-on-demand services, see, e.g., [24], and some went out of business rapidly [25]. The Group Ride Vehicle project in New York was intended to replace closed public transit connections with ride-sharing taxis, but the service was discontinued only months after it was started [19]. The CARLOS project in Switzerland suffered an 80% decrease in the number of rides during the duration of the pilot project [26]. Car pooling of private vehicles has remained at the low level of about 9% ever since it peaked in the 1970s at 20% [27], and there is no conclusive explanation of the reasons yet [28]. Changing demand patterns can influence the potential to share rides, see, e.g., [29]. However, if it is not possible to influence the demand itself, the only possibility to improve system metrics is to use well-designed *operational policies*.

B. Operational Policies

An operational policy for a coordinated mobility-on-demand system determines the behavior of every vehicle in the fleet; in the 1MoD case, two types of commands are sufficient. A vehicle can either pick up a travel party and transport it to the destination, or it can reposition to another location, a process referred to as rebalancing or repositioning. A large variety of policies exist based on mathematical optimization, clustering algorithms, model predictive control, or other methods. In this work, we have chosen a 1MoD policy for the comparison that is globally applicable, performs well, and is not adapted to a particular scenario; the *Global Bipartite Matching Policy (GBM)* [10] assigns open requests and available vehicles based on a continuously updated solution of the Euclidean bipartite matching problem between the two sets of available vehicles and open requests.

In the RMoD case, the set of possible actions is larger; pickups, drop-offs, and eventual rebalancing actions can be arranged in many different ways as long as certain constraints are met; every pickup has to be followed by exactly one drop-off, and the number of travel parties in the vehicle must not exceed its capacity at any point in time. Proposed solution methods from the literature are based on heuristics [22]; efficient setup and maintenance of data structures [15]; mixed-integer linear programming [17], [30]; or combinations of these approaches. In this work, we only assess systems in which customers request a ride to a certain location on demand, which is then served completely; i.e., no time-windows, pre-booking, repetition of trips, or segmentation of the trips are used or assumed, as they are in other setups, e.g., [31], [32]. Based on detailed study of the algorithms and the frequency of usage in the literature, we have chosen four RMoD operational policies for this study.

1) High-Capacity Shared Autonomous Mobility-on-Demand Algorithm: (HCRS) The principle of this well-formalized policy that was presented in [17] is the relatively efficient exploration of most possible options with integer linear programming. HCRS composes so-called trips out of two elements: 1) the vehicle, including the set of passengers on board, and 2) the set of passengers the vehicle is scheduled to pick up. During the exploration step, trips are constrained to a maximum wait time and a maximum increase of the total travel time with respect to the shortest path. These constraints also apply to passengers in vehicles. After exploration, the cost of each possible trip is computed as the sum of the total travel delay of all the passengers involved in it. A passenger may also be deliberately ignored by the system at a high cost. The solution that minimizes the sum of the costs of chosen trips is then computed with an integer linear program. After each assignment, if there are both ignored requests and idling vehicles at the same time, idling vehicles are sent towards these requests.

2) T-Share Policy: The T-Share policy presented in [15] was one of the first contributions exploring the efficiency gains that result from sharing single-use taxis. The algorithm assumes that a unit-capacity mobility-on-demand system is in place. Then, it acts on the collection of vehicles currently transporting a single travel party and evaluates in two steps whether additional travel parties can be added to the vehicle. Whenever a customer transportation request arrives, the algorithm identifies a set of occupied vehicles, which could potentially host the transportation request by adapting the current schedule. This set is of the smallest possible cardinality, i.e., the iterative algorithm terminates as soon as it finds a nonempty set. Then, for this set of potential taxis, another algorithm identifies the vehicle and schedule insertion permutation that can handle the additional request with minimal additional mileage while respecting constraints on the latest passenger pickup and arrival. The T-Share operational policy was extended to also allow for ride sharing of more than two travel parties.

