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Designing a Transit-Feeder System using Multiple Sustainable Modes: Peer-to-Peer (P2P) Ridesharing, Bike Sharing, and Walking

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Abstract

Peer-to-peer (P2P) ridesharing is a relatively new concept that aims to provide a sustainable method for transportation in urban areas. Previous studies have demonstrated that a system that incorporates both P2P ridesharing and transit would enhance mobility. We develop schemes to provide travel alternatives, routes and information across multiple modes, which includes P2P ridesharing, transit, city bike-sharing and walking, within the network. This study includes a case study of the operation of the multimodal system that includes P2P ridesharing participants (both drivers and riders), the Los Angeles Metro Red line subway rail, and the Los Angeles downtown bike-share system. The study conducts a simulation, enhanced by an optimization layer, of providing travel alternatives to passengers during morning peak hours. The results indicate that a multi-modal network expands the coverage of public transit, and that ride- and bike-sharing could be effective transit feeders when properly designed and integrated into the transit system.

Metropoles such as Los Angeles are encountering serious congestion issues owing to high demand for transportation and the limited capacity of the street networks. In such cities, public transportation plays a significant role in alleviating congestion on the street network. However, the problem of transporting people to and from public transport stations, also known as the first- mile/last-mile problem, remains an issue. Commuters who would have otherwise used public transportation choose to drive their vehicles owing to the difficulty of access to public transportation stations.

Introducing sustainable transportation alternatives to provide access to public transportation allows for the reduction of congestion and its side-effects. These alternatives include Peer-to-peer (P2P) rideshare, bike share, walk, and transit. First, these alternatives encourage people to reduce the usage of personal low-occupancy vehicles, which would reduce greenhouse gas emissions. Second, mode combination allows the sustainable modes to complement each other, overcoming the weaknesses of each one, were they to be used as the main mode of transportation. Last but not least, the combination of modes may even reduce travel time and improve reliability. This research proposes a transit-feeder system that combines several modes of transportation to provide door-to-door transportation.

In P2P ridesharing, drivers who are traveling to perform activities use empty seats in their vehicles to transport passengers who have spatiotemporal proximity with them. Masoud et al. proposed a transit feeder system to promote transit ridership by connecting riders to transit using P2P ridesharing (*1*, *2*). Their matching algorithm has a multi-hop property in which a passenger can transfer between multiple vehicles/modes of transport. They also allow for each vehicle to carry multiple passengers at the same time. The system will take over the routing of drivers to place them in spatiotemporal proximity with passengers.

This research extends works of Masoud et al. by integrating multiple shared-mobility alternatives (*1*). In this study bike sharing will also be integrated into the transit

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feeder system, along with P2P ridesharing, in an attempt to increase accessibility to transit stations and improve transit ridership. Bikes offer several advantages compared to normal vehicle usage: (i) they are not affected significantly by the street traffic conditions, and (ii) while drivers' pre-specified schedules and the transit system's fixed routes and schedules constrain the potential for matches, the route and schedule of bikes are flexible as long as bikes are available at stations. By guiding riders to walk some distance to the nearby bike stations and P2P ridesharing go-points and therefore aggregating the demand (*3*), the ride matching rate could potentially increase as well.

Integrating multiple modes into the transit-feeder system is accompanied by certain challenges in the design and operational management, which this paper attempts to address. First of all, we introduce a comprehensive multi-modal platform in which each transportation alternative is allocated a separate layer in a multi-layer network. This multi-modal platform can be regarded as a super network. A layer dedicated to a single mode of transportation can contain the mode's specific characteristics, reduce the computing time to find the shortest path, and provide the basis for efficient management of the network database (*4*).

This research evaluates the proposed transit feeder system by applying it to P2P ridesharing participants (both drivers and riders), the Los Angeles Metro Red line and the bike-sharing program in downtown LA. The reason why we selected this area is because the ridership of the Metro Red line has declined in recent years (*1*). In addition, a recently launched bike-sharing program in downtown LA has experienced low usage. The goal of the transit system feeder is to increase the ridership of both.

Related Literature

A lot of the past research results show that there is a significant correlation between the accessibility and transit ridership (*5–9*). The goal of transit feeder services is to improve transit ridership by improving accessibility to the transit system. Transit feeder systems can use multiple modes of transportation to connect travelers to transit, and have been receiving more attention during recent years.

Several studies have focused on integrating bikes and transit to promote transit ridership (*10–13*). These studies have concluded that combining the two modes of transportation can be beneficial to travelers by increasing their accessibility, and to the transit and bike-share systems by increasing their utilization rates as a result of establishing a mutually complementary relationship between them. Riders in this multi-modal network can take advantage of the benefits of both modes: transit is reliable and affordable, and can be faster than the average private vehicle in some regions; bikes can enlarge the catchment area of transit with low costs, reducing congestion, and provide environmental and health benefits (*14*). Integrating bike-sharing into the transit-feeder system reduces the number of passengers who drive to, or are dropped-off at metro stations by having them switch to bikes.

