Transport Commons: A community based public transport system

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Abstract— **In this paper we present a generalization of the concept of car-pooling for a public transport system, in which members of the community donate their trips to the 'transport commons'. The proposed system will then match the passengers to vehicles based on a range of criteria, including trip times, personal choices and economic incentives. We develop an analytical model to determine the probability of obtaining a ride from the transport commons in a worst-case scenario. The results of the analysis as well as simulation study demonstrate that the transport commons can provide a practical basis for a dependable public transport service.**

Index Terms— **Intelligent Transport Systems, Public Transportation Systems, Vehicular Ad hoc Networks**

I. INTRODUCTION

Most modern cities face significant traffic congestion problems with all the associated costs, such as environmental damage, psychological stress and economic loss. There is little doubt that effective provision and use of public transport systems can reduce these externalities. However, the experience of past several decades demonstrates that large-scale adoption of this mode of transport faces major hurdles. This is often despite increased efforts in modernizing public transport systems by introducing new and smarter technology, geographical information systems and coordination among various modes of transport (e.g., [1], [2], and [3]).

In Australia, for example, the number of private vehicles grew by an average of 4.2% during 1960 – 2010 period, much faster than the population growth (Fig. 1) and the usage of public transport lagged behind the personal cars by an increasing margin (Fig. 2). This trend is likely to be repeated in many emerging economies.

Ironically, with the soaring number of cars on our roads, there is also a corresponding increase in the capacity to carry more passengers in the form of empty seats in these vehicles. Our congested cities, therefore, are faced with a paradoxical situation: *We are experiencing shortage of reliable transport services while a massive over-supply of transportation capacity is choking our streets*.

For many drivers, the marginal cost of carrying an extra passenger would be small or zero, and they would be willing to offer a ride to others provided there were a system that could coordinate all the trips, guarantee safety and eliminate potential awkward social interactions that may emerge. Many cities have been supporting car-pooling by providing designated lanes or parking incentives and there are many car-pooling websites that attempt to help with coordination of trips amongst the users. Nevertheless, the impact of traditional car-pooling on traffic congestion has been insignificant, primarily because successful car-pooling requires serendipity, negotiation and coordination among people and a certain degree of trust.

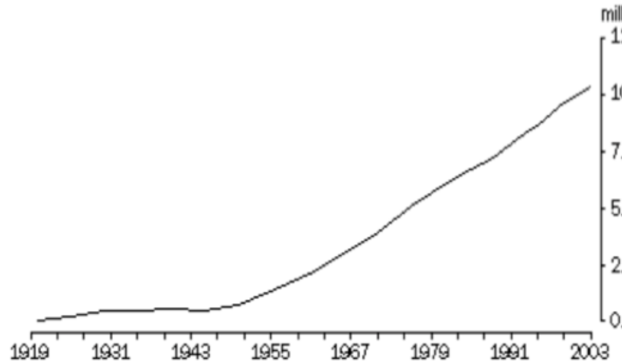

Fig. 1: Number of registered cars in Australia [4]

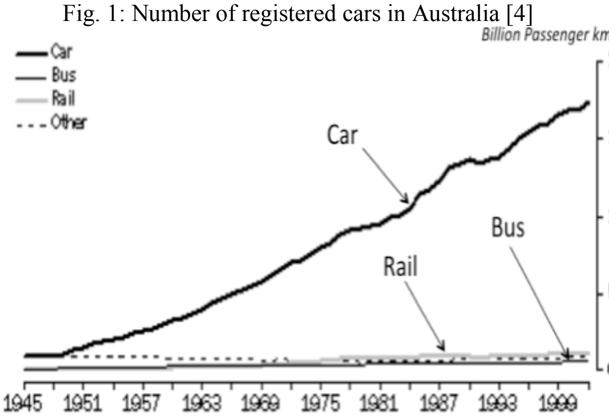

Fig. 2: Urban passenger transport usage in Australia [5]

In this paper, we consider a generalization of the concept of car-pooling at large-scale to tap into the underutilized transportation resources of the community. We now have all the necessary technological ingredients to create and properly *manage* what we refer to as the 'transport commons'. These ingredients include: affordable devices that can run location-based services for passengers and vehicles; a reliable vehicular ad hoc network (VANET) augmented with a ubiquitous wireless backbone (3G or

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4G); a generalization of the concept of social networking applied to spatially distributed users; and cloud-based services for calculation and coordination of routes.

Early signs of such a service are already apparent in several efforts to use smart phones and location-based services to facilitate transport sharing (for example, [6]). It will be only a matter of time when these concepts create a revolution in the way that we think about public transport services. To our knowledge, the transport commons at the scale described in this paper has not appeared before. Therefore, we present a brief description of the system and consider some of the key issues with respect to provision and dependability of this service. We have developed a prototype of the complete system and details of its components will be deferred to future publications.

