# Modeling and Evaluation of a Ridesharing Matching System from Multi-Stakeholders' Perspective

Md Tawhidur Rahman<sup>1</sup>, Kakan Dey<sup>1\*</sup>, David R. Martinelli<sup>1</sup>, Sabya Mishra<sup>2</sup>

<sup>1</sup>Department of Civil and Environmental Engineering, West Virginia University, G68 Engineering Science Building, 1374 Evansdale Drive, Morgantown, West Virginia, 26506, USA.

<sup>2</sup> Department of Civil Engineering, The University of Memphis, 104 Engineering Science Building, Memphis, TN, 38152, USA.

\*kakan.dey@mail.wvu.edu

Abstact: Matching riders and drivers in ridesharing considering conflicting objectives of diverse stakeholders is challenging. The objective of this research is to formulate and evaluate the performance of four ridesharing matching-objectives (i.e., system-wide minimization of passengers' wait time, minimization of VMT, minimization of detour distance, maximization of drivers profit) considering interests of diverse mobility stakeholders (i.e., drivers, riders, matching agencies, government transportation agencies). A grid roadway network was used to compare the performance of the four matching-objectives in serving a ridesharing demand scenario. Performance comparison of matching-objectives revealed that system-wide VMT minimization matching-objective performed best with least sacrifices on the other three matching-objectives from their respective best performance level. Also, system-wide VMT minimization was the best matching-objective, when drivers and government transportation agencies' expectations were prioritized. System-wide drivers' profit maximization matching-objectives for drivers and riders in terms of maximizing profit and travel cost savings, respectively. System-wide minimization of detour distance was found to be least flexible in providing shared rides. The findings of this research provide useful insights on ridesharing matching system modeling and performance evaluation based on different matching-objectives and can be used in developing and implementing ridesharing service considering multiple stakeholders' concerns.

#### 1. Introduction

According to the 2015 Urban Mobility Scorecard, United States (US) travelers lost seven billion hours and wasted three billion gallons of fuel due to traffic congestion [1]. Shared transportation modes are the emerging transportation demand management (TDM) strategies to better utilize limited transportation infrastructures and improve transportation system performance. Ridesharing, a form of shared mobility service, has been growing in popularity and has the potential to reduce emissions, fuel consumption, system-level vehicle miles traveled (VMT), and most importantly, traffic congestion [2], [3]. Modern-day ridesharing services, enabled by information technology (i.e. mobile apps) face several operational challenges (e.g., efficient drivers' and riders' matching, maintaining acceptable service reliability and flexibility, integration with multimodal options, and multi-institutional collaboration) [4]. Several studies have explored optimizationbased drivers' and riders' matching algorithms considering single and multiple matching-objectives to evaluate the ridesharing service performance (e.g., in terms of minimizing VMT, minimizing travel cost, maximizing the total number of matching) [5], [6]. Although the selection of matchingobjective of ridesharing service may vary with stakeholders' (e.g., government transportation agencies, matching agencies, drivers, and riders) interest, past studies have not focused on evaluating the relative performance of the matching-objectives used in matching optimization from various stakeholders' perspectives.

Matching among drivers and riders is one of the most important tasks in ridesharing services. There are several stakeholders involved in ridesharing service. Understanding and addressing their needs is critical for the successful implementation of ridesharing. Since drivers' and riders' matching significantly controls the outcome of ridesharing, selection of appropriate matching-objective has paramount importance. The goal of this study is to investigate how optimization of one ridesharing drivers' and riders' matchingobjective influences the other matching-objectives. The relative effectiveness of individual matching-objective towards achieving interests of multiple ridesharing stakeholders will be determined to understand the effect of each matching-objective on system-level performance in terms of each stakeholders' interest and on mobility policy development. The ridesharing service model considered to evaluate the matching-objectives has taken both drivers' and riders' origin-destination (O-D) into account. Usually, the drivers in commercial ridesharing (e.g., UberPool and Lyft Line), whose primary interest are making profit however, results negative implications for the goal of ridesharing. Drivers spend significant amount of their time with no passenger in their backseat and look for new passengers [7]. Due to this, there exists a surplus of drivers in the system to meet the travel needs for passengers except in some cases (e.g., during the peak demand). Thus, commercial ridesharing services are found adding system-wide VMT, thereby increasing congestion rather lessening it [8]. Assigning drivers with fixed origin, destination, and travel time constraints could solve the negative aspect of commercial ridesharing services. Ridesharing services then would be more demand responsive and ensure that each vehicle on the road would serve a purpose (i.e. have a particular O-D) rather than looking for passengers and increasing VMT, congestion, and pollution.

The rest of the paper is organized as follows. The Literature Review shows implications of past studies related to this research, The Methodology explains ridesharing matchingobjective models and solution method, Analysis and Results discusses the findings of the ridesharing matching-objective models evaluation considering a hypothetical grid roadway network, Implications in Ridesharing Policy discusses the research findings on ridesharing policy decision making and Conclusions presents concluding remarks, contributions of this research, and future research directions.

## 2. Literature Review

Solving the ridesharing problem based on received requests is similar to the dial-a-ride problem that provides ondemand service to passengers requesting trips between two points [9]. However, ridesharing drivers' and riders' matching with existing requests has additional constraints such as drivers' acceptable trip time windows, drivers' own origin and destination, which reduces the search space and complicates the problem [6]. Different techniques were adopted by researchers to solve ridesharing drivers' and riders' matching issues. A switching role approach between drivers and riders was used by Armant and Brown with system-wide VMT minimization as a matching-objective, where drivers and riders could change their role (i.e., when ride demand is too high, some potential passengers can decide to act as drivers and provide rides, instead of requesting a ride) [5]. The limitation of this matching-method is that the driving route between a pair of locations was considered similar regardless of existing requests, and thereby, drivers do not have to cover any detour distance which provides fewer incentives to riders as sometimes they need to walk or use some other modes for first-mile and lastmile transportation. A ridesharing matching algorithm proposed by Ehsani and Yu [10] predicted total system-wide VMT reduction using the New York City Taxis and Limousine Commission dataset focusing on the maximization of the number of matching. However, shared rides used by all users in the dataset was an unrealistic assumption. Liu et al. [11] focused on minimizing unassigned trip requests by using future ridesharing demand and supply estimation. With forecasted demand and supply, an algorithm developed by the authors guided matching among drivers and riders in real-time. Ren et al. [12] optimized travel cost (i.e., vehicle operation cost, user time cost, user rental cost) of ridesharing with electric vehicles. The authors reported that the proposed routing optimization model improved the utilization of the electric vehicles, and reduced user cost and VMT.

Several studies solved the ridesharing drivers' and matching problem by applying multi-objective riders' optimization techniques [2], [6], [13], [14], [15], [16], [17]. A ridesharing routing optimization model to minimize drivers' operational cost and maximize riders' satisfaction illustrated that ridesharing could reduce taxi demand by 24% and systemwide VMT by 19% [13]. Multi-objective route planning algorithms were adopted by Herbawi and Weber for the dynamic multi-hop ridesharing problem, where a single rider's trip request was served by multiple drivers [14], [15]. Passenger's origin to destination trips for this ridesharing type is shared by multiple drivers who do not need to change their original route. However, transferring in between trips may result in inconvenience to passengers. An improved version of this approach considered multiple riders instead of a single rider sharing trips with the available drivers along with time windows

for pick-up and drop-off, and drivers' detour requirements [6]. A genetic algorithm was used to solve this ridesharing matching optimization problem considering multiple matchingobjectives i.e., minimizing travel time, minimizing travel distance, and maximizing the number of drivers' and riders' matching. This algorithm was able to serve 73% of riders' requests using the trip-demand scenario of Northeastern, Illinois when drivers with longer travel distance were selected from a pool of travelers. However, when drivers were chosen randomly, the algorithm was only able to match 42% of riders' requests with comparatively lesser sacrifice in the direct travel distance and direct travel time. A dynamic riders' request handling mechanism was developed by Agatz et al. [16] by minimizing system-wide VMT and travel cost. A simulation study was conducted using travel demand data collected from metropolitan Atlanta, GA, USA to evaluate the optimization model. The proposed rolling-horizon technique substantially increased matching and reduced VMT compared to greedy matching technique. Khademi-Zareh et al. [17]focused on minimizing total trip time in addition to maximizing earliest departure time of ridesharing participants with same travel destinations. A numerical experiment justified selecting two matching-objectives, as ignoring either of the matchingobjective resulted in inefficient matching. Ozkan [18] optimized both matching and pricing dimensions of ridesharing and recommended matching and pricing policies in different demand and supply scenarios. The authors proposed a decrease in fare when there were excess drivers in the system and vice versa.