Personal vehicles or taxi and ride-share vehicles can also be utilized as a transit feeder. According to Mo, 10% of Metro rail passengers in LA are dropped off by another personal vehicle (*7*). Nam et al. and Wang and Ross analyzed taxi trip characteristics using GPS data and found that a meaningful portion of transit passengers utilize taxis for their last mile (*15*, *16*). Regue et al. proposes Car2work for integrating ridesharing into existing public transit systems (*17*). Masoud et al. focuses on designing a system to feed the LA Metro Red line using peer to peer ridesharing and found that ridesharing can improve transit ridership (*1*).

A multi-modal transit feeder system can benefit from the different characteristics that each mode has to offer. For example, a multi-modal transit-feeder system can promote health through bike-sharing, and make public transportation more attractive and accessible by covering the proverbial first/last mile. This paper introduces a system to better integrate the components of multi-modal transportation systems by proposing desirable itineraries to travelers. The system provides easier access to public transit, partially by using non-motorized transport options, and partially by having individuals share motorized transportation options, therefore decreasing the number of vehicles on the street network. Lastly, the proposed transit-feeder system provides better accessibility to public transportation, specifically by addressing the last-mile challenge faced by public transit.

This system requires an elaborate ride-matching algorithm that is capable of processing multimodality. Finding the best route for a passenger in a multimodal network can be formulated as an optimization problem. Several ride-matching techniques have been formulated recently, based on time-expanded network models (*1*, *2*, *18–20*). We use the special case for the formulation proposed in Masoud and Jayakrishnan that uses a dynamic programming algorithm to find the optimal route for a passenger in a matter of a few seconds (*2*). This algorithm has been applied in Masoud et al., showing reasonable matching results between riders, drivers and transit (*1*). We further enhance the dynamic programming algorithm proposed in Masoud and Jayakrishnan to include bike-sharing and walking (*2*).

Multi-Hop and Multi-Modal Ride-Matching System

In this paper we devise a multi-hop and multi-modal ride-matching algorithm. The proposed algorithm provides a traveler with an itinerary with multiple potential connections, such as walk-ridesharing-transit-bike. This

Table 1. Types of Locations in the Multi-Modal Shared-Ride Network

Station type	Symbol	Description
Go-points-vehicles	S_V	Points where a rider starts/ends their journey by taking a ridesharing vehicle $\forall S_V \in S_G$
Go-points-bike	S_B	Points where a rider starts/ends their journey by bike-sharing $\forall S_B \in S_G$
Go-points-connection points	S_C	Points where an individual can connect to other drivers or modes (bike, transit) $S_C \in S_V, S_C \in S_B, \forall S_C \in S_G$
Go-points-transit stations	S_T	Points where an individual can transfer to/from a transit station $\forall S_T \in S_C, \forall S_T \in S_G$
Riders' origin/destination	S_O, S_D	Points where a rider starts/end their journey - is connected to go-points by walking

information provides travelers with door-to-door guidelines on how to combine several modes of transportation for their trips. The goal of the ride-matching algorithm is to find passengers' itineraries that can provide them with the highest utility, in which utility is defined as a weighted combination of mode travel time, travel cost, waiting time and transfer penalty. Each passenger will be asked to provide the trip origin (S_O) and the trip destination (S_D), along with the earliest starting time (ES) and the latest arrival time (LA) of the trip. Passengers are also encouraged to state their preferences about the maximum number of connections (between different modes of transportation, or different vehicles of the same mode), modes of transportation, and characteristics of the vehicles on which they travel. It is possible to even elicit preferences on the type of individuals with whom they may share rides. Based on user input and available modes of transportation, the system will devise itineraries within the travel time windows specified by passengers, and propose these to them.

The dynamic programming algorithm proposed by Masoud and Jayakrishnan has a flexible, multi-hop routing scheme (*21*), and Masoud et al. apply the algorithm to design P2P ridesharing to be a transit feeder (1). This algorithm, however, only considers the combination of P2P ridesharing and transit. We reformulated the algorithm to include bike-sharing and walking to access the transit-feeder system. With algorithm enhancement and network expansion, the proposed method allows a rider's itinerary to include as many modes of transportation as desired. We redefined a network structure to efficiently manage multiple modes of transportation and introduced methods to improve the matching rate and provide utility-maximizing itineraries to travelers.

To model the transit feeder system, we discretize the study time horizon into short time periods (5-min periods in this study). Furthermore, we define locations in the network where travelers can start and end their trips, and/or transfer between transportation alternatives. Note that in this study we have several types of locations with different functionalities, elaborated in Table 1. The proposed algorithm has a node-link network structure. Let us define a node n_i to be a tuple of the time period (t_i) and the station (s_i), that is, $n_i = (t_i, s_i)$. A link is denoted as (t_i, s_i, t_j, s_j), such that it can be interpreted as a trip that starts from the station s_i at time t_i, and ends at the station s_j at time t_j. We define a set of "go-points", denoted by S_G, as pre-specified locations where riders can start or end a (leg of a) trip in a driver's vehicle, start or end a shared-bike ride, or transfer between modes. Our research does not assume, however, that every rider starts their journey from a go-point, as was done in past research. We allow riders to walk a certain distance between a go-point and their actual start/end points (S_O and S_D). This additional level of flexibility introduces advantages over the earlier schemes in which trips were assumed to start and end only at go-points: (1) it reflects the actual behavior of riders which can be extended to real mobile services: (2) it increases riders' route flexibility because they are not always restricted to one selected go-point; and (3) the ridesharing system can have a higher matching rate owing to this flexibility.

