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SIMULATION ANALYSIS OF A DYNAMIC RIDESHARING MODEL

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ABSTRACT

A dynamic ridesharing service is a system that enables drivers and riders to arrange one-time shared rides, with sufficient convenience and flexibility to be used on a daily basis. The quality of a dynamic ridesharing service is critical for commuters who need to reach their end destination on time every day. To ensure satisfactory quality, the waiting times in a ridesharing service must be low. This paper describes a dynamic ridesharing model proposal for commuters living in a small community in the Barcelona metropolitan area. The proposal solves transport problems between the community and a communication hub served by trains and buses. A survey was sent to community residents to find out whether they would be interested in the idea and willing to participate in a pilot test. A simulation model was built to determine to most suitable type of dynamic ridesharing model given the limited numbers of responses received and the heterogeneous mobility patterns of drivers and riders in the community. Reasonable good results are obtained for the morning commute but improvements are needed for the return commute in the afternoon. Further work will be required to increase the number of drivers interested in the ridesharing service.

1 INTRODUCTION

Increasing suburban population densities and rising car use in cities are making traffic congestion a commonplace phenomenon in urban areas, causing air pollution and leading to a general waste of energy and people's time. One potential answer to this problem is public transportation, but high capital costs are generated by the demands of peak-hour services and services to sparsely populated areas, due to resource idleness during off-peak periods and the cost of reaching low-demand areas. Another solution would be to take advantage of levels of private vehicle ownership, which have risen even in countries with high fuel prices, good public transport systems and high population densities. However, while this may seem a very attractive option, it presents the same environmental and efficiency drawbacks as described above. This is where carpooling and dynamic ridesharing can come into play, moving the same number of people with fewer cars.

Carpooling systems (a non-dynamic service) are ideal for groups of people and/or neighbors who travel to a common workplace or area using a shared private vehicle. This method reduces each person's fuel and toll costs, as well as the stress of driving, and is a more environmentally friendly and sustainable transport solution, decreasing carbon emissions, traffic congestion and demand for parking spaces. For the system to work, the group needs to be stable and must operate according to a pre-arranged schedule, which brings a loss of flexibility, since everyone must be at the same location at the same time in order to make the return journey together. This has a potential impact on social dynamics, for instance by preventing group members from carrying out unplanned activities at the end of the working day.

The use of a dynamic ridesharing system (real-time ridesharing or single-trip ridesharing) solves the problem of low flexibility (Correia and Viegas 2005), easing the interaction between drivers and riders by enabling single-time ridesharing matches between people with similar departure times and destinations. Moreover, it provides sufficient convenience and flexibility to be used on a daily basis. The main advantage over a non-dynamic service is that a request for ridesharing can be made close to the time of travel, meaning that groups can quickly be formed between groups of drivers and riders able to meet at a convenient roadside location, for example by using an information technology-based ride-matching system with GPS support. This can also be considered as an alternative for areas that are not served by public transportation, where it would act as a transit feeder service.

Following the successful implementation of dynamic ridesharing systems in Norway, United States and France (Chan and Shaheen 2012; Hentmeg 2013; Sharemyfare 2013), drivers can make more effective use of the empty seats in their cars, thus lowering fuel consumption and reducing transportation costs. It also can serve to limit the volume of car traffic. The quality of a dynamic ridesharing service is critical for commuters, who usually need to reach their end destination at a given time every day. To ensure satisfactory quality, the waiting times in a ridesharing service must to be low.

This paper describes a dynamic ridesharing model proposal for commuters living in a small community in the Barcelona metropolitan area. The text is organized as follows: section 2 reviews the state of the art in methods to solve dynamic ridesharing problems; section 3 presents the specific problem considered and an analysis of the survey of potential users; section 4 presents the proposed simulation model; section 5 offers a discussion of the main social, legal and economic issues; and section 6 presents a series of conclusions and proposals for future research strategies.

2 STATE OF THE ART

A dynamic ridesharing service is a development of the classic carpooling service. It is a system that enables drivers and riders to make one-time ride matches close to their departure time, with sufficient convenience and flexibility to be used on a daily basis.

To understand the nature of the dynamic ridesharing problem is interesting to start with the description of the problem characteristics given in Agatz et al. (2011). These authors classify three types of models: (i) basic ridesharing; (ii) dynamic ridesharing, in which new rideshare drivers continuously enter and leave the system; and (iii) multi-model ridesharing, where instead of providing door-to-door transportation, the rideshare concept is integrated with other modes of transport, such as public transportation. For the basic ridesharing problem, Agatz et al. (2012) define the ridesharing variants shown in Table 1.