The concept of stability in ridesharing was introduced by using a stability constraint in the optimization of VMT, where trips having negative VMT savings were not rejected, but, balanced with trips that generated positive VMT savings [19]. This approach can serve riders with trip origins away from the travel routes of drivers and cause additional system-wide VMT. One major concern of this approach is that some drivers would experience less satisfaction due to required detours to pick-up passengers if there is no reward scheme (e.g., additional profit) for detouring. Li et al. [20] demonstrated that matching between drivers and riders can not be established, if their travel inconveniences cross a certain threshold. They argued that this type of matching failure could not be fixed by adjusting the compensation scheme. A matching algorithm developed by Aydin et al. [21]assigned new travel requests to the unmatched distance of ridesharing drivers' routes, which improved the satisfaction levels of drivers and reported a 33% increase in matching among drivers and riders.

Fixed meeting points instead of door to door pick-up and drop-off locations could save en-route delays for in-vehicle passengers and drivers, can serve more passengers, and can increase operational flexibility. An extensive simulation study based on real-world traffic data evaluated the "meeting point concept" and found that meeting points increased the number of matches and decreased total system-wide VMT [22]. Using this meeting point concept for ridesharing, Li et al. [23] minimized travel time cost and cost of walking time to and from pick-up and drop-off points, respectively, and reported 2.7% to 3.8% travel time savings for a small-scale ridesharing system. Park and ride locations were used as meeting points by Kaan and Olinick [24] to minimize cost in vanpool service. The assumption of common origins and destinations (i.e., pick-up and drop-off at park and ride locations only) for all passengers was the limitation of this model's applicability for ridesharing.

While several past studies considered single and multiple matching-objectives in developing ridesharing service matching models, no study evaluated the relative performance of the matching-objectives considering the interests of diverse stakeholders involved in ridesharing service matching decision making. In this research, a hypothetical ridesharing service scenario was used to evaluate the relative performance of four matching-objectives. This research evaluated the consequences of optimizing the system for one matching-objective considering the associated tradeoffs in terms of the other three matching-objectives. Besides, this research estimated the impacts of selecting one matching-objective on stakeholders' specific interests in ridesharing (e.g, trip times of drivers and passengers, cost savings of passengers, monetary gains of matching agencies). Findings of this research will help transportation policy decision-makers in developing ridesharing drivers' and riders' matching system by considering system performance of the four matching-objectives and accommodating diverse stakeholders' interests.

#### **3. Methodology: Drivers' and Riders' Matching Optimization Models and Solution Method**

In this research, four ridesharing drivers' and riders' matching-objectives were selected to evaluate their relative effectiveness from different ridesharing stakeholders' perspectives. Four selected matching-objectives are: (i) minimization of system-wide passengers' wait time, (ii) minimization of system-wide vehicle miles traveled (VMT), (iii) minimization of system-wide detour distance, and (iv) maximization of system-wide drivers' profit. Each of the four matching-objectives has potential to provide maximum benefit to some stakeholders while negatively affecting other stakeholders.

## 3.1 Selection of Matching-objective Functions

One of the significant benefits of ridesharing is the elimination of parking inconveniences (i.e., parking cost and search time) to find parking spaces in business districts. Ridesharing customers can also perform other activities (e.g., reading papers/magazines) en-route instead of driving their own vehicles [25]. However, riders in ridesharing trips may incur longer wait times for rides at their trip origins and longer trip time due to pick-up and drop-off other passengers. As ridesharing service matching-objective, minimization of system-wide passengers' wait time (*matching-objective 1*) can ensure the attractiveness of the service and travel convenience.

One of the selling points of ridesharing services is the reduction in system-level VMT while serving equal numbers of passenger miles traveled. Thus, considering the minimization of system-wide VMT (*matching-objective 2*) during matching riders and drivers may reduce congestion levels during rush hours, and reduce emissions, fuel consumption, and overall travel costs [19,21].

Excessive detour distance in matching drivers and riders can affect drivers and onboard passengers' travel plans by increasing their total trip time. While detours are unavoidable in most ridesharing trips, it is important to consider both drivers' and passengers' maximum trip time flexibility to limit unexpected detour distance/time and ensure service quality and satisfaction. Drivers usually prefer passengers' pick-up and drop-off points en-route between their origin and destination with minimum or no detour to pick-up and drop-off passengers. Again onboard passengers prefer to travel in the shortest route to their destination. Ridesharing service providers want a match among drivers and riders with minimum detours as possible to improve users' satisfaction. Minimizing systemwide detours (matching-objective 3) can reduce the travel time of a trip that not only increases riders' satisfaction but also ensures more available drivers to serve new requests.

For ridesharing, drivers may need to perform substantial detour, and incur additional trip times due to passenger pick-up and drop-off between their origins and destinations. Ridesharing drivers may need to sacrifice more than riders in terms of travel convenience and freedom in return for travel cost savings/earning enabled by sharing the trip cost with riders. An appropriate pricing scheme and a matching mechanism are necessary to maximize drivers' profit (*matching-objective 4*) to attract drivers for participating in ridesharing.

#### 3.2 Model Parameters and Indices

Service providers for ridesharing receive a stream of trip requests from participants with their specific trip origins and destinations. Trip announcements in ridesharing can be classified into two parts: trip requests from drivers and riders. The matching agency requires diverse trip-related information from drivers and riders to develop matches among them. The trip-related information required from drivers include current location, available seats, destination, and acceptable late arrival time at destination. In contrast, pick-up location, destination, number of passengers in a request, maximum acceptable wait time, and ride time are required from passengers.

 $L^{P}$  represents any link in the roadway network. p varies from 1 to *m*, where *m* is the total number of links. Links generate the connection between nodes  $(L_n^P)$ . R is the set of requests received from passengers. A request from single or multiple passengers is represented by *i*.  $v_{ti}$  indicates the drivers available for sharing a ride, where t is the type of vehicle which ensures that the developed model is capable to consider different vehicle type and capacity for ridesharing purpose. V is the set of all available drivers for ridesharing. In this study, ridesharing requests from passengers for a given time were optimized based on available drivers in the system. Passengers were assigned to vehicles based on the matching-objective and constraints, and the drivers were informed about the all passenger requests assigned to them and passengers' pick-up and drop-off locations before the start of their trips. Table 1 represents the indices and parameters used in the formulation of ridesharing matching optimization models.