3) Dynamic Ride-Sharing Strategy: (DRSS) This operational policy presented in [22] searches for vehicles that can host an additional request by checking a set of five conditions: 1) the total travel time of the scheduled parties may increase by at most 20%; 2) the remaining travel time of the scheduled parties must not increase by more than 40%; 3) the total travel time of the unassigned party may increase by no more than 3 minutes or 20% of the expected travel time of a direct drive, whichever is greater; 4) the unassigned party must be picked up within the next five minutes; and 5) the total planned time to serve all travel parties must be shorter than the time to serve the scheduled parties plus the time to serve the unassigned party individually. If no valid ride-sharing possibility can be found, the closest free vehicle is assigned to the travel party. Idle vehicles are rebalanced using a so-called block-balance method, in which the local imbalance of free vehicles and demand between adjacent cells is used to compute rebalancing commands.

4) Extended Demand Supply: (Ext-DS) This policy is an extension of the 1MoD policy presented in [33] with a ride-sharing heuristic. For the unit-capacity assignment, an oversupply and an undersupply case are distinguished with more available vehicles than open requests or vice versa. Then, the set with higher cardinality is iterated in random order for each vehicle (or request) and the closest request (or vehicle) is assigned. The ride-sharing extension additionally searches for vehicles where there are open requests within a radius of no more than 0.62 miles with no more than a 5 degree deviation of their destination from that of the onboard passengers. These requests are also served by the traveling vehicle.

A more detailed description of all policies as well as an overview of policies found in the literature is provided in the complementary materials.

III. Simulation Environment and Setup

In this work, we quantify RMoD systems with a queuing-based network simulator, namely MATSim [34]. In previous work, e.g., [4], [5], and [7], we have already used MATSim for quantitative analyis of 1MoD systems. For this purpose, we wrote and published the open-source software framework AMoDeus [10], which allows rapidly implementing, testing, assessing, and comparing operational policies and guarantees their smooth and seamless execution in the MATSim environment. In this work, the interface of AMoDeus was extended such that most ride-sharing operational policies can be implemented as well. The interface can be accessed online [35] and is described in detail in the complementary materials, together with the simulation approach. The chosen environment allows an accurate quantification of ride-sharing mobility-on-demand scenarios for two principal reasons. First, although the vehicle dynamics, e.g., braking and acceleration, are not modeled explicitly, the vehicles and the requests are preserved as *individual entities*, thereby removing the risk of distortion from spatial or temporal aggregation. Second, the simulation engine is rapid enough to allow for simulating large scenarios on fully resolved road networks. Clearly, the resolution of the road network in relation to the number of requests assessed will influence the "shareability" of requests; specifically, a low-resolution road network combined with large numbers of requests will represent the case for ride sharing too positively. In this work, we use the full road-network resolution available on OpenStreetMap [36], and the ratio of trips to network links is $\approx$ 0.1. For various existing approaches, this value is substantially higher, e.g., $\approx$ 42 in [13]. In the presented simulations, we evaluate each scenario with different RMoD policies and a 1MoD policy (GBM) for different fleet sizes. Operational efficiency is characterized by the vehicle miles traveled (VMT), the service level by the mean total travel time, and the suitability for ride sharing by the sharing rate and the occupancy levels of the vehicles. The sharing rate is defined as the fraction of the trips that shared at least a part of the ride with another travel party.

IV. The Case of Urban Mobility on Demand

Dense urban areas are an often cited use case for ride-sharing mobility on demand. To represent that case, we have analyzed taxi traces recorded in the city of San Francisco, presented in [37], and created a reproducible mobility-on-demand scenario with the same requests [10]. The scenario contains a total of 16 439 requests which are served by the mobility-on-demand system on a road network with 153 327 roads. A series of simulations with different fleet sizes and operational policies yields the resulting mean total travel times and the vehicle miles traveled shown in Fig. 2 and the sharing rates in Fig. 3. We identify 350 vehicles as a sensible operation point with $\approx$ 4:46 minutes average wait time; a further increased fleet size will only result in minor service level improvements. For all assessed fleet sizes, the HCRS policy yields the biggest decrease in VMT; the resulting efficiency gains from the application of this policy compared to 1Mod are summarized in Table I; an RMoD operation with 250 vehicles would result in an increase in total travel time of 15%, yield a 29% reduction in fleet size, and an 11% reduction of vehicle miles traveled. The occupancy of vehicles during the day is shown in Fig. 3; 6576 trips were unshared, 5983 trips shared segments with at most 1, 2685 with at most 2, and 1194 with at most 3 to 6 other travel parties. Interestingly, 40% of requests are served with a single travel party. Note that a trip is shared if it shares any part of the ride with another travel party. In contrast, the vehicle status shows the fraction of vehicles with multiple travel parties at every time instant. An important consideration, especially for the urban case, is the density of requests. How close together in space and time must travel requests be in order for ride sharing to pay off? To ensure that the number of requests in this urban scenario is high enough we have taken the constant ratio of total requests to vehicles of $\frac{16439}{350} \approx 47$ and evaluated the sharing rate for different numbers of requests. The resulting graph shown in Fig. 4 reveals that the critical density to harvest the benefits of ride sharing was reached and that