Table 1: Basic rideshare variants.

	Single rider	***Multiple riders***
Single driver	Matching of pairs of drivers and riders	Routing of drivers to pick up and deliver riders
Multiple drivers	Routing of riders to transfer between drivers	Routing of riders and drivers

Several studies have been carried out of each of these variants. To take the example of "single driver", Pentico (2007) proposed a theoretical approach to the assignment problem and Amey (2011) applied this approach to a Massachusetts Institute of Technology community.

For dynamic ridesharing, Agatz et al. (2011) addresses the problem of matching drivers and riders in a dynamic ridesharing system using optimization-based approaches. The aim of the study was to minimize the total system-wide vehicle miles incurred by system users, and their individual travel costs. The simulation was based on 2008 travel demand data from metropolitan Atlanta. The simulation results showed that the use of sophisticated optimization methods instead of simple greedy matching rules can substantially improve the performance of ridesharing systems.

Taking up the idea of using optimization to improve overall system performance, (Herbawi & Weber, 2012) presented a genetic and insertion heuristic algorithm to address the dynamic ride-matching problem with time windows in dynamic ridesharing. One of the problems they highlighted was the non-compliance of users. An interesting study of the same problem was also carried out by et al. (2000), who stated that the inherent uncertainty of the problem reduces the globally optimal solution value, questioning "*whether rigorously optimal solutions are useful in a dynamic setting*". Following on from this statement, several studies consider the use of agent-based systems, among them Winter and Nittel (2006), who show that short-range communications devices such as Bluetooth or Wi-Fi do not have an impact on the quality of the solution. Xing et al. (2009) considered a highly dynamic rideshare system with several characteristics, including smoking or non-smoking preferences and en-route matching of drivers and riders. They suggested that to make ridesharing an attractive alternative to public transportation methods, a critical volume of available drivers is needed. For the multi-model ridesharing model, Santos and Xavier (2013) presented a study of a dynamic ridesharing and taxi sharing problem with time windows. The authors proposed to solve the NP-hard problem with the aid of a heuristic implemented in a framework designed to help people find shared rides.

3 DESCRIPTION OF THE PROBLEM AND SURVEY ANALYSIS

Our study focuses on the multiple riders-single driver variant, examining a dynamic ridesharing model for commuters living in a small community called Begues travelling to and from a communication hub located 10 km from the community that is served by trains and buses. Begues is a middle-class community with a total population of approximately 6000. Transport links with the Barcelona metropolitan area are poor, as a result of which some two thousand private cars leave Begues every day to work, mainly in offices or universities. This study was conducted with the collaboration of the Council of Mobility and Transport of Begues.

A survey was posted on the local council website to find out about the mobility patterns and interests of local residents. The survey contained a series of questions that can be grouped as follows:

Interest in the proposal. Ninety-two per cent of respondents considered the proposed transportation model to be an attractive option. The remaining 8% gave several reasons for rejecting the idea: some had no interest in sharing a vehicle with strangers; others did not have Internet access from their cellphones; others did not fully understand how the model works. The survey was completed predominantly by people aged 18−21 (20%), 22-30 (10%), 31−40, (28%), and 41−50 (20%). These percentages indicate that there is greater interest among those age groups with mobility requirements. This survey was completed by almost an equal number of men and women. After age, the second most important variable is user profile: of the potential users, 29% would be drivers, 28% riders and 35% could fill either role. This suggests that there is a good balance between prospective drivers and riders, which is conducive to the successful implementation of the proposal.

Security. We presented a number of ideas to address potential security issues in the implementation of the proposal. Eighty-nine per cent of respondents stated that it is very important that only registered users have access to the service. Moreover, 82% thought that it would be a good idea for riders to keep logs of fellow passengers. A rating system for drivers and riders was supported by 78% of respondents. Some respondents were concerned about insurance cover in the event of an accident and related issues.

Mobility patterns. We asked respondents which neighborhood they live in. Figure 1 shows a map of the community. Sixty-four per cent of respondents live within the area circled in yellow. The remainder live in more sparsely populated neighborhoods within the brown contour. The figure also shows a regional road in dark blue and an internal commuting road used to enter/leave the town, in light blue. With respect to departure times, the majority of respondents (85%) leave for work between 6 a.m. and 9 a.m. The results are more varied for return times, which range mainly from 3 p.m. to 10 p.m. Ninety-five per cent of respondents pass by or commute via the communication hub in the nearby town of Gavà.