# Table 1 Model parameter and indices

Parameters and Indices	Symbol					
Roadway Related						
Length of a link, $L^{P}$	$l_{L^P}$					
Distance between two consecutive nodes	$l_{L_{n, L_{n}}^{P}L_{n(next)}^{P}}$					
Distance between two nodes a and b	TD a,b					
A node $L_n^P$ on link $L^P$ with an attribute, a	$L_{n,a}^{P}$					
Passengers Related						
Request ID	i					
Set of requests	R					
Number of passengers in request i	N <sup>i</sup>					
Pick-up node of request <i>i</i>	$L^{P}_{n, o_{i}}$					
Destination node of request <i>i</i>	$L_{n,d_i}^P$					
Number of pick-up and drop-off nodes associated with a passenger(s)' ride request	b					
Pick-up time of trip request i (in vehicle $v_{tj}$ ) from the origin node $L_n^p$	$T_{L_{n,o_i}^P o_i}$					
Drop-off time of trip request i (in vehicle $v_{tj}$ ) at the destination node $L_n^p$	$T_{L_{n,d_i}^p}$					
Acceptable late pick-up time of a request, <i>i</i>	$T_{lp_i}$					
Maximum travel time allowed by a passenger request, I between origin and destination	$T_i^M$					
Penalty for unassigned passengers' wait time	U <sub>W</sub>					
Penalty for unassigned passengers' VMT	$D_F$					
Penalty for unassigned passengers' detour distance	$DD_F$					
Drivers/Vehicles Related						
Vehicle ID (vehicle type, <i>t</i> and vehicle ID, <i>j</i> )	$v_{tj}$					
Total number of drivers or vehicles	V					
Fare per unit distance	F					
Capacity of a vehicle type, t and vehicle number, j	$v_{tj}^c$					
Starting time of vehicle $v_{tj}$ from its origin node $L_n^P$	$T_{L_{n,ov_{tj}}^{P}}$					
Arrival time of vehicle $v_{tj}$ at its destination node $L_n^p$	$T_{L_{n,dv_{tj}}^{P}}$					
Acceptable late arrival time of driver in vehicle, $v_{tj}$ at driver's final destination	$T_{la_{v_{tj}}}$					
Number of on-board passengers in the vehicle before new pick-up	N <sub>E</sub>					
Number of on-board passengers in a vehicle at any node after pick -up and drop-off	$N_{L_n^P,v_{tj}}$					
Additional ride time due to an en-route pick-up or drop-off at a node by vehicle $v_{tj}$	M <sub>vtj</sub>					
Ridesharing fare in vehicle $v_{tj}$ at the link between nodes $L_n^p$ and $L_{n(next)}^p$	$RF_{L_{n}^{P},v_{tj}}$					
Percentage of total profit gained by drivers	Р					
Cost and Optimization Related						
Timestamp	Т					
Congestion delay	С					
Fare inflation factor	α					
Fuel cost per mile	f					

# 3.3 Decision Variables

i.

The following three decision variables are considered in this research:

 $y_{i,v_{tj}}$  provides a decision on a match between a vehicle or driver  $v_{tj} \in V$  with a request  $i \in R$ .

<sup>•</sup> If the driver of vehicle  $v_{tj}$  can serve the request *i*,  $y_{i,v_{tj}} = 1$ 

- If the driver of vehicle  $v_{tj}$  cannot serve the request  $i, y_{i,v_{tj}} = 0$ .
- ii.  $X_{L_n^p, v_{tj}}$  represents the requirement of pick-up or dropoff associated to a node for vehicle or driver  $v_{tj}$ 
  - If there is a pick-up or drop-off request at a node for vehicle  $v_{tj}, X_{L_{p,v_{tj}}^{p}} = 1$ .
  - If there is no pick-up or drop-off request at a node for vehicle  $v_{tj}$ ,  $X_{L_{n}^{p}v_{tj}} = 0$ .
- iii.  $Z_i$  denotes if a request, *i* is served by a match or not
  - If there is no match available for the request  $i, Z_i=1$ .
  - If the request, *i* is assigned,  $Z_i=0$ .

#### 3.4 Model Formulation

In this subsection, we have formulated four matchingobjectives considered to evaluate their relative effectiveness in serving the purpose of ridesharing stakeholders. The following assumptions were made in the model formulations:

- i. Each request will be fulfilled by one driver.
- ii. As the ridesharing system may not be able to serve all trip requests due to optimization of certain objective function and constraints, any unassigned requests are assumed to use an alternative mode transportation of (e.g., ridehailing, public transportation, personal vehicle).
- iii. Request execution of drivers and riders will be static rather than dynamic. Available requests will be executed by available drivers at that time.
- iv. For a particular request, delay due to other requests' pick-up and drop-off, will be counted at nodes other than pick-up and drop-off nodes of that particular request.
- v. Total fare will be shared by both drivers and passengers.
- vi. Pick-up and drop-off will occur at nodes only.
- vii. The problem formulations will consider 'ride now' type of ride requests, and not applicable for 'ride later' type of requests.

Matching-objective 1: Minimization of system-wide wait time of passengers

$$\min \sum_{i \in \mathbb{R}} \sum_{v_{tj} \in \mathbb{V}} \left[ \left\{ (T_{L_{n,o_{i}}^{P} - T_{L_{n,d_{i}}^{P}}) + \sum_{L_{n,o_{i}}^{P} }^{L_{n,d_{i}}^{h}} \{M_{v_{tj}} * (X_{L_{n,v_{tj}}^{P} - b}) \right\} + \sum_{L_{n,o_{i}}^{P} }^{L_{n,d_{i}}^{P}} C_{L_{n}^{P}} \}^{*} y_{i,v_{tj}} + U_{W} * Z_{i} ]$$

This matching-objective function consists of four wait time components. The first component represents the wait time of the ride request at the pick-up node. The second component represents wait time related to the en-route pick-up and dropoff requests, which will be counted at nodes other than pick-up and drop-off nodes of the request concerned. The third component reflects the wait time due to congestion. The fourth component represents a wait time penalty for unassigned passengers to account for the requests that could not be matched with available drivers. This matching-objective function is subjected to the following constraints:

$$T_{lp_i} \ge T_{L_{n,o_i}^p}$$
 where  $\forall v_{tj} \in V, \forall i \in \mathbb{R}$  (1)

$$\sum y_{i,v_{tj}} * N^{i} + N_{E} \leq v_{tj}^{c} \qquad \text{where } \forall v_{tj} \in V, \forall i \in \mathbb{R} \quad (2)$$

$$\sum y_{i,v_{tj}} + Z_{i} = 1 \quad \text{where } \forall v_{tj} \in V, \forall i \in \mathbb{R} \quad (3)$$

$$T_{L_{n,di}^{p}} - T_{L_{n,oi}^{p}} \leq T_{i}^{M} \text{where } \forall v_{tj} \in V, \forall i \in \mathbb{R} \quad (4)$$

$$T_{L_{n,d_{v_{tj}}}^{P}} \le T_{la_{v_{tj}}}$$
 where  $\forall v_{tj} \in V$  (5)

Constraint (1) guarantees that the latest pick-up time acceptable to each request is not violated. Constraint (2) ensures that the sum of existing onboard passengers in a vehicle and passengers in the new request assigned to the same vehicle never exceeds vehicle seating capacity. Constraint (3) is used to ensure that each request will be fulfilled by one vehicle. Constraint (4) assures that the total ride time of any request does not exceed the maximum acceptable ride time. Constraint (5) is used to confirm that the driver's acceptable arrival time at his/her destination is not violated.

$$\begin{split} &Matching-objective \; 2: \; Minimization \; of \; system-wide \; VMT \\ &\min \sum_{i \in \mathbb{R}} \sum_{v_{tj} \in \mathbb{V}} \; [ \; \{y_{i,v_{tj}} * (\sum_{L_{n}^{P}, o_{v_{tj}}}^{L_{n}^{P}, d_{v_{tj}}} \; l_{L_{n}^{P}, L_{n}^{P}(next)}) \} + \{ \; Z_{i} \; * \\ & D_{F} \; * \; (\sum_{L_{n}^{P}, o_{i}}^{L_{n}^{P}, d_{i}} \; l_{L_{n}^{P}, L_{n}^{P}(next)}) \} ] \end{split}$$

The first component of this matching-objective function represents VMT by all assigned requests, and the second part represents the VMT by all unassigned requests. This matching-objective function is also subjected to constraints (1) to (5).