To allow multiple modes, we introduce a super network concept that utilizes an independent layer for each mode and integrates all modes using connections at mode-transfer stations. The locations (physical nodes in the network) are categorized into five types as shown in Table 1. To promote transit ridership, we restrict Go-points for bikes to be connected only to transit stations in this study.

In a multimodal system, we should consider the various characteristics of each mode. The network contains four different modes (P2P ridesharing, Bike-sharing, Transit, and Walking), which would result in four separate network sub-layers. In Figure 1, black, red and green lines represent the three different layers, and the blue lines represent the rider network (which contains the walking mode for the rider as well as the entire rider path). In this example, as the rider travels from his origin (O) to destination (D), the rider would walk to a bike station, ride a bike, then transfer to transit, and a ride-share vehicle will be used for his last mile. This ride matching can be accomplished through optimization on such a multimodal network, along the lines of those used in Masoud and Jayakrishnan (*2*).

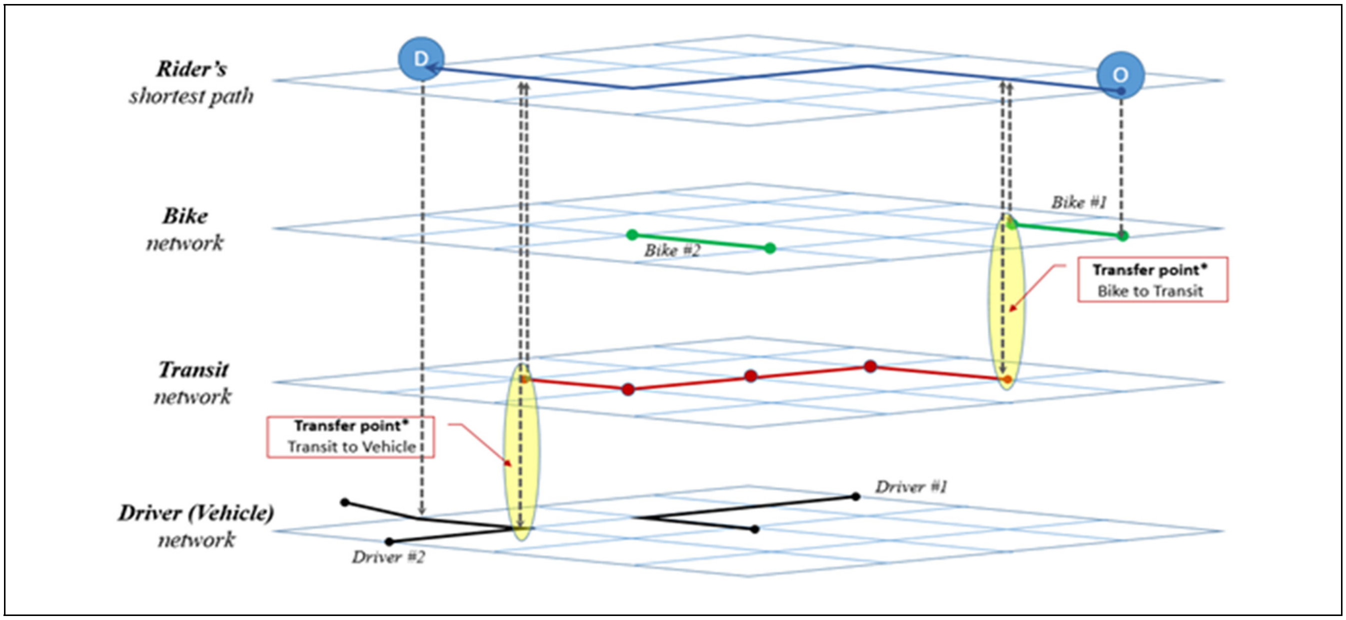


Figure 1. Layers of transportation alternatives in the super network of the transit-feeder system.

The P2P ridesharing network only contains vehicle related link-node information such as the travel routes of drivers, turn restrictions, tolls and travel times of vehicles, as it is designed only for vehicles. The bike network would only include availability of bikes, cost, and routes to nearby subway train stations. The transit network would only have information about frequencies, routes, and fares. The layer for each travel mode is independent except for the connection points of time and space. The riders' travel can be accomplished through a certain combination of several modes. Furthermore, riders should walk to a nearby go-point from an actual origin point and from a go-point to an actual destination, where the origins and destinations are typically homes or work/shopping locations. For simplicity, we use a straight line for any walk link, though it can also be represented as a separately found walking route.

Each connection go-point (S_C) is represented by separate tuples (t_i, s_i) corresponding to each mode because each mode has a different available time window. Our decomposed optimization algorithm for ride-matching in a ridesharing system can optimize a multi-modal system in a similar fashion, essentially by considering a bike or a transit vehicle as similar to a virtual "driver" in a ridesharing system.