One important aspect highlighted by the survey responses is that most people do not have a fixed schedule. The daily departure and return times of individual respondents were usually subject to variations in the order of half an hour to two hours. This strong variability in the daily commuting times, particularly for the return journey, makes it very hard to achieve quasi-static matching of drivers and riders.

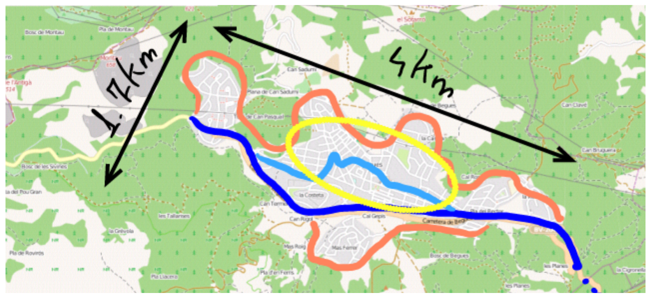

Figure 1: Target community area for the dynamic ridesharing study.

Questions for drivers. Most car owners have a private vehicle for several reasons: for their job, because of the comfort it provides, to save time, and for the scheduling flexibility it allows (as the bus timetable is somewhat limited). Nevertheless, 60% of the drivers would feel comfortable changing the way they travel to work. To determine the collecting capacity for the proposal, we asked prospective drivers how many spare seats are available for other riders: 32% drivers could offer 3 spaces and 22% 4 spaces. Drivers were also asked whether they thought that riders should contribute to the cost of the commute: 58% considered it important, 28% did not.

Questions for riders. This set of questions revealed the difficulties of commuting via public transport. Many have to travel by car with a family member of friend because of the low frequency of the local bus service. Pick-up points to collect riders were distributed in such a way as to facilitate mobility and to improve safety when getting in or out of the car. The potential riders were then asked what distance they would be willing to walk to a pick-up point. The next question concerned the waiting time potential riders considered acceptable at a pick-up point. The longest they would be prepared to wait was 10 minutes: 28% of potential riders said that they would wait 10 minutes and 38% said they would wait 5 minutes, which makes more than 50%. As with the drivers, the riders said that it would be appropriate to contribute to the cost of the commute (69% agreed with this option).

4 DYNAMIC RIDESHARING MODELS AND SIMULATION RESULTS

One of the key factors in the success of a dynamic ridesharing model for daily commuters is the reliability of the service. As the main performance indicators we chose the mean and maximum waiting times for a rider requesting a ride. The main hypothesis of the proposed model is that riders request a ride in real time; thus, a rider sends the request when he/she is ready to be collected at a pick-up point. Several ridesharing models can be implemented and analyzed in order to choose the most appropriate, taking into account the quality of service and the technical complexity:

- Model 1 is a point-to-point dynamic ridesharing system. The easiest approach is to establish one pick-up point in the community and another near the transportation hub in Gavà where cars will have to pass through on the way to their final destinations. The main disadvantage of this approach is that riders may need to walk as much as 2 km every day. Moreover, drivers may need to drive more than 3 km in the opposite direction to their desired route in order to pick-up riders. These, and a series of other reasons, make this an impractical solution (it should be considered, however, that if the quality of the waiting time performance indicator is insufficient, the results of alternative models will not be satisfactory either).

- Model 2 consists of multiple pick-up points along or near to the main mobility axis in Begues and one pick-up point at the communication hub. Each rider chooses the pick-up point closest to his/her neighborhood. Eight existing bus stops were chosen as pick-up points because they are evenly distributed along the main mobility axis. Drivers may be required to travel 1 km more than their normal route if they have to pick up a rider. Riders are assigned to cars using a "first-in-first-serve" policy, independently of the pick-up point.
- Model 3 consists of multiple pick-up points along the two main mobility axes. Additional pick-up points are located along the additional mobility axis leading to pick-up points for riders living in nearby homes. On average, riders are required to walk shorter distances. However, if we assume the constraint that drivers moving along one of the exit mobility axes will not pick up riders at points on the other mobility axis, the interarrival times for cars passing each pick-up point will be longer since the cars are distributed along both mobility axes. This approach requires a large number of cars to maintain the quality of the service. The model structure is the same as the structure of model 2. However, the results of model 3 have not been included in this paper since they are not satisfactory.

A complex IT platform is not needed for the application of these models because the pick-up points are fixed. Other models could be considered, such as picking up riders at their home address or at other requested points within the community. However, we have chosen a simple approach that does not alter the daily mobility patterns of the riders. It is questionable whether a more flexible model would be acceptable, due to the probable loss of the cost-benefit balance that is needed in order for the proposal to be accepted.