*Matching-objective 3: Minimization of system-wide detour distance* 

$$\min \sum_{i \in \mathbb{R}} \sum_{v_{tj} \in \mathbb{V}} [\{ TD_{L_{n,o_{v_{tj}}}^{P}, L_{n,d_{v_{tj}}}^{P}(after)} - TD_{L_{n,o_{v_{tj}}}^{P}, L_{n,d_{v_{tj}}}^{P}(before)} \} * y_{i,v_{tj}} + (TD_{L_{n,o_{i}}^{P}, L_{n,d_{i}}}^{P} * Z_{i} * DD_{F})]$$

This matching-objective function is the sum of total detour distance traveled by all drivers and unassigned passenger requests. This matching-objective function is also subjected to constraints (1) to (5).

Matching-objective 4: Maximization of system-wide drivers' Profit

$$\max \mathbf{P} * \sum_{i \in \mathbf{R}} \sum_{v_{tj} \in \mathbf{V}} \left[ \sum_{L_{n,o_{v_{tj}}}^{P}} \{ RF_{L_{n,v_{tj}}} * l_{L_{n,L_{n}}^{P}} \sum_{u_{n,o_{v_{tj}}}} * N_{L_{n,v_{tj}}} * (1 + \alpha) \} \right]$$

where 
$$RF_{L_{n,}^{P}v_{tj}} = \frac{l_{L_{n,}^{P}L_{n}^{P}(next)^{*}(F-f)}}{N_{L_{n,}^{P}v_{tj}}^{+1}}$$
 (6)

The total base fare of a trip between two nodes is evenly distributed among onboard passengers and the driver. In

commercial ridesharing, the total fare is distributed only among passengers. In this study, we have assumed that drivers will also carry an equal portion of the fare with the concept that drivers share the seat of their vehicles with passengers between their origin and destination. This matching-objective function is also subjected to constraints (1) to (5) with one additional constraint corresponding to the fare inflation factor (constraint 7) [26].

# $\alpha \ge 0$ where $\alpha \in (0,1)$ is the fare inflation factor (7)

The fare inflation factor increases the total true trip fare by a certain percentage to ensure drivers' monetary benefit for providing ridesharing service. These additional fares (beyond the true trip cost) collected from riders could act as an incentive for drivers to participate in a ridesharing service. However, the fare inflation factor should be adjusted in such a way that there will be sufficient number of drivers and riders in the system to provide reliable service while ensuring monetary benefit to drivers and cost savings to riders. An inappropriate fare inflation factor may result in supplementary ridesharing drivers or ridesharing riders rather than a balanced proportion of drivers and riders that can satisfy all trips.

#### 3.5 Matching and Routing Solution Development Method

As explained before, ridesharing matching and routing problem consists of matching and generating routes for passengers and available drivers in the system by satisfying a set of constraints. The objective of this study was to determine the approximate solution for this complex problem. The solution of matching and routing problem was based on clustering passenger requests around each driver at first and then generating drivers' routes by satisfying optimization constraints. After clustering of passenger requests for the available drivers, a combination of routes was selected for drivers so that constraint 1 to constraint 5 were satisfied. Two strategies presented in Herbawi and Weber [6] were used to generate alternative matching and routing combinations- (i) reassigning passengers among drivers, and (ii) altering routes of drivers to serve unmatched passengers. An example of generating matching and routing combinations for four drivers (donated by A, B, C, D) and twelve passenger requests (denotated by number 1 to 12) in a ridesharing scenario is illusteated in Table 2. Initially a matching and routing combination of drivers A, B, C, and D is generated (matching and routing combination 1). In the matching and routing combination 2, passenger request 2 is reassigned to driver B from driver C, and passenger request 4 is reassigned to driver C from driver B. In the matching and routing combination 3, passenger request 10 is assigned to driver A by replacing passenger requests 6 and 9. Similarly, all alternative matching and routing combinations of drivers and passengers can be developed. Example matching and routing combinations 1, 2, and 3 accommodated 10,10, and 9 passenger requests, respectively.

For this study, Floyd algorithm was implemented in Matlab to generate shortest routes between drivers' origins and destinations. Considering the shortest routes and passenger requests, matching with passenger requests and drivers' routes were selected so that drivers do not need to deviate much from the shortest routes. All alternative matching and routing combinations of available drivers and passengers were used to estimate the value of the four objective functions. Evaluating all alternative matching and routing combinations, optimized value for each objective function was selected. Optimization of four objective functions provided four different matching and routing combinations (i.e., separate matching and routing combination for each objective function). The matching and routing combination from each matching-objective function's optimization was the best from the set of generated matching and routing combinations.

**Table 2.** Example ridesharing matching and routing combinations between 4 drivers and 12 passenger requests ridesharing scenario. +/- denote the pick-up/drop-off of passenger requests or origin/destination of drivers.

Matching and routing combination 1	Driver A	$\mathbf{A}^{+}$	1+	6+	9+	6-	1.	9-	A-
	Driver B	$\mathbf{B}^+$	<b>4</b> <sup>+</sup>	4-	3+	3-	B-		
	Driver C	<b>C</b> <sup>+</sup>	<b>2</b> <sup>+</sup>	11+	11 <sup>-</sup>	2-	C-		
	Driver D	$\mathbf{D}^+$	<b>5</b> <sup>+</sup>	<b>8</b> <sup>+</sup>	5-	<b>7</b> <sup>+</sup>	7-	8-	D-
	Driver A	$\mathbf{A}^{+}$	1+	6+	<b>9</b> <sup>+</sup>	6-	1-	9-	A-
Matching and routing combination 2	Driver B	$\mathbf{B}^+$	<b>2</b> <sup>+</sup>	3+	2-	3-	B-		
	Driver C	$\mathbf{C}^+$	<b>4</b> <sup>+</sup>	11+	11 <sup>-</sup>	4-	C-		
	Driver D	$\mathbf{D}^+$	<b>5</b> <sup>+</sup>	<b>8</b> <sup>+</sup>	5-	<b>7</b> <sup>+</sup>	7-	8-	D-
Matching and routing combination 3	Driver A	$\mathbf{A}^{+}$	1+	<b>10</b> <sup>+</sup>	1.	10-	A-		
	Driver B	$\mathbf{B}^+$	<b>4</b> <sup>+</sup>	4-	3+	3-	B-		
	Driver C	$\mathbf{C}^{+}$	<b>2</b> <sup>+</sup>	<b>11</b> <sup>+</sup>	11	2-	C-		
	Driver D	$\mathbf{D}^+$	<b>5</b> <sup>+</sup>	<b>8</b> <sup>+</sup>	5⁻	<b>7</b> +	7-	8-	D-

#### 4. Study Case

For numerical experiments and demonstration of four matching-objective models, we used a hypothetical grid roadway network to evaluate the performance of four matchingobjectives in providing ridesharing service (Fig. 1). The size of the grid network is 10 miles  $\times$  10 miles with one-mile spacing between parallel links (i.e., roadways). It was assumed that all 121 nodes where cross streets intersect can be used for passenger pick-ups and drop-offs (i.e., meeting points). The length of each link between two consecutive nodes is one mile. The hypothetical ridesharing system had 16 ride requests consisting of 24 passengers (8 requests with single rider and 8 requests with two riders), where six drivers were available to serve those requests. The passenger capacity of each vehicle was limited to four excluding the driver. The assumed average travel speed between any two nodes was 40 mph. The pick-up and drop-off locations for ride requests' and drivers' origins and destinations were chosen randomly before developing drivers' and riders' matching and routing combinations. Pick-up and drop-off time at any node was assumed as 30 seconds. Fig. 1 illustrates the hypothetical grid roadway network along with each drivers' trip O-D and each passenger or passengers' requested pick-up and drop-off location at the beginning of ride-matching.