The integrated multi-modal network improves efficiency in pre-processing, ride-matching and managing of the database. The optimization algorithm includes multiple shortest path calculations in pre-processing and ride-matching. The multimodal network structure reduces computing time for shortest path calculations by restricting the number of node explorations from any node to only those of the associated mode, except at the connection nodes between the mode layers (mode transfer nodes). For database management during path optimization, this network structure reduces the search time to find feasible drivers, as the user limits his/her preferences to only certain modes. The query process then searches for feasible drivers in only the preferred-mode set, which is a relatively small database when compared to one that includes all modes.

The demand generation process is designed to reflect a realistic spatial distribution among the riders. As explained above, previous research has assumed that riders' origin/destination are predefined locations, as shown with blue dots in Figure 2 (*1–3*). In reality, however, riders should access one of the go-points by walking unless their starting/ending points are exactly at the go-points. We design our ride matching network to reflect the riders' actual starting/ending points. Instead of assuming that demand exists at a representative point, we randomly disperse the travel demand for a transportation analysis zone (TAZ) within the associated TAZ, as red dots in Figure 2. In other words, we consider accessibility to/from a go-point.

To connect the randomly generated riders' origin and destination points to the network of go-points, we introduce dynamic walk links as connectors to the nearby go-points. They are indicated by the dashed line in Figure 3. We design the dynamic walk links to be connected to the nearest *n* go-points. These dynamic links are temporarily generated in our network when a rider requests a ride. After finishing the ride-matching process, the walk links are eliminated from the network for the next process.

blue dot : go-point, red dot: randomly generated riders' location

Figure 2. Example of demand generation.

This dynamic process allows a simpler network structure for further processing.

Multiple dynamic connectors from an origin to go-points, and to a destination from go-points have the potential to increase matching rates, as shown in Figure 3. Connecting a walk link to only one go-point has the limitation that the available drivers and possible routes are spatially restricted. Figure 3*a* and *b* show an example of a ride-matching failure with a single connection. In the example, Rider 1's origin is R1 in a circle and his/her destination is R1 in a rectangle. Figure 3*a* indicates that the rider's go-points are G1 for origin and G3 for destination.

There are two drivers in the sample network. Driver 1 traverses D1-G1-G2-D1 and Driver 2 travels to D2 through G4. If there is no driver going to the riders' solely connected go-point near his destination, the rider's trip cannot be matched. This problem could be solved if we find the second nearest go-point and search a route again. However, it is computationally expensive as the matching process should be repeated until the ride is matched. The concept of multiple connectors can solve this problem, as shown in Figure 3*c* and *d*, as multiple connected links can include drivers/modes near multiple go-points. Although introducing the connectors marginally increases the computational time owing to the increased network size, the better matching rate more than compensates for this.

Another advantage of dynamic links is to find better paths for riders. The two sample networks in Figure 3*e* and *f* showcase this property in the following example. Here we assume that there are three drivers: 1) D1-G1-G2-D1, 2) D2-G2-G3-D2, and 3) D3-G4-D3. Figure 3*e* shows the case when we connect only one walk link to the nearest station. Rider 1 will be guided to walk to G1 from the origin because the nearest go-point is go-point 1. She will then transfer to Driver 2 at go-point 2 (G2) and be dropped off at go-point 3. The total travel time for this itinerary is 20 minutes (5 min walk). In comparison, our proposed network structure, as shown in (f), can reduce the travel time to 15 minutes and with no transfer, although a rider must walk little longer (8 min). Here, three driver candidates are considered for Rider 1.

Case Study

Research Scope and Data

For a parametric study of the application of our ride matching system, we selected the city of Los Angeles, as in our earlier study, which developed a network based on the Southern California Association of Governments (SCAG) RTP 2040 Travel Demand Model 2016 Scenario 3 (*1*). We enhanced that network to include multi-modal layers and the current bike-sharing stations in LA downtown as shown in Figure 4. Actual coordinates of the bike stations were collected and used to build the network. We used various data and actual travel time information, such as the LA Metro time table, and the Google directions API (*22*) for automobiles, bikes, and walk modes. Spatial connections between bike stations and transit stations are included in the network design step to efficiently improve accessibility to transit stations. Bike stations near transfer points (including metro stations) were selected as connection points.

In the preprocessing step, participants (riders and drivers) are randomly selected from the vehicle origin-–destination trip table of the SCAG demand model, as the interest is in finding how many vehicles travelers will change their mode to our system. Then, as discussed in the demand generation step, we randomly placed the selected-riders in the given TAZ, as shown in Figure 2.