The rest of this paper is organized as follows. Section II presents a brief description of how a public transport service based on the transport commons concept may be implemented. Section III develops an analytical model for the probability of obtaining a successful ride from the transport commons. Section IV presents simulations results and finally Section V providers the concluding remarks.

II. Description of the Transport Commons

The ‘commons’ refer to any resource that is collectively owned or shared by the community. In the past, these were typically natural resources, such as water supply of a village, fisheries, grazing grounds or forests. Today, we also have artificial commons such as works of art or software. Because our economic incentives are based on private ownership, humanity has always had difficulty with the management of commons, as exemplified by Hardin’s “Tragedy of Commons” [7]. Nevertheless, modern economic studies show that with suitable institutions for effective management, the commons can be a source of substantial benefit to the society [8].

With current technology, it is now possible to create a transport commons management entity (TCM) that is accountable for safe operation of the system, able to enforce rules, moderate supply and demand, incentivize the right behavior and weed out perverse incentives. TCM may be private and/or government owned.

People can use the transport commons as *passengers* or contribute to it as *drivers*. Of course, a given individual may be a passenger at one instance and a driver at some other time. Both passengers and drivers must register with the TCM, which may involve some procedures to ensure their good standing and suitability. Note that the ownership of vehicles remains with the drivers. The drivers donate any ‘trip’ that they desire to the transport commons. We now describe the operation of the transport commons from the perspective of passengers and drivers.

Consider a passenger who intends to use the transport commons to get to work in the morning. The screen shots of two phases of the *TCM passenger app* running on the passenger mobile device are shown in Fig. 3. The picture on left presents the options that the TCM can offer the passenger. These options can include an integrated view of traditional public transport services and their timetable. If the passenger selects the transport commons option, the screen shot on the right may provide him/her with more detailed choices about the path of travel, the pick up point, the estimated arrival time at the destination, and the cost of the trip (if any). By choosing an offered path, the passenger is assigned to the chosen vehicle and the respective driver would be informed about the pick up location. The passenger can then make way to the pick up point and a handshake between the TCM apps on his/her mobile and the driver’s device will confirm the right selection.

Fig. 3: Screen shots of the passenger app

On the other hand, a driver who is registered with TCM can elect to donate any trip to the transport commons, for example, while going to work in the morning. A screen shot of the *TCM driver app* running on a suitable device in the vehicle is shown in Fig. 4. During this trip, the driver app will use the device to establish a VANET and communicate with other transport commons vehicles as well as the TCM servers. The information gathered is used to calculate the expected delay incurred in choosing various paths and also suggest suitable passengers to the driver. In the example

Fig. 4: Screen shot of the driver app

shown in Fig. 4 two alternate paths are suggested to the driver. After the driver chooses his/her desired path, he/she is expected to follow the designated path to completion.

A. Economic and social considerations

By donating a trip to the transport commons, drivers will provide a community service and also enjoy lower congestion levels on the roads. They may also receive some financial benefits. For example, the cost of the trip may be tax deductible and/or the driver may receive a share of payments collected from the passengers.

The economics of the transport commons can be designed to provide incentives for drivers and passengers to adjust supply and demand. For example, a driver may be informed that there are many empty vehicles on the road today and it is better to consider becoming a passenger.

The drivers and passengers can also exercise some choice in the type of trip companion they will accept using social networking techniques. Passengers may also be able to 'rate' a driver to help others with their choices.

B. System Architecture

Fig. 5 shows the overview of the system architecture for this service. The TCM road status server collects various information, such as vehicle locations, their average speed and congestion levels on the road to aid with the routing

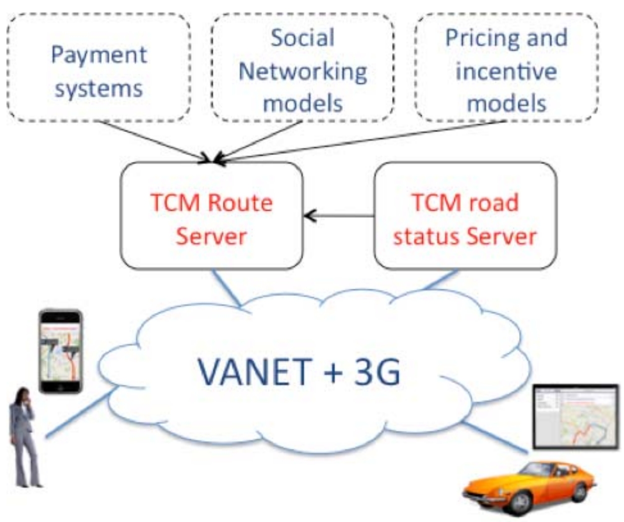

Fig. 5: Overview of the system architecture

and also estimation of trip times. The TCM route server performs the appropriate route selection and assigning of passengers to vehicles based on this information and possibly other considerations, such as pricing, social networking options and so forth. These additional functions (shown as boxes with dashed line) are not currently implemented in our prototype.