To accommodate ridesharing, both drivers and riders need to allow extra time for detours required to pick-up and drop-off passengers. Between drivers and passengers, drivers require longer trip time as they need to cover all detours, pickups, and drop-offs during the trip and reach their destination after serving all assigned trips. Amey [27] identified ridesharing drivers within MIT community, who allowed a maximum 150% increase of direct travel time between their origin and destination. For this analysis, we assumed that drivers and passengers will allow a maximum 100% and 70% extra ride time respectively to accommodate ridesharing. Further, it was assumed that there was no congestion on the roadways. The maximum wait time acceptable by passengers at pick-up points was assumed to be 15 minutes. A 2016 survey in Ohio reported that more than 50% of the public transit riders routinely waited more than 30 minutes [28]. This hypothetical ridesharing system was assumed to cut 50% of transit riders' wait time. Fare and fuel cost per mile were assumed as \$2 [29] and 10 cents [30], respectively. On fare sharing, Uber and Lyft distribute fare to drivers after keeping 25% and 20% of fare, respectively [31]. This study assumed that the matching agency will keep 20% of the fare. The fare inflation factor was assumed to be 0.4 [26].



**Fig.1.** Hypothetical grid roadway network, drivers' O-D and passenger(s)' requested O-D used in drivers' and passengers' matching optimization

#### 5. Analysis and Results

#### 5.1 Performance Comparison of Four Matching-objectives

Matching of ridesharing drivers and riders may vary if all foreseeable interests of stakeholders are considered. These numerous interests cannot be achieved at the same time because of the computational complexity. For this reason, we focus on some overarching matching-objectives that can, in general, fulfill the other interests of stakeholders too. However, it is very difficult to obtain a single optimal solution for a problem where multiple matching-objectives are involved. Usually, there exists no single solution that optimizes each matchingobjective function simultaneously. The solution found from the optimization of one matching-objective function may have negative effects on other matching-objective functions because of their conflicting nature. For instance, maximizing profit for drivers (matching-objective 4) in ridesharing may increase VMT in the system (matching-objective 2). In this section, we compared the ridesharing system performance, when the system was optimized for one matching-objective by considering the tradeoffs that needed to be accepted in terms of the other three matching-objectives. Quantification of tradeoff values will help planners to select the best matching-objective that minimizes tradeoffs in terms of the other three matchingobjectives when each of the four matching-objectives was considered important. While determining avearage tradeoff of selecting one of the four matching-objectives (presented in table 3), absolute values of individual tradeoffs with equal weight were used.

5.1.1 Minimization of System-wide Passengers' Wait Time as the Matching-objective: Optimization of the ridesharing matching service considering minimization of system-wide passengers' wait time (matching-objective 1) increased systemwide detour distance by 40.4% from the lowest detour distance value found for the set of generated matching and routing combinations and four matching-objectives' optimization. Although optimizing the service by minimizing system-wide passengers' wait time is favorable to passengers, as they wait less at pick-up locations, drivers may be less motivated as they need to do take longer detours to serve passengers. In addition, drivers incurred 7.5% profit reduction compared to the best profit level in this example ridesharing scenario. Compensating drivers in terms of additional profits and onboard passengers in terms of lower trip costs for longer detours could be an option to encourage longer detours for passenger pick-ups and dropoffs. A detour-based pricing scheme can be considered in this regard, which will improve both drivers and onboard passengers' service satisfaction. This scheme will incentivize detouring, increase profit for drivers, save travel costs for passengers, and minimize passengers' wait time. However, as optimization of ridesharing drivers' and riders' matching under this matching-objective increased system-wide VMT by only 2.09% from the lowest VMT value, selection of this matchingobjective can ensure nearly minimum use of fuel and transportation infrastructure.

5.1.2 Minimization of System-wide VMT as the Matchingobjective: System-wide VMT minimization (matchingobjective 2) performed relatively well as tradeoffs for the other three matching-objectives were relatively low. The solution from optimization of this matching-objective increased systemwide passengers' wait time (11.0%), and system-wide detour distance (21.2%). These were the least possible tradeoffs from the respective lowest values found for the set of generated matching and routing combinations and all four matchingobjectives' optimization. Optimizing the ridesharing service in terms of VMT reduced drivers' profit by 8.7% from the best profit level as drivers were not allowed to pick-up more passengers by additional/longer detours which could increase system-wide VMT. A detour-based pricing scheme can limit tradeoffs related to drivers' profit and, at the same time, incentivize detouring among drivers and passengers [32].

5.1.3 Minimization of System-wide Detour Distance as the System-wide *Matching-objective*: detour distance minimization (matching-objective 3) increased system-wide VMT by 3.58% compared to the lowest VMT found in evaluation (i.e., when the system was optimized for minimization of VMT). In this drivers' and riders' matching optimization scenario, the system-wide wait time of passengers (matching-objective 1) increased by 19.9% and system-wide drivers' profit (matching-objective 4) declined by 20.8% from their respective best values. In this scenario, ride requests could be fulfilled by minimizing detour distance through minimum deviation from the shortest path between drivers' origin and destination. Although minimization of the detour distance matching-objective did not increase VMT much from the lowest VMT level, the minimum number of requests were served and the passengers of unassigned requests need to look for alternative travel options other than ridesharing. Moreover, minimization of the detour distance matching-objective reduced drivers' profits, as fewer passengers shared rides due to minimum detour distance. Applying this matching-objective could demotivate drivers due to a lower monetary incentive.

5.1.4 Maximization of System-wide Drivers' Profit as the Matching-objective: Performances of the other three matching-objectives were relatively poor under the system-wide drivers' profit maximization (matching-objective 4) scenario. The possible reason was that to maximize profit, drivers needed to

travel greater detour distances to serve more passengers, which increased system-wide VMT. When the system-wide drivers' profit maximization matching-objective was applied, systemwide VMT and detour distance increased by 8.1% and 76.8% respectively from their respective lowest values. As a single driver needs to accommodate multiple passengers' requests, overall passengers' wait time also increased. In this case, overall system-wide passengers waited 145.5 minutes, which was 23.3% longer than the lowest wait time scenario (found from optimization with matching-objective 1). From the perspective of governmental transportation agencies, the increased value of system-wide VMT under this matchingobjective could increase congestion levels in already congested cities. However, using a system-wide drivers' profit maximization matching-objective for drivers and passengers matching may reduce passenger's travel cost as more passengers share the trip cost. This scenario could also act as a monetary incentive for riders who will continue ridesharing at the expense of a higher system-wide VMT, detour distance, and wait time.

Comparison of matching-objectives revealed that minimization of VMT generated the least average tradeoff (13.6%) compared to the other three matching-objectives' respective best values for the set of generated matching and routing combinations (Table 3). This matching-objective can be selected as the best matching-objective based on this tradeoff analysis. In contrast, system-wide drivers' profit maximization generated the largest average tradeoff (36%) compared to the other three matching-objectives' respective best values. The solution generated from the optimization of this matchingobjective has the greatest impact on the performance of the other three matching-objectives.