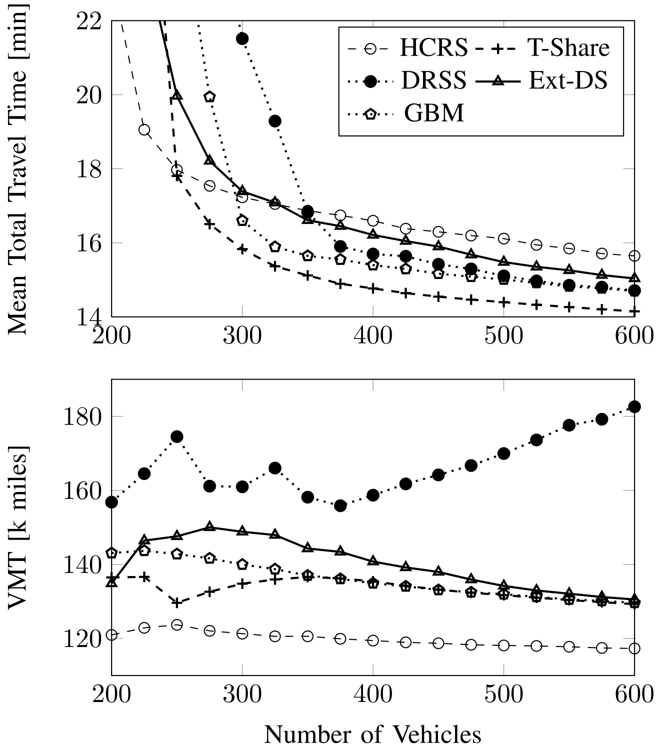

Fig. 2. Mean total travel time (above) and vehicle miles traveled (below) for the urban mobility-on-demand case.

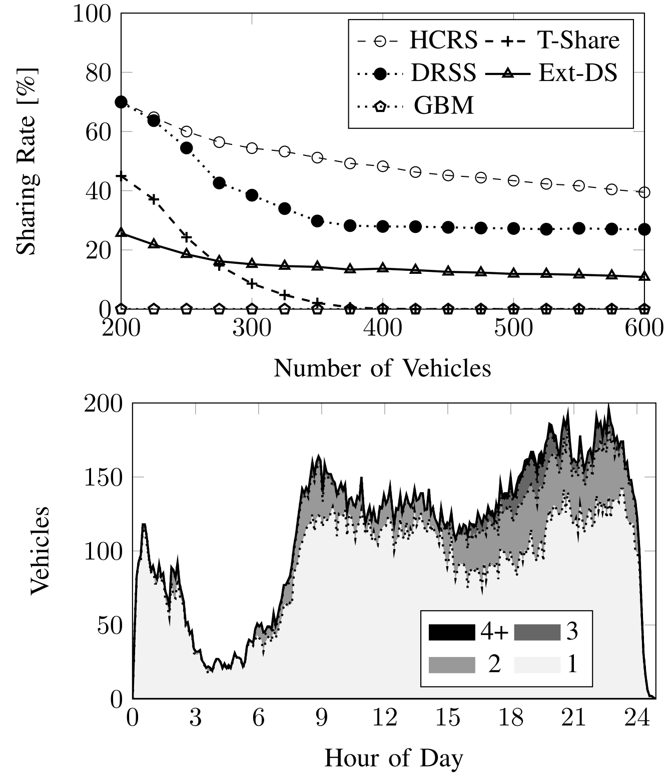

Fig. 3. Sharing rate (above) and vehicle occupancy (HCRS, 250 vehicles) during the day (below) for the urban mobility-on-demand case.