4.1 Model 1: Point-to-point dynamic ridesharing

Figure 3 shows a Colored Timed Petri Net (CTPN) of this nonrealistic model, upon the arrival of the driver at the single pick-up point. The driver picks up riders until the spare service capacity (color *sc*) is zero (transition T3) or there are no more riders waiting at the time point (transition T4).

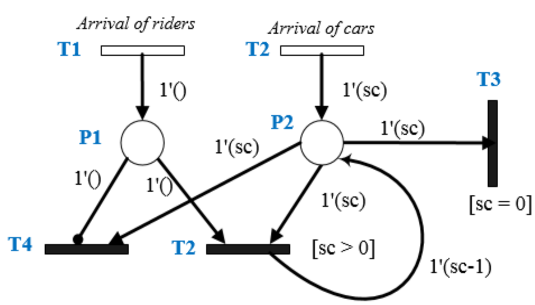

Figure 2: CTPN of the point-to-point dynamic ridesharing system.

Input data for the model is taken from the survey. The data available for each potential user is,

- The leaving time interval when exiting home and the returning time interval. Each rider o car follows a uniform distribution which upper and lower time values have been specified by the rider or driver in the survey
- The rider or driver role. Since 35% of the users could both, the driving or riding role, a probability of 0.5 is assigned to the driving role in these cases
- The number of the available seats if the citizen is a driver.

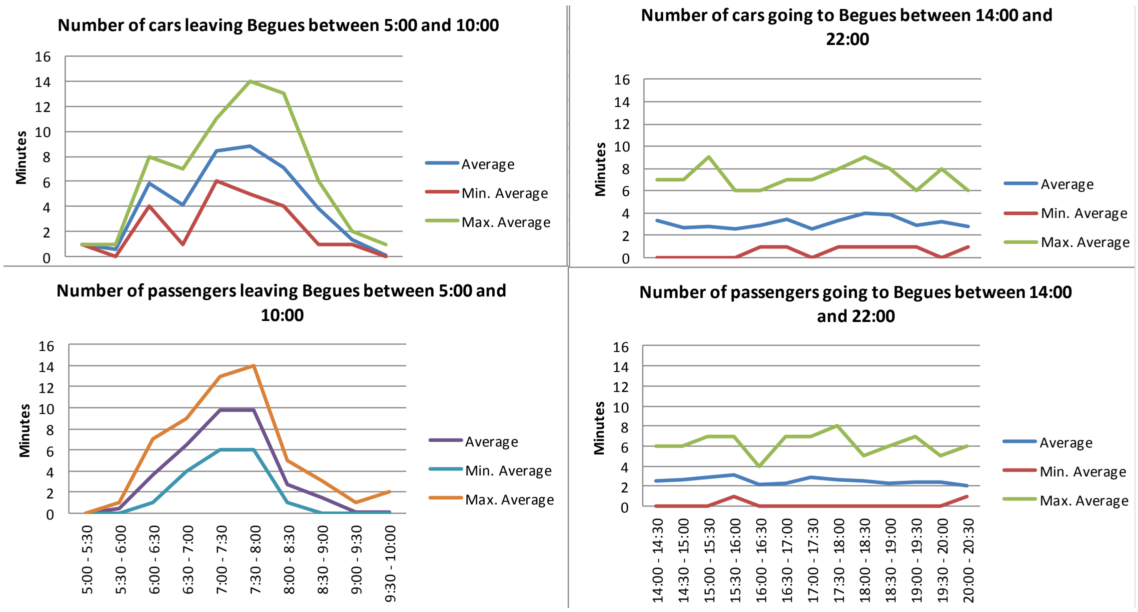

Figure 3: Point-to-point dynamic ridesharing simulation results.

The simulation results are shown in Figures 3 and 4. They are reasonably good from the morning commute out of the community, during the 6:30-8:30 rush hour, when the average waiting time is less than 5 minutes, although it can rise to 10 minutes on specific days (Figure 4). However, the results are poorer for the afternoon commute back to the community, when the average waiting time can rise to 40 minutes on a specific day for certain time periods. The simulation model could be extended to include the public bus service; this may help to reduce the waiting time for specific riders, but the overall results would remain largely unchanged because the bus only runs once per hour.