# 5.2 Relative Effectiveness of Ridesharing Matching-objectives towards Achieving Multiple Stakeholders' Interest

The development of any mobility service has consequences and can affect many stakeholders within the service jurisdiction. For example, while ride-hailing services provide a new form of mobility through a mobile app, these services often contribute to congestion in major cities [33]. Thus, although ride-hailing meets travel demand, it fails to meet expectations of government transportation agencies, which primarily regarded this service as an alternative to personal vehicles and as a mean to lessen system-wide VMT and congestion. Thus, before implementing any mobility service, it is important to assess its relative tradeoffs in terms of utility among diverse stakeholders to ensure that some stakeholders

**Table 3** Summary of percentage tradeoff values with the adoption of one matching-objective with respect to the other three matching objectives

Matching-objective considered for optimization	Percenta	A bsolute value of			
	System-wide passengers' wait time	System-wide VMT	System-wide detour distance	System-wide drivers' profit	average tradeoff (%)
System-wide passengers' wait time	0	2.1	40.4	-7.5	16.7
System-wide VMT	11	0	21.2	-8.7	13.6
System-wide detour distance	19.9	3.6	0	-20.8	14.8
System-wide drivers' profit	23.3	8.1	76.8	0	36.0

are not adversely affected. This study has selected four stakeholders related to ridesharing: passengers, drivers, matching agencies, and government transportation agencies. For all of the four matching-objectives, the relative tradeoffs from the best values in terms of stakeholders' expected utility from ridesharing are discussed in this section.

5.2.1 Evaluation of Ridesharing Matching-objectives from Passengers' Perspective: Passengers are the most important stakeholders in ridesharing. Other stakeholders in ridesharing are derived to serve the trip purposes of passengers. To establish ridesharing as a sustainable mode of transportation, passengers of personal vehicles should be given sufficient incentives for sharing a ride to foster this mode over single-occupant vehicles. Passengers in ridesharing generally offer the least flexibility in terms of their expected wait time and trip time. Moreover, they envisage a reduction in travel costs for using ridesharing service. Three performance measures (i.e., passengers' wait time, trip time, and travel cost) were selected for the evaluation of ridesharing matching-objectives. The performance of the four matching-objectives in terms of passengers' wait time was measured through a wait time index [2]. Wait time index is the ratio of average passengers' wait time at the pick-up locations for ridesharing service and average ride time between passengers' O-D without any delay in a no ridesharing condition. In no ridesharing condition, passengers are assumed to reach their destinations without any delay involved in ridesharing (i.e., minimum travel time). Here delay accounts for the extra riding time occurred in ridesharing (e.g., delay due to pick-up and drop-off, congestion and detour) compared to ideal travel condition. Minimization of system-wide passengers' wait time (matching-objective 1) performed best in terms of wait time index. For the ridesharing service system scenario considered in this study, average passengers' wait time at pickup locations was equivalent to the 39% of average direct travel time between trips' origins and destinations under ideal condition (Fig. 2).



Fig. 2. Wait time index of different drivers' and riders' matching-objectives

This excessive system-wide wait time could discourage passengers from participating in ridesharing. However, this higher wait time index was primarily due to relatively short travel distances between O-D pairs considered in this example ridesharing scenario. For the same amount of wait time and longer travel distances, the wait time index will be lower and will be less discouraging to passengers. A ride time index (ratio of ridesharing passengers' average ride time between O-D to the average ride time of passengers between O-D in ideal condition without any delay in a no ridesharing scenario) was used to evaluate ridesharing passengers' trip time for four matching-objectives of drivers and riders. System-wide detour distance minimization (matching-objective 3) performed best in terms of the ride time index. Passengers incurred approximately 16% more travel time for participating in ridesharing service, which was the lowest compared to the other three matchingobjectives (Fig. 3).



Fig. 3. Ride time index of different drivers' and riders' matching-objectives

Minimization of system-wide VMT also performed well among the four matching-objectives in terms of the ride time index (1.18). On the contrary, system-wide passengers' wait time minimization and system-wide drivers' profit maximization performed relatively worse (1.24 and 1.23 respectively) as matching-objectives. Travel cost savings in a ridesharing environment primarily depends on the number of ridesharing passengers, fare per mile, fuel cost per mile, and the fare inflation factor. Performance evaluation of the four matchingobjectives considered in this research revealed that the maximization of system-wide drivers' profit (matchingobjective 4) provided maximum cost savings to passengers (Fig. 4).



*Fig. 4.* Average travel cost saved by each passenger for different drivers' and riders' matching-objectives

In this case, the ridesharing system optimized by using matching-objective 4 generated \$10.34 per passenger savings compared to a direct taxi service between passengers' origin and destination. To gain maximum profit, drivers usually needed to share rides with the maximum number of passengers

(not exceeding vehicle capacity), and passengers saved travel costs as more passengers shared total trip costs which made per person travel cost lower. System-wide passengers' wait time minimization (matching-objective 1) provided the least savings (\$8.73 per passenger). Optimization of the ridesharing service for matching-objective 1 prevented drivers from providing rides to those passengers who required a significant amount of pickup time due to long detours which led to fewer passengers in each vehicle to share the total trip cost. The average tradeoff value of the four matching-objectives revealed that systemwide passengers' wait time minimization (matching-objective 1) can be selected as matching-objective if planners want to benefit or prioritize passengers in the system (Table 4(a)). For average tradeoff determination, it was assumed that the three performance measures are equally important to passengers. System-wide passengers' wait-time minimization generated the lowest tradeoff (7.49%) in terms of the three performance measures from their respective best results. Passengers saved minimum in terms of trip cost when system-wide passengers' wait-time minimization was used as the matching-objective. However, they waited less for rides. System-wide detour distance minimization generated the highest tradeoff (10.93%) in terms of the three performance measures from their respective best results, and thus generated least benefit for passengers in the system. Though less detour reduced trip time between origin and destination, less number of passengers were served in this scenario. The unmatched passengers increased system-wide wait time, as they needed to look for alternative transportation modes (e.g., public transit).

5.2.2 Evaluation of Ridesharing Matching-objectives from Drivers' Perspective: Rather than allocating dedicated drivers, this study assumed that drivers in this example ridesharing scenario will perform ridesharing during their own trip. For this reason, they have limited flexibility in terms of trip distance and most importantly, trip time. Moreover, ridesharing systems should provide sufficient monetary incentives to drivers. These incentives will help drivers to accommodate inconveniences of ridesharing, e.g., passengers' pick-up and drop-off delays, invehicle travel inconveniences, additional travel time, and detour distance. Drivers' interest in ridesharing was evaluated considering two performance measures i.e., drivers' travel time and drivers' profit. The highest profit for drivers was achieved with the highest travel time (matching-objective 4) (Fig. 5 and Fig. 6).



*Fig. 5. Drivers' travel time for different drivers' and riders' matching-objectives* 



*Fig.* 6. Drivers' profit for different drivers' and riders' matching-objectives

However, drivers, as a stakeholder, prefer to incur minimum travel time between their O-D pairs. Average tradeoff analysis revealed that, although optimization with the matching-objective 3 and matching-objective 4 could result in maximum benefit for drivers through minimizing travel time and maximizing profit, respectively, none of the two matching-objectives' optimization can be recommended as a matching-objective from drivers' perspective (Table 4(b)). These two matching-objectives generated higher average tradeoffs compared to optimization of matching-objective 2 (System-wide VMT minimization). System-wide VMT minimization as a matching-objective provided a balance between drivers' incurred travel time and earned profit in ridesharing.

5.2.3 Evaluation of Ridesharing Matching-objectives from Matching Agencies' Perspective: The goal of matching agencies is to ensure the maximum number of matching among drivers and riders while maximizing profit to remain in business. In terms of passenger handling capacity, minimization of system-wide wait time of passengers (matching-objective 1) and minimization of system-wide VMT (matching-objective 2) both served 75% of the total requests. System-wide detour distance minimization (matching-objective 3) served the least percentage of passengers (~67%) as this matching-objective allowed limited flexibility in terms of detours (Fig. 7).