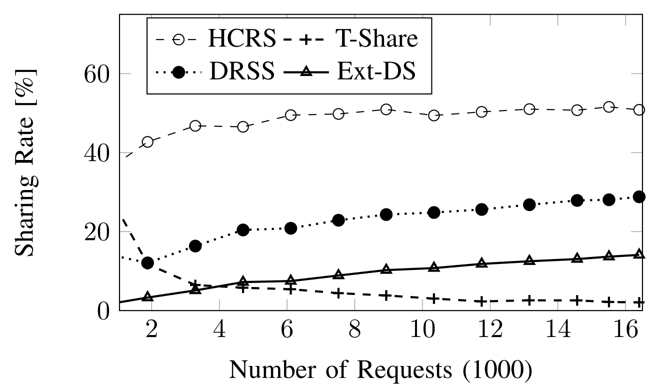

Fig. 4. Sharing rate with constant request/vehicle ratio of 47.

further increase of request density would only lightly increase the number of shared trips.

V. Substitution of Public Transportation Lines

The potential efficiency gains of ride sharing certainly depend on the spatio-temporal distribution of the travel demand. While the study in the urban setting utilizes high request density, the rural case attempts to exploit the spatial distribution of requests. To explore this possibility, we have analyzed a scenario in which a train line in a rural area of Switzerland is substituted with a hypothetical RMoD system. The travel demand of 1000 daily requests that is currently served by train is now served door-to-door by the taxi fleet. The road network has a total of 9049 roads, see [4] for details. As in the urban case, the scenario was evaluated in simulation under all the operational policies and for different fleet sizes. The resulting mean total travel times and vehicle miles traveled are shown in Fig. 5 and the sharing rates in Fig. 6. We identify 35 vehicles ($\approx$ 2:32 minutes average wait time) as a sensible operation point after which an additional increase in fleet size will not significantly improve the service level.

The HCRS and Ext-DS policies both yield similar reductions in VMT, but the HCRS does so at consistently lower total travel times; its efficiency gains compared to 1MoD are summarized in Table I. Assuming that the stakeholders would not like to increase the total travel time of the system when introducing RMoD, they could chose an operating point with 25 vehicles which represents a 28% reduction of the fleet size and a 12% reduction of the vehicle miles traveled at the cost of a 3% increased mean total travel time. Also in this case, a large percentage (68%) of trips traveled without other parties; 678 trips were unshared, 236 shared trip segments with at most 1 other party, 61 with at most 2, and 25 with at most 3 to 5 other travel parties.

VI. Conclusion

In this work, we have investigated whether ride sharing allows for large system-efficiency gains without impairing the service level. For this purpose, we have developed new capabilities for a publicly available and open-source simulation environment, which we use to compare ride-sharing and unit-capacity mobility-on-demand systems in different highly resolved transportation scenarios. From these quantitative results, we conclude that it is not necessarily true that ride sharing decreases vehicle miles traveled and required fleet sizes without impairing the service level. In the assessed scenarios, it is debatable whether the efficiency gains due to ride sharing are sufficiently high to compensate for the potential loss of privacy and for the higher total travel times. Furthermore, a generally low occupancy of vehicles was observed; from this, we conclude that it is also not necessarily true that mobility-on-demand systems should generally be designed with larger vehicles, e.g., minibuses. Instead,