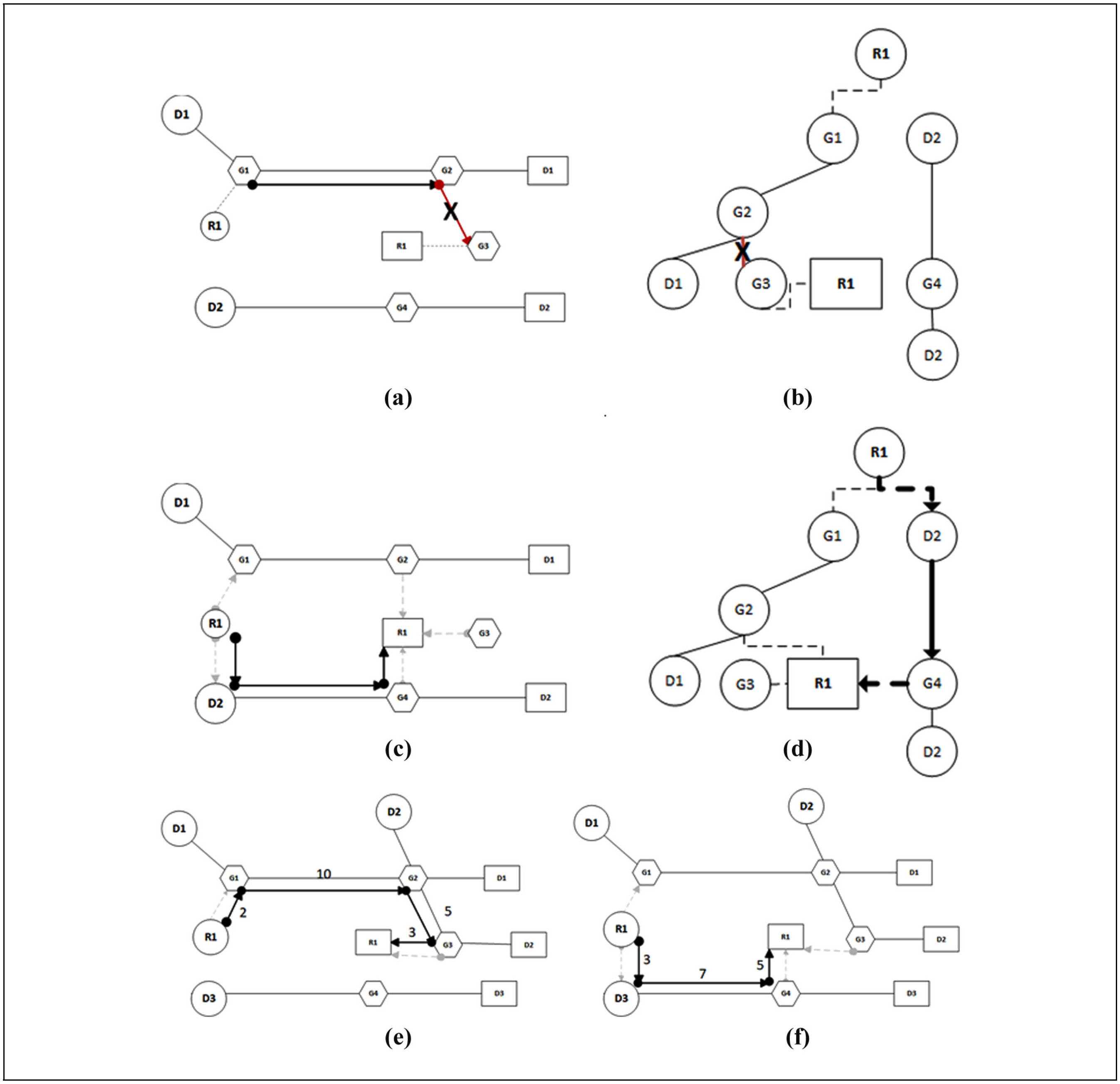


Figure 3. Advantage of multiple connectors: (*a*) ride-match failure case with single connector; (*b*) graph representation of ride-match failure case (single connectors); (*c*) ride-match success case with multiple connectors; (*d*) graph representation of ride-match success case (multiple connectors); (*e*) matched-rides result with a single connector (walk-D1-D2-walk); (*f*) matched-rides results with multiple connectors (walk-D3-walk).

The demand in the OD table is at an aggregated level containing the origin ID, destination ID, and the travel volume. SCAG also provides the geo-locations of each TAZ (both points and polygons). Points are generally located at the center of the associated polygons. A point and a related polygon are mapped by a key index. Using python programming and geographic information system (GIS) libraries, all riders' origin–destinations are randomly generated and located.

Within the constraints of the travel time budget, which is the difference between the earliest start (ES) and the latest arrival (LA) times that are specified by any rider, the dynamic matching algorithm finds the multi-hop paths maximizing each rider's utility. The utility function in our algorithm is expressed as a linear combination of the rider's cost components: travel time, mile-based travel cost, connection penalty, and bike-sharing cost. In this research, we use default values of \$20/hour for the value