*Fig.* 7. Percentage of passengers served through optimization of different drivers' and riders' matching-objectives

Maximization of system-wide drivers' profit had a positive correlation with the matching agency's monetary gains, as the matching agency was assumed to claim a fixed portion of total profit (Fig. 8).



*Fig. 8.* Matching agency's monetary gains from ridesharing trips for different drivers' and riders' matching-objectives

Thus, this matching-objective resulted in maximum monetary gains for the matching agency, too. Average tradeoff analysis in terms of these two performance measures revealed that system-wide drivers' profit maximization as a matching-objective generated the lowest average tradeoff (Table 4(c)). Maximization of drivers' profit required a higher number of matching among drivers and riders. Thus, this matching-objective served matching agencies best compared to the other three-matching objectives. System-wide detour distance minimization as a matching-objective generated the highest average tradeoff. As minimum detour resulted in a minimum number of matches among drivers and riders, matching agencies gained less profit from ridesharing trips.

5.2.4 Evaluation of Ridesharing Matching-objectives from Government Transportation Agencies' Perspective: Rapid increases in personal single-occupancy vehicle usage generate the necessity to implement ridesharing programs. Organizations involved in transportation-system related decision making see ridesharing as a means of vehicle reduction. When multiple passengers' requests are handled in a single-vehicle, ridesharing has the potential to reduce VMT and, thereby, congestion. This study selected the percentage of vehicle reduction and systemwide VMT reduction as performance measures of ridesharing from government transportation agencies' perspective. Optimization of system-wide detour distance led to the smallest reduction in vehicles (50%) compared to a scenario where each participant of ridesharing travel in a single-vehicle (Fig. 9).



*Fig. 9. Percentage reduction in vehicle due to ridesharing for different drivers' and riders' matching-objectives* 

All of the other three matching-objectives reduced vehicles by 55%. System-wide minimization of VMT as a matching-objective produced maximum VMT reduction (31.28%) (Fig. 10).



*Fig. 10.* System-wide VMT reduction due to ridesharing for different drivers' and riders' matching-objectives

In contrast, system-wide maximization of drivers' profits had the smallest impact on VMT, as drivers generating maximum profit needed to serve more passengers which generated additional VMT in the system. System-wide minimization of VMT provided the best results in average tradeoff analysis in terms of vehicle and VMT reduction (Table 4(d)). This matching-objective performed best from government transportation agencies' perspective as a lower number of vehicles and VMT reduce congestion level. On the contrary, maximizing drivers' profit (matching-objective 4) could not serve the purpose of government transportation agencies. However, government transportation agencies to serve their own interests in ridesharing need to sacrifice drivers' monetary incentives.

## 6. Implications in Ridesharing Policy

Interests of ridesharing stakeholders were found to be accommodated by the selection of different drivers' and riders' matching-objectives. Though implementation of multiple matching-objectives is not practical in the same region, the results of this study could be implemented if decision-makers want to prioritize a particular group of stakeholders in the system. Moreover, tradeoffs in terms of other matching-

objectives and ridesharing stakeholders' interests corresponding to the implementation of a single matchingobjective could also be used during decision making. Systemwide drivers' profit maximization showed highest tradeoffs in terms of the other three matching-objectives (Table 3), but this matching-objective generated the highest monetary incentive for both drivers and riders in the system (Fig. 4 and Fig. 6). Therefore, before the selection of matching-objective for implementation, a comprehensive ridesharing user expectation survey should be performed to understand the user perspective. Ride time index determined for all four matching-objectives although ranked system-wide detour distance minimization as the best (Fig. 3), this matching-objective however, generated the least number of matching among drivers and riders (Fig. 7). System-wide VMT minimization, in contrast, could be implemented by sacrificing some trip time while providing the maximum number of matching.

None of the matching-objectives selected in this study could serve all the passenger requests satisfying optimization model constraints associated with each matching-objective function. Therefore, three potential strategies can be considered to serve more passenger requests: (i) Rather than achieving an

Table 4 Tradeoff (in percentage) in terms of stakeholders' interests when each matching-objective was optimized

(a) Tradeoff considering passengers' interests in ridesharing							
Matching-objective	Passengers' wait time (%)	Passengers' trip time (%)	Passengers' average travel cost savings (%)	Absolute value of average tradeoff (%)			
System-wide passengers' wait time	0	6.89 -15.57		7.49			
System-wide VMT	12.82	1.72	-12.19	8.91			
System-wide detour distance	20.51	0 -12.28		10.93			
System-wide drivers' profit	17.94	6.03	0	7.99			
(b) Tradeoff considering drivers' interests in ridesharing							
Matching-objective	Drivers' travel time (%)	Drivers' profit (%)		Absolute value of average tradeoff (%)			
System-wide passengers' wait time	10.42	-8.07		9.25			
System-wide VMT	6.51	-8.67		7.59			
System-wide detour distance	0	-20.81		10.41			
System-wide drivers' profit	18.24	0		9.12			
(c) Tradeoff considering matching agencies' interests in ridesharing							
Matching-objective	Percentage of passengers served (%)	Monetary gains from ridesharing (%)		Absolute value of average tradeoff (%)			
System-wide passengers' wait time	0	-7.54		3.77			
System-wide VMT	0	-8.43		4.22			
System-wide detour distance	11.1	-20.63		15.87			
System-wide drivers' profit	5.56	0		2.78			
(d) Tradeoff considering government transportation agencies' interests in ridesharing							
Matching-objective	Percentage of vehicle reduced (%)	VMT reduction (%)		Absolute value of average tradeoff (%)			
System-wide passengers' wait time	0	4.57		2.29			
System-wide VMT	0	0		0			
System-wide detour distance	9	7.8	6	8.43			
System-wide drivers' profit	0	17.71		8.86			

optimal solution, a near-optimal solution can be used to serve more passengers by accepting a certain amount of sacrifice from the optimal performance of each matching-objective [15]. Though this strategy may not generate optimal performance, it can lead to mobility equity for passengers without personal vehicles who rely on ridesharing. (ii) The "switching role concept" can be used to maintain the balance between riders and available drivers to serve ride requests. In this concept, some users of the ridesharing system switch their roles between drivers and passengers to serve the demand [5]. For example, some passengers can take the role of drivers to increase the availability of drivers to fulfill unmet ride requests. (iii) The matching agencies can adjust fares among different locations to divert drivers towards high demand locations. Price should be adjusted in a way that does not discourage passengers. In today's ridesharing context, this concept is known as "surge pricing". When there is high demand in a particular area, ridesharing companies increase trip cost to encourage more drivers to get to that area to serve more passengers [34], [35]. The selection of drivers' destination and travel time constraint during matching optimization is not suitable for regions where high demand for rides exist compared to driver volume. This study, however, developed drivers' and riders' matching optimization models focusing on the reduction of redundant drivers in the system.

## 7. Conclusions

Ridesharing services have a strong potential to improve the performance of the transportation system by serving transportation demand with a relatively small number of vehicles. The most common challenge in developing an efficient ridesharing service is the selection of appropriate matching-objective(s) to achieve certain system-level performance. The matching of drivers and riders based on different matching-objectives reflecting multiple stakeholders' concerns have different levels of system performance efficiencies. This study considered four matching-objectives and evaluated tradeoffs considering only one matchingobjective over the other three matching-objectives in a hypothetical ridesharing scenario. Also, the relative effectiveness of four ridesharing matching-objectives was demonstrated considering diverse stakeholders' interests. Tradeoff evaluation of matching-objectives revealed that system-wide VMT minimization matching-objective performed best with least sacrifices on the other three objectives from their respective best performance levels for the set of generated matching and routing combinations. On the contrary, system-wide drivers' profit maximization matching-objective imposed highest sacrifices on the other three matchingobjectives from their respective best performance level, though this matching-objective provided the highest monetary incentives for drivers and riders. System-wide minimization of detour distance was found to be least flexible in providing shared rides. Relative performance analysis of matchingobjectives from multiple stakeholders' perspectives revealed that the system-wide VMT minimization as matching-objective could be implemented to benefit both drivers and government transportation agencies. System-wide minimization of passengers' wait time and system-wide maximization of drivers' profit could be implemented as matching-objective to benefit passengers and matching agencies, respectively.