From a practical point of view, this ridesharing proposal for the journey between the community and the transportation hub is not feasible due to the low availability of drivers during the return commute in the afternoon. The journey from the commuting hub to the community is the critical aspect that causes the large number of car journeys in the daily commute. In the mornings, commuters can synchronize their departure with the local bus timetable. In the afternoons, however, it is difficult to synchronize arrival at the communication hub with the bus timetable, and most commuters would obviously prefer not to wait 45 minutes for the next bus in the middle of winter. Thus, the bus is usually chosen only by young, low-income residents.

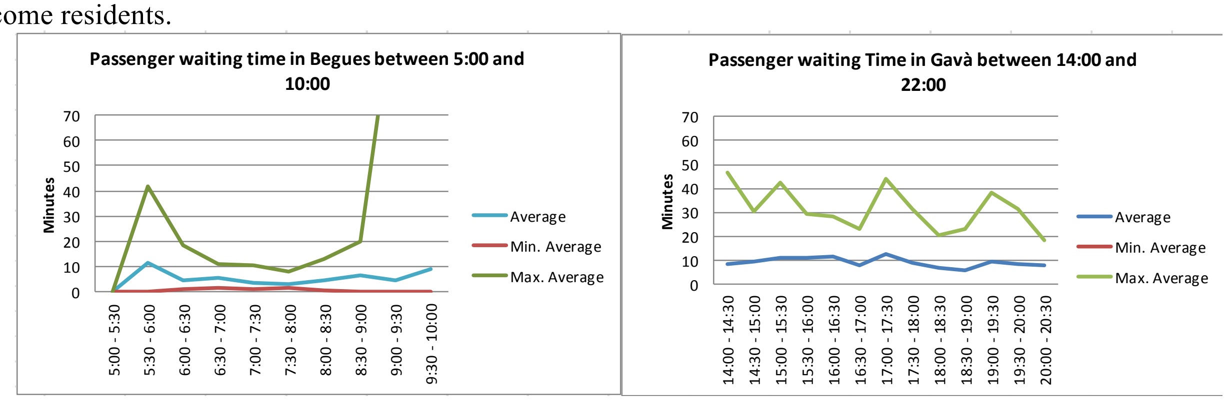

Figure 4: Point-to-point dynamic ridesharing simulation results.

4.2 Model 2: Multiple pick-up points along or near the main mobility axis

Although the results of model 2 are poor for the afternoon journey, it is interesting to evaluate their quality for the morning commute. The main assumptions are as follows:

- Drivers can extend their normal journey up to one kilometer if they have to pick up a rider. A driver will divert from his/her normal route only if there are requests at reachable pick-up points.
- When a driver signals his/her departure from home, a route and specific pick-up points is assigned statically. The route is not modified dynamically afterwards. However, new riders can be dynamically assigned if the pick-up point is on the assigned route.
- Riders wait for the assigned car, even though a car with free spaces passes early.

Cars chose the route and riders to pick-up trying to maximize the total current waiting time of the chosen riders, this selection problem is modeled as an optimization problem with the following sets,

P, set of pick-up points
R, set of waiting riders
PATHS, set of paths segments between network significant points
RP, rider to pick-up point assignment

the parameters,

d{PATHS}, driving distance between pick-up points
rwt{RP}, riders current waiting time
seats, number of available seats in the car
rd, driving distance across town using the normal exit route

the decision variables,

xd{PATHS}, 1 if the path segment is selected; 0 otherwise
xr{RP}, 1 if the rider is selected; 0 otherwise

the maximization function,

maximize $\sum_{(r,p)\in RP} xr_{r,p} rwt_{r,p}$

and the constraints,

$\sum_{(r,p)\in RP} xr_{r,p} \leq seats$, the number of selected riders has to be less or equal to the number of available seats

$(\sum_{(p1,p2)\in PATHS} xd_{p1,p2}) * 10 \geq \sum_{(r,p2)\in RP} xr_{r,p2} \quad \forall p2 \in P$, the number of selected riders has to be zero if a path to the pick-up point is not selected

$\sum_{(s,p)\in PATHS} xd_{s,p} = 1$, there must be a path leaving from starting node; node associated to the driver neighborhood

$\sum_{(p,x)\in PATHS} xd_{p,x} = 1$, there must be a path arriving to the end node, last node of the town street network

$\sum_{(p1,p3)\in PATHS} xd_{p1,p3} = \sum_{(p2,p1)\in PATHS} xd_{p2,p1} \ \forall p1 \in P - \{s,x\}$, there must be an input path and an output path for each selected pick-up point.

$\left(\sum_{(p1,p2)\in PATHS} d_{p1,p2} * xd_{p1,p2}\right) - rd \leq 1000$, the increment of driving distance with respect to the reference distance *rd* has to be less or equal than 1000 meters.