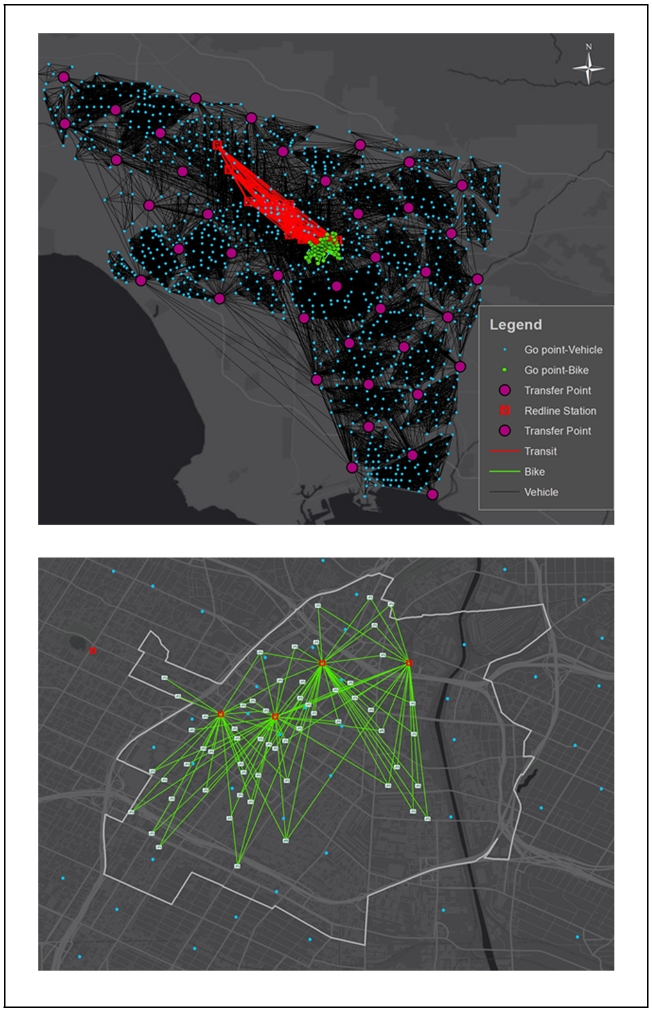


Figure 4. Node-link set and bike network expansion (Los Angeles region and the study area).

of time, and \$ 0.25 for each mile of ridesharing. Finally, we postulate a \$ 0.1 additional cost for each connection, and for each time period spent in waiting for a connection. In downtown LA, usage of a bike is priced at \$1.5 by a half hour period. When a bike is used in our matching system, it must be returned to another bike station.

Metro Rail Stations Accessibility

Reducing the first/last mile for the transit ridership implies improvements of accessibility to transit stations. Improved accessibility to the Metro increases transit ridership. Walking is a main mode to access to rail stations. Mo shows that about 52% of Metro users in LA County are willing to walk to Metro stations (*7*). Furthermore, they tend to walk when their walking time is less than 10 min. Therefore, we set the accessibility criteria as 10 min in our model. Our main expectation is that our proposed method attracts more riders by providing improved accessibility to Metro stations and reduced accessing time. In addition, it is evident that current riders, who walk to stations, can also benefit from the proposed method.

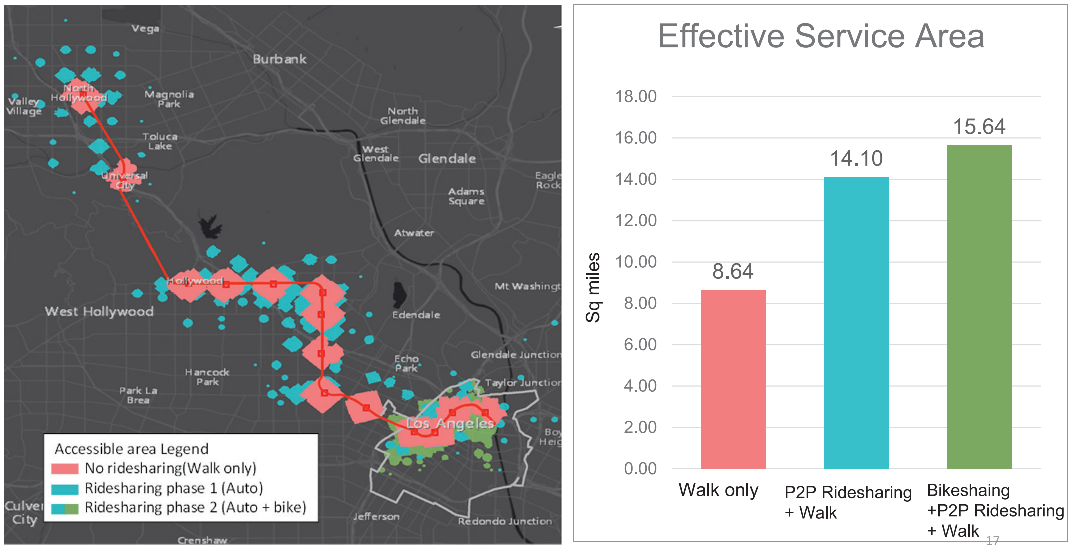
We examined how the proposed system improves accessibility to the Metro Red line subway stations in the morning peak. Assuming that riders only access the Red line stations if the access time is less than 10 minutes, we found the possible catchment region from where riders are willing to use our system. To identify catchment areas, this study applied a network analysis with our multi-modal network. To measure improvements to the catchment regions, we set access time to the Red line stations as an index. Access time to a metro station s is decomposed into access time by mode m from a go-point i to a metro station s, that is, ($tt^{m}_{i,s}$), and walking time to a go-point I, that is, (tt^{walk}_{i}), in Equation 1. Here $tt^{m}_{i,s}$ has three components: driving time from a go-point i to metro station s, denoted as ($tt^{m}_{inmode,i,s}$), waiting time for mode m at a go-point I, denoted as ($tt^{m}_{wait,i}$), and processing time for a mode at go-point I, denoted as ($tt^{m}_{process,i}$):

$$\text{Access Time}_s = tt^{m}_{i,s} + tt^{walk}_{i} \tag{1}$$

where $tt^{m}_{i,s} = tt^{m}_{inmode,i,s} + tt^{m}_{wait,i} + tt^{m}_{process,i}$