In this research, a ridesharing system was optimized, considering one matching-objective at a time. A multi-objective optimization technique can be used to consider multiple matching-objectives simultaneously. Also in future research, matching-objective models and algorithms that accommodate real-time ride requests should be used. Moreover, a real-world transportation network and ridesharing service demand and supply data should be used to evaluate the ridesharing system performance, which will provide more reliable insights on the relative effectiveness of the matching-objectives and the proposed models. The findings of this research will help researchers and practitioners to execute ridesharing services considering multiple matching-objectives and meeting stakeholders' expectations.

## 8. References

[1] Schrank, D., Eisele, B., Lomax, T., et al.: '2015 urban mobility scorecard' (The Texas A&M Transportation Institute, 2015).

[2] Jung, J., Jayakrishnan, R., Park, J. Y.: 'Design and modeling of real-time shared-taxi dispatch algorithms', Transportation Research Board 92nd Annual Meeting, 2013.

[3] Shaheen, S., Cohen, A.: 'Impacts of shared mobility' (Transportation Sustainability Research Center, University of Berkeley, 2018).

[4] Amey, A., Attanucci, J., Mishalani, R.: 'Real-time ridesharing: opportunities and challenges in using mobile phone technology to improve rideshare services', Transportation Research Record, 2011, 2217, pp 103-110.

[5] Armant, V., Brown, K. N.: 'Minimizing the driving distance in ride sharing systems'. IEEE 26th International Conference on Tools with Artificial Intelligence, 2014, pp 568-575.

[6] Herbawi, W., Weber, M.: 'The ride matching problem with time windows in dynamic ridesharing: a model and a genetic algorithm', IEEE Congress on Evolutionary Computation, 2012, pp 1-8.

[7] 'Uber and Lyft are creating more traffic and congestion instead of reducing it, according to a new report', https://www.businessinsider.com/uber-lyft-creating-trafficcities-bruce-schaller-2018-7, accessed 15 November 2018.

[8]'Services like UberPool are making traffic worse, study says', https://www.washingtonpost.com/news/drgridlock/wp/2018/07/25/a-new-study-says-services-like-

uberpool-are-making-traffic-worse/, accessed 14 October 2019. [9] Jørgensen, R. M., Madsen, O. B., 'Dial-a-ride' (Technical University of Denmark, 2003), 87-91137-10-1.

[10] Ehsani, P., Yu, J. Y.: 'The merits of sharing a ride'. 55th Annual Allerton Conference on Communication, Control, and Computing (Allerton), 2017, pp 776-782.

[11] Liu, Y., Skinner, W., & Xiang, C.: 'Globally-optimized realtime supply-demand matching in on-demand ridesharing', In The World Wide Web Conference, 2019, pp. 3034-3040.

[12] Ren, C., Wang, J., You, Y., & Zhang, Y.: 'Routing Optimization for Shared Electric Vehicles with Ride-Sharing,' Complexity, 2020.

[13] Lin, Y., Li, W., Qiu, F., et al.: 'Research on optimization of vehicle routing problem for ride-sharing taxi', Procedia-Social and Behavioral Sciences, 2012, 43, pp 494-502.

[14] Herbawi, W., Weber, M.: 'Comparison of multi-objective evolutionary algorithms for solving the multi-objective route planning in dynamic multi-hop ridesharing'. IEEE Congress of Evolutionary Computation, 2011, pp 2099-2106.

[15] Herbawi, W., Weber M.: 'Ant colony vs. genetic multiobjective route planning in dynamic multi-hop ridesharing'. IEEE 23rd International Conference on Tools with Artificial Intelligence, 2011, pp 282-288.

[16] Agatz, N., Erera, A. L., Savelsbergh, M. W., et al.: 'Dynamic ride-sharing: a simulation study in Metro Atlanta', Procedia-Social and Behavioral Sciences, 2011, 17, pp 532-550.

[17] Khademi Zareh, H., Ghaffari, S., Sadeghieh, A., & Mostafaeipour, A.: 'Designing a ride-sharing transportation system for assignment and transfer of passengers to a common destination', Journal of Industrial and Systems Engineering, 2019, 12(3), 141-153.

[18] Özkan, E.: 'Joint pricing and matching in ride-sharing systems', European Journal of Operational Research, 2020, 287(3), 1149-1160.

[19] Wang, X., Agatz, N. Erera, A.: 'Stable matching for dynamic ride-sharing systems', Transportation Science, 2017, 52, pp 850-867.

[20] Li, Y., Liu, Y., & Xie, J.: 'A path-based equilibrium model for ridesharing matching', Transportation Research Part B: Methodological, 2020, 138, 373-405.

[21] Aydin, O. F., Gokasar, I., & Kalan, O.: 'Matching algorithm for improving ride-sharing by incorporating route splits and social factors', PloS one,2020, 15(3), e0229674.

[22] Stiglic, M., Agatz, N., Savelsbergh, M., et al.: 'The benefits of meeting points in ride-sharing systems', Transportation Research Part B: Methodological, 2015, 82, pp 36-53.

[23] Li, X., Hu, S., Fan, W., et al.: 'Modeling an enhanced ridesharing system with meet points and time windows', PloS One, 2018.

[24] Kaan, L., Olinick, E. V.: 'The vanpool assignment problem: optimization models and solution algorithms', Computers & Industrial Engineering, 2013, 66, pp 24-40.

[25]'Cracks in ridesharing market-and how to fill them', https://www.mckinsey.com/industries/automotive-and-

assembly/our-insights/cracks-in-the-ridesharing-market-and-how-to-fill-them, accessed 9 September 2018.

[26] Ma, S., Zheng, Y., Wolfson, O.: 'T-share: a large-scale dynamic taxi ridesharing service'. IEEE 29th International Conference on Data Engineering (ICDE), 2013, pp 410-421.
[27] Amey, A.: 'A proposed methodology for estimating rideshare viability within an organization, applied to the mit community'. TRB Annual Meeting Proceedings, 2011, pp 1-16.

[28] Litman T.: 'Public transportation impact on rural and small towns', (The American Public Transportation Association, 2017).

[29] 'How much does Uber cost? -A comprehensive guide', https://www.ridester.com/uber-rates-cost/, accessed March, 2020.

[30] 'AAA reveals true cost of vehicle ownership', https://newsroom.aaa.com/tag/driving-cost-per-mile/, accessed March, 2020.

[31] 'Ridester's 2018 independent driver earning survey', https://www.ridester.com/2018-survey/, accessed March 2019.
[32] Biswas, A., Gopalakrishnan, R., Tulabandhula, T., et al.: 'Impact of detour-aware policies on maximizing profit in ridesharing', arXiv, 2017, 1706.02682.

[33]'Studies are increasingly clear: Uber and Lyft congest cities', http://www.chicagotribune.com/bluesky/technology/ct-uber-lyft-congestion-20180225-story.html, accessed 15 June 2018.

[34] 'Maximize Uber earnings when driving', https://www.ridester.com/maximize-uber-earnings/, accessed November, 2018.

[35] 'Lyft comes through on ridiculous surge pricing', https://runningwithmiles.boardingarea.com/lyft-surge-pricing/, accessed October, 2018.