In addition to the data from model 1, the driver living neighborhood and the normal route through when crossing the town is also taken from the survey. The rider pick-up point it the one close to his neighborhood and the driver normal exit route is the one specified in the survey. Moreover, the driving time between significant streets network points are supposed to be deterministic and have been obtained by driving through the network. Figure 3 shows an informal CTPN of this model. The model colors are: *pp* (rider pick-up position); *sc* (driver spare service capacity); *nb* (driver neighborhood); *ci* (car identification number); *id* (car id assigned to the rider); *cp* (car current position); *np* (car next position); and *cr* (car route).

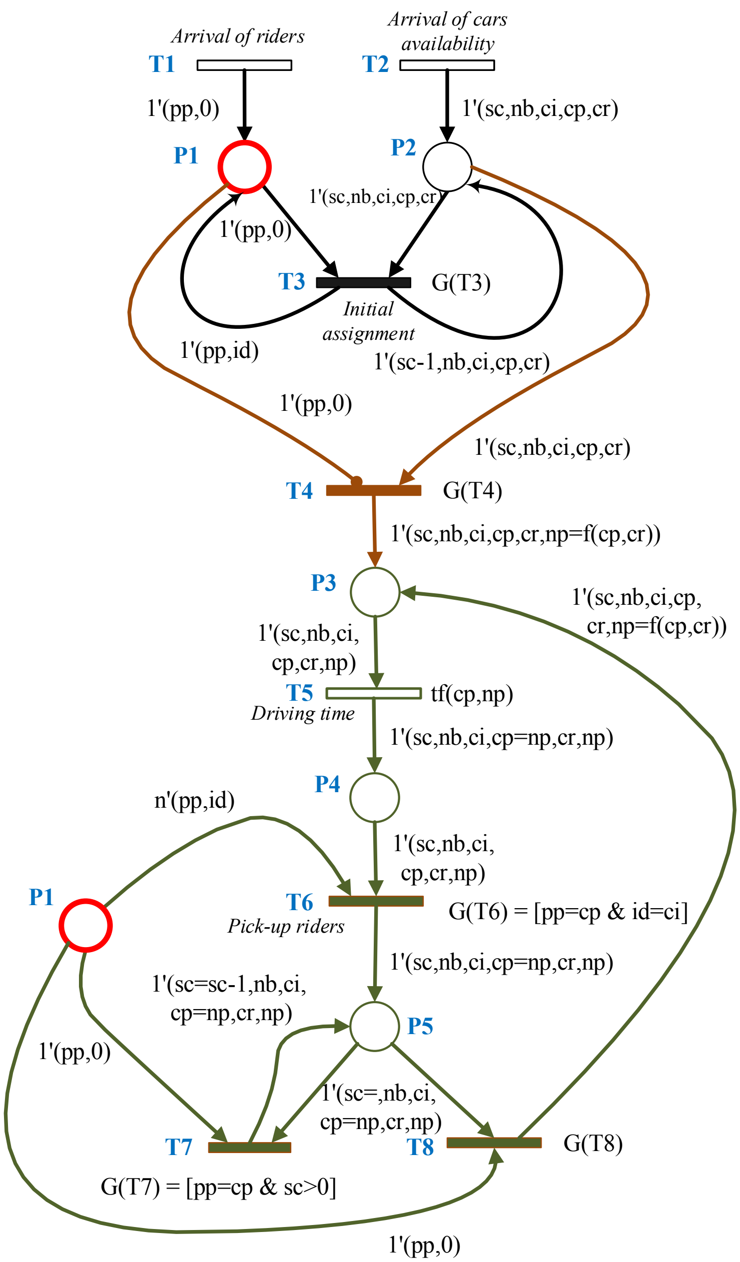

Figure 5: CTPN of several evenly distributed pick-up points.

The guard functions on the transitions are:

- G(T3) = [sc>0 & pp ∈ reachability(cp)], a rider is assigned to a car if its current spare service capacity is greater than 0 and the rider pick-up position is reachable from the driver current position.

Transition T3 statically assigns (before starting the route) riders to drivers using the optimization model described above.

- G(T4) = [sc=0 | ∀ pp, pp ∉ reachability(cp)], the assignment process finishes when there is no spare service capacity or the remaining riders are not reachable by the driver.
- G(T6) = [pp=cp & id=ci], upon reaching a pick-point along the route, the car will pick up the rider assigned to the car.
- G(T7) = [pp=cp & sc>0], additional riders can enter the car at the pick-up position if the car has spare service capacity.
- G(T8) = [sc=0 | ∀ pp, pp=cp], the car will move on to the next position if it has no spare service capacity or there are no riders at the pick-up point.