From our multi-modal network, in which the actual travel times during the morning peak hour are found from the Google Directions API (*22*), a Dijkstra shortest path search identifies all possible go-points where mode travel time ($tt^{m}_{inmode,i,s}$) is less than a certain limit (in minutes). Each mode layer has mode-specific characteristics such as average wait time ($tt^{m}_{wait,i}$) for the mode m at a go-point i, and processing time ($tt^{m}_{process,i}$)of a mode m at a go-point i as presented in Equation 1. Average wait time for transit is calculated as half of the average transit headway (i.e., 1/frequency), which technically assumes, implicitly, that the scheduled headways are generally uniform and that there is no substantial schedule variance. The waiting time for bikes is set to zero and the processing time for bike rental is assumed to be 2 minutes. Our network does not include actual walk links, thus we again utilized a private API which provides walking level travel time and geographic boundaries from a point (*23*).

Figure 5 shows the accessible area to Red line stations, which indicates that our ridesharing system improves accessibility of Red Line stations in the morning peak. Red areas show the case when no feeder mode exists (except walking). Blue areas imply that more travelers can reach their nearest station by P2P ridesharing. We found the system to improve the area of accessibility from 8.64 square miles to 14.10 square miles. The proposed method with bike-sharing also has the potential to improve accessibility to 15.64 square miles. An interesting fact is that the bike-sharing system in the downtown area has more potential to increase the Red line's



Accessibility improvement by Ridesharing and Bikesharing

Figure 5. Accessibility improvements by P2P ridesharing and bike-sharing: (*a*) accessible area to Red line stations; (*b*) effective service area.

catchment area than an automobiles-based ridesharing system as bikes are generally faster than automobiles that may become stuck in downtown congestion.

Parametric Study

Under the assumption that travelers will change their mode from personal automobiles, our simulations involve increasing the number of riders stepwise from 1,000 to 4,000, and increasing the number of drivers respectively from 1,000 to 10,000. The matching rate increases sharply at the beginning when we increase the number of drivers, as can be seen in Figure 6*a*. Then the marginal matching rate decreases. When we increase the number of drivers from 1,000 to 5,000, the matching rate triples. We may conclude that, the number of riders, drivers and the ratio between riders and drivers affect the matching rate. When the number of riders is small and the number of drivers increases to twice that of the riders, the matching rate would increase sharply. When the number of drivers is a relatively large number, doubling the number would not increase the matching rate to the same level. If the ratio continues to increase beyond two, the improvement in the matching rate is not as significant as before. The general pattern is similar to that reported in Masoud et al. (*1*), but we can see that the matching rate in our study is significantly higher. The network expansion, addition of bike-sharing, multiple-layer network, and dynamic walk connectors that we propose will enable riders to have more alternatives.

Increasing metro rail and bike usage among those who use automobiles is our main research interest. A series of simulations was designed, so as to understand how the usage numbers change when we increase the number of riders and drivers. We expect the number of Metro rail and bike users to also linearly increase when the number of total participants increases linearly. The usage results are shown in Figure 6*b* and *c*.

Firstly, for metro users, we can observe an approximately linear trend when we increase the number of participants. Out of the entire simulation sample (224,196 individuals), not all have direct access to the metro system (i.e., origins and destinations are far away from metro stations). Out of all of the individuals in the much larger area, around 8,400 individuals were potential metro users (as only Metro Red line is included in this study, and it covers only a small portion of the area). For a sampled 4,000-rider case, there are about 150 potential metro users, and 5 of whom are matched with a metro usage (3.3%). When the rider-to-driver ratio is high (which means the rideshare service may be in shortage, or not broad enough to cover all areas), the algorithm tends to match more riders with metro services. Therefore, designing a proper proportion of rider/driver ratio would help the usage of metro transit.