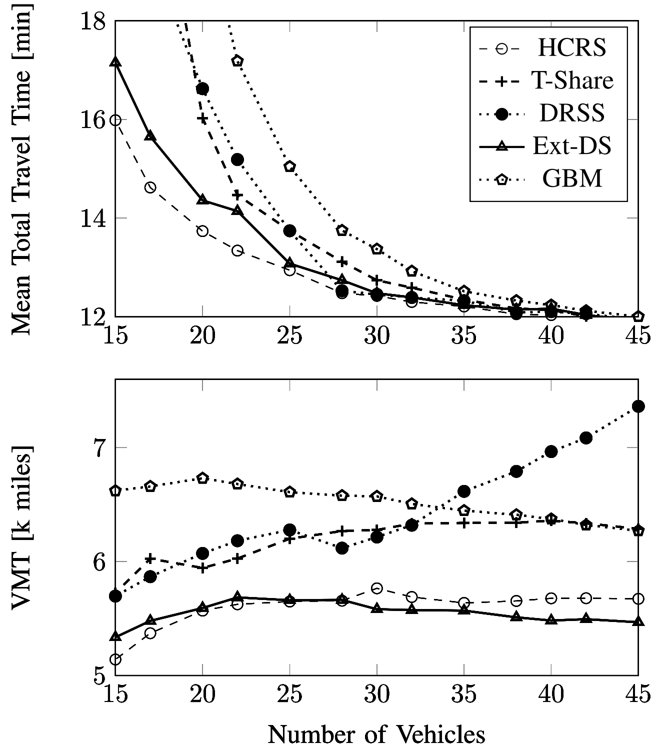

Fig. 5. Mean total travel time (above) and vehicle miles traveled (below) for the substitution of a rural public transportation line.

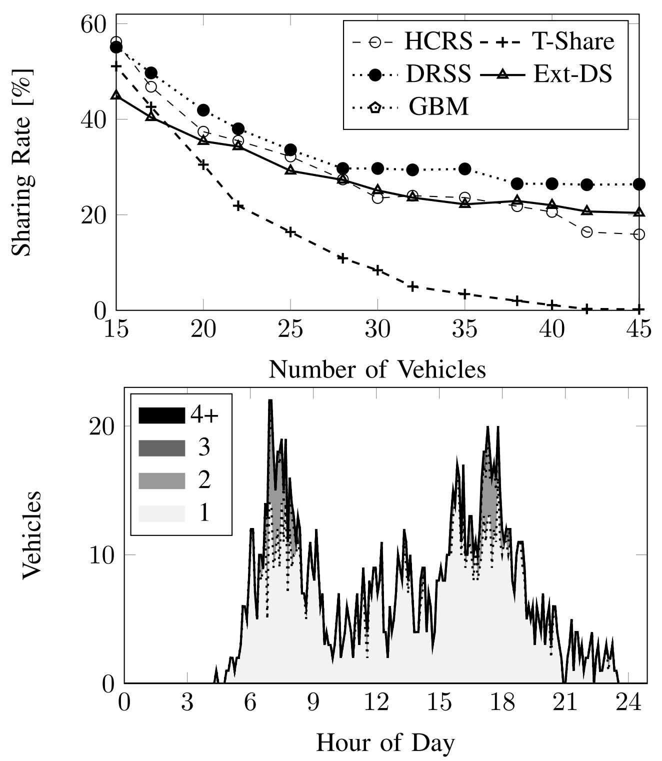

Fig. 6. Sharing rate (above) and vehicle occupancy (HCRS, 25 vehicles) during the day (below) for the substitution of a rural public transportation line.

small 4–6-seated vehicles capable of handling occasional ride sharing and used in combination with high-capacity transit links such as subways or trains could be preferable. We aim to continue research in several directions. First, additional operational policies will be implemented and tested. Then, we plan to theoretically evaluate the difference between high-capacity transit links and ride-sharing mobility on demand, and to understand whether there are cases in which ride-sharing mobility on demand would be advantageous in comparison to both high-capacity transit links and unit-capacity mobility-on-demand. Furthermore, we plan to conduct additional studies to verify and validate the simulation outputs and we aim to explore whether certain adaptions to the setup, e.g., pre-booking of trips, can improve system efficiency. Finally, we aim to explore other applications of ride sharing, e.g., relieving congestion, or increasing vehicle availability.

TABLE I

EFFICIENCY GAINS OF RMoD (HCRS) VS. 1MoD UNDER A BASIC GLOBAL BIPARTITE MATCHING POLICY IN THE URBAN AND RURAL SCENARIOS

Operational Policy	Fleet Size	VMT [miles]	Mean Total Travel Time [min]
Urban Scenario			
1MoD (GBM)	350	137 022	15:39
RMoD (HCRS)	350	120 587	16:52
RMoD (HCRS)	300	121 301	17:13
RMoD (HCRS)	250	123 686	17:58
RMoD (HCRS)	200	120 956	23:09
Rural Scenario			
1MoD (GBM)	35	6447	12:31
RMoD (HCRS)	35	5637	12:12
RMoD (HCRS)	25	5649	12:56
RMoD (HCRS)	15	5140	15:58
RMoD (HCRS)	10	4365	23:01

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