The simulation results are shown in Figure 6 for the morning rush period, from 6:30 to 8:30, since the results outside this interval are not satisfactory. The average waiting time, although slightly longer than in the previous model, it is still a relatively good result. The results are fairly similar since most potential drivers and drivers live in the same area. Moreover, riders living in nearby areas can be reached by the drivers. Even though the results are reasonably good, we question the acceptability of the waiting times, since 22% of the values are above than 10 minutes and the maximum waiting time is between 15 and 22 minutes, depending on the time period. We feel that these values are sufficiently low for daily commuting. Thus, as for the previous model, more drivers are needed to make the service a success.

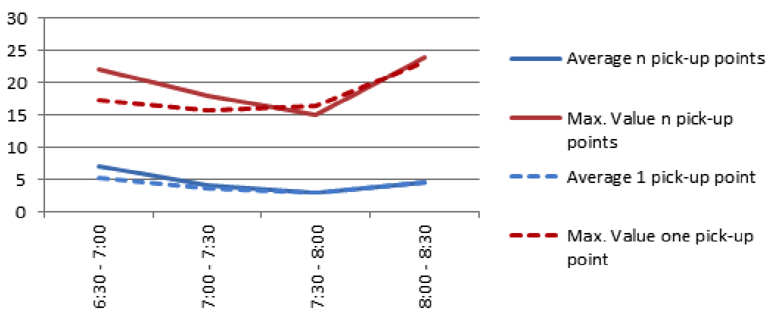

Figure 6: Single point versus multiple pick-up points (analysis of 30 one-day replications).

5 SOCIAL, LEGAL AND ECONOMIC ISSUES

The implementation of a dynamic ridesharing model for commuters poses what can be considered a chicken-or-egg dilemma: potential riders will not use the ridesharing service because there are not enough drivers, and potential drivers will not make the effort to sign up because there are no riders. The success of ridesharing services of this kind is also hampered by social and legal issues. Many people are wary of accepting a ride from someone they do not know, which makes the dynamic ridesharing experience harder to implement. One way to overcome this problem might be to a nonprofit association. Carpooling clubs are a means of involving members in a traditional and dynamic ride-matching system as they "manage the scale problem while building trust between members" (Correia and Viegas 2005). Certain legal aspects also need to be considered. For example, some months ago Uber launched its rideshare service in the most densely populated part of the Barcelona metropolitan area. The response from the Spanish taxi confederation was given after the Uber announcement: "*Uber is, to the best of our knowledge, a totally illegal business that incites the use of "pirate" transportation without any guarantee for the consumers as well as fomenting the black economy as none of those transactions are registered as economic activity or under administrative control [...] If no immediate correction measures are taken, we might be on the verge of an imminent nationwide protest.*" As explained at http://tech.eu/news/uber-drives-legal-obstacles-time-barcelona/, the problem that Uber faced in Barcelona is that its operations are clearly illegal in Spain. According to article 101 of the current

Spanish transportation legislation: “Private transportation is qualified as such if it is used for personal or domestic transportation needs of the owner or close relatives. [...] Under no circumstances, will the private driver receive any kind of direct or indirect remuneration except for food money or transportation costs.”

The problem is that ridesharing service companies are implementing a non-collaborative model with respect to traditional stakeholders (Figure 7) in an effort to secure a share in the market mostly covered by taxi cab companies, but without competing on a level playing field. Public authorities have reacted by barring such ridesharing initiatives elsewhere. A non-competing or collaborative ridesharing transportation cost model in which a win-win relationship is established between the ridesharing community and traditional stakeholders (public transportation system in Figure 7) is a guarantee of success. As straightforward as this may sound, it remains a complex challenge, but one that must be successfully addressed in order to reduce energy wastage, air pollution, congestion and transportation costs.