For bike users, the situation is similar. The trend is approximately linear when the total number of participants increases. As the study designs bikesharing only for a transit feeder, it does not include bike-only usage for temporary travel within the downtown region. In the 4,000-rider case, 75 riders have either the origin or the destination located in the downtown area. We identify this group of people as potential bike users. Among 75 riders, a single rider was matched with a bike (1.4%). If

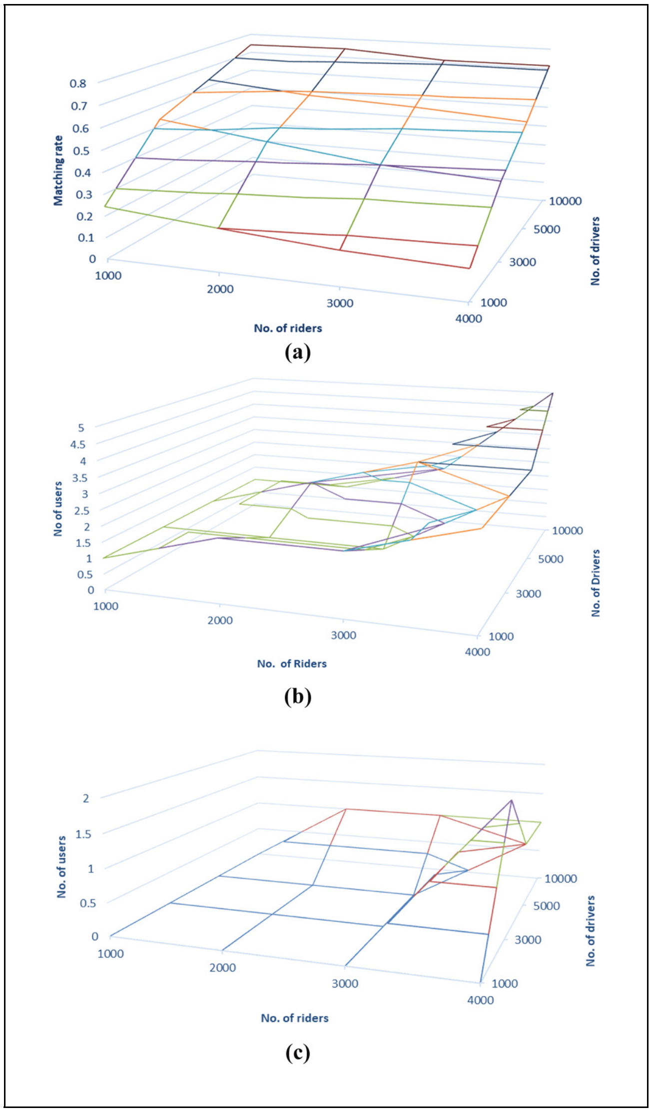


Figure 6. The results of the parametric study: (*a*) matching rate; (*b*) number of transit users according to the participants; (*c*) number of bike-sharing system users according to the participants.

we include bike-only travel, we will however see a higher bike usage rate in the downtown area.

Conclusion

This paper introduced schemes to study sustainable transportation alternatives that provide access to public transportation. Extending our earlier study (*1*), the paper contributes to the literature of ridesharing and transit feeder systems in the following ways.

First, we designed a transit feeder system that finds itineraries for riders using multiple sustainable travel modes: P2P ridesharing, bike-sharing, walk, and transit. For an efficient multi-modal model and easy data management, we introduced a super network concept that allocates each travel mode's network to a different layer that ensures each mode's operation is independent but at the same time accounts for transfers between modes. Riders are matched with different modes by moving across different mode layers. Green transportation modes in the system can be mutually beneficial for improving ridership, saving costs and increasing mobility.

Second, this paper proposes a scheme to achieve increased matching rates. Realizing that connecting a rider's origin to only one go-point (ridesharing/transit/bike station) can restrict the riders' mobility, a multiple-connector concept was proposed. These multiple connectors link the starting point to multiple go-points for each passenger, which contributes not only to increasing ride-matching rates for the system, but also to finding shorter travel-time itineraries for the riders.

The proposed system was tested in LA County. Target modes were the Metro Red line subway, Metro bike-sharing program in Downtown Los Angeles, walking, and P2P ridesharing. Geographical analysis for accessibility indicates that both P2P ridesharing and bike-sharing can enlarge the catchment area of the Red line stations. In the morning peak, bikes are more effective in Downtown LA towing to the existence of exclusive bike lanes, and because bikes are generally not affected by downtown street congestion. The parametric study indicates that our system generally improves matching rates when we compare it to our previous study on the rideshare system only being a feeder to transit (*1*).

The insights gained from our parametric study include the following. First, the matching rate is determined by the number of riders and drivers and the rider-to-driver ratio. When both the number of riders and drivers are small, the rate increases sharply at first and then remains relatively stable when the number of drivers is more than two times that of riders. When the number of drivers is a relatively large number (which means their routes are broad enough to cover whole areas), a further increase in the number of drivers would not improve the matching rate significantly. Besides, both P2P ridesharing and shared bikes are used as transit feeders by some riders. The usage would increase linearly when the availability of drivers and bikes increases.

One limitation, which is also a future research topic, is that this study only included travel demand from personal vehicle demands. In other words, this study focused on the rideshare matching potential from personal vehicle travel, and not the total travel demand (vehicle and transit). In future research, transit demand data could be included to study the potential improvements and mode shift. To reflect the actual travelers' behavior in the system, more elaborate behavior models, such as random utility models, should be implemented in our future research. Some sensitivity analysis could also be included in future research, so as to measure the effects of pricing, transfer and waiting time on riders' choice behavior.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: DN, DY, RJ, NM; data collection: DN, JY and SA; analysis and interpretation of results: DN, DY; draft manuscript preparation: DN, DY, RJ. All authors reviewed the results and approved the final version of the manuscript.

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