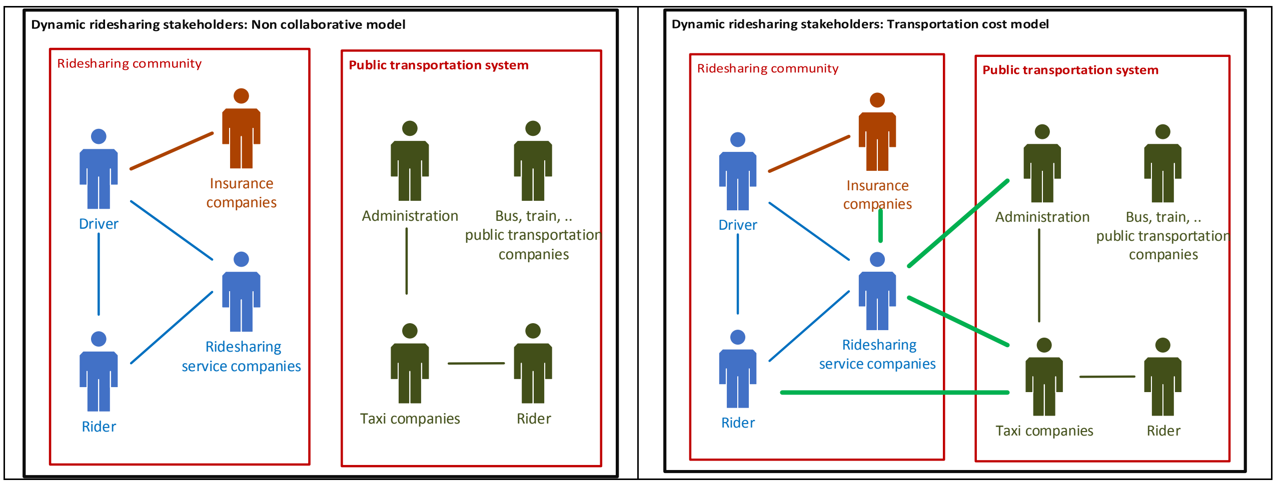

Figure 7: Stakeholders in dynamic ridesharing models: non-collaborative versus transportation cost model.

A simple example can be used to illustrate the collaborative service model. Approximately 2,000 cars leave Begues each working day and complete a return trip *of at least 20 km*. Just counting the 20 km for 5 days a week, 4 weeks a month, 11 months per year and average gas consumption of 6 liters/km, the minimum gas consumption per year scales to 0.5 million liters just for commuting due to this community alone. A 30% saving on gas through the successful adoption of a dynamic ridesharing model would lead to overall savings of 221 thousand euros per year, based on an estimated cost of 1.4 euros/liter of gas. The benefits to the stakeholders in this hypothetical example are as follows:

- Drivers: Lower gas bills, since riders contribute to the cost of the commute.
- Riders: No need to use their own cars. Taxis are not a viable alternative. Commuters cannot afford to pay 30 euros per day for a taxi plus 4 euros for public transport from the communication hub to their end destination.
- Local taxi cab drivers: Currently, taxis are used mainly for specific purposes but not for daily commuting. Taxis could be used in a collaborative dynamic ridesharing system to provide a backup service in the event of excessive waiting times.
- Bus and train transportation system: Increase the number of users moving though the commuting hub and using public transportation to reach their end destinations.
- Ridesharing service companies: A commission for each service provided.
- Administration: Reduced congestion and pollution. The increase in the number of users of public transport could alleviate the pressure on subsidized transportation networks.

6 CONCLUSIONS

We have presented a dynamic ridesharing model for commuters living in a small community in the Barcelona metropolitan area. Dynamic ridesharing could facilitate greater mobility and reduce transportation costs for many small and medium-sized communities in the Barcelona metropolitan area that are not served by the main transport corridors.

To acquire data for the study, a survey was sent to local residents to determine their interest in the model and identify potential users. Although responses were received from only 2.1% of the total population, the data were useful in defining different alternatives for modeling the problem. The resulting simulation studies have shown that additional efforts are needed to reach a critical mass of drivers leaving the community during the morning rush hour and returning in afternoon. This case study gives an interesting perspective on the difficulties arising in solving dynamic ridesharing problems of this kind. Moreover, the experiment was a useful means of testing the degree of acceptance of a proposed ridesharing solution and the technology-penetration rate of the proposed system for the management of the solution. Simulation has a role to play in designing a collaborative transportation cost model for a ridesharing service. In addition to the support of local residents and public authorities, success depends on achieving the critical mass needed to compensate for the cost of the backup taxi service in the event of excessive waiting times. Simulation could aid decision-making with regard to ridesharing service costs as a function of the number of riders, the number of drivers and the waiting time threshold in order to cover the expense of the taxi backup service, compensate riders for the cost of the commute, and guarantee a commission for the ridesharing company that manages the service.

Given the increasing scarcity of resources and the ecological stress to which our planet is subjected, significant efforts are needed to optimize the use of available resources. It is the responsibility of all stakeholders to agree to a legal framework that will allow for the fast introduction of ridesharing models.

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