III. Analytical Model

A key metric that determines suitability of using the transport commons is *service dependability*. A major contributor to service dependability is *the probability that passengers find suitable rides* to their destinations. We denote this probability as p_s and are interested to determine the important factors that influence this probability.

Let us consider a simplified model of a square city as shown in Fig. 6, where there is a road network in the form of a regular grid. There are NxN intersection points in this city. We use these intersection points as the vertices of the road graph, i.e., places where new cars enter or leave the road network and passengers are picked up or dropped off. We assume that the arrival and departure of vehicles and passengers are uniformly distributed among the intersection points.

With respect to routes that vehicles adopt to reach their destination, we assume that traffic management at each intersection favors those vehicles that go straight over the turning vehicles. Consequently, to go from point b to e, the driver will use the two sides of the right-angled triangle as opposed to the hypotenuse (Fig. 6). This means that for each trip, there are two possible paths shown as solid and dashed lines in the Fig. Given the symmetry, the analysis of both paths will be similar.

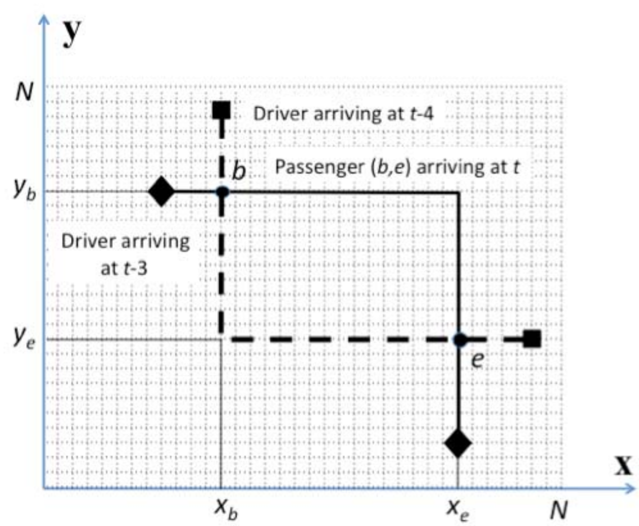

Fig. 6: A city with regular grid road network

Define a *unit of time* as the time that takes for a vehicle to travel from one intersection point to the next. Using this unit, we divide the peak traffic period into a number of unit duration intervals. At a time interval t, denote the arrival rate of new vehicles whose drivers have donated their trip to the transport commons as $\lambda(t)$. We assume that the arrival of vehicles is uniformly distributed *in time* during the peak period, i.e., $\lambda(t) = \lambda$ for all intervals t.

We also need to consider the willingness of passengers to wait. Assume that passengers are only prepared to wait *one unit of time* as defined above.

Consider now a passenger who arrives during the time interval t at the intersection b with coordinates (x_b, y_b) and intends to travel to point e with coordinates (x_e, y_e). Let s be a random variable representing the number vehicles that have a *compatible* path with this passenger, that is, those vehicles that can pick up the passenger at b within the constraints of the waiting time and drop off the passenger at e without altering their own path. Clearly, s can only take non-negative integer values. We can model the arrival of statistically independent vehicles as a Bernoulli trial, where 'success' means having a compatible path with the passenger. Therefore, s will have a binomial distribution with parameters (n, p), where n is the number of trials and p is the probability of success for each trial. We now intend to derive these parameters for our model. Let us first consider path 1 (solid line in the Fig. 6).

With respect to time interval t, the number of vehicles that enter the road network during this time interval is λ. The probability of 'success' can be calculated by noting that only a subset of vehicles would be eligible to provide a ride to this passenger. This subset includes all the vehicles that their entering points are (x_b-1, y_b) or (x_b, y_b), AND they have chosen path 1 for their journey AND their destination points are anywhere between (x_e, y_e) and (x_e, 0). There are a total of $2y_e$ of such routes, each with the probability of N^{-4}. However, assuming that each vehicle has an equal chance of choosing between the two available paths, only half of the vehicles will follow this path. Hence, if we define a random variable s_t as the number of suitable rides for this passenger from the vehicles arriving at time t, this random variable will have a Binomial distribution with the following parameters:

$$s_t \sim B(\lambda, \frac{y_e}{N^4})$$

What about the vehicles that are already on the road? There are λ vehicles that entered the system at t – 1. Among these, only those that entered at (x_b-2, y_b) or (x_b-1, y_b), AND chose path 1 AND with the same destination possibilities as before are able to pick up this passenger. This is a shifted pattern of arrivals by one compared to the vehicles arriving at t. Hence, we obtain the same Binomial distribution for this case:

$$s_{t-1} \sim B(\lambda, \frac{y_e}{N^4})$$

Continuing in this fashion for t – 2, t – 3, … we will eventually reach the city boundary (assuming that the duration of peak period is long enough). There will be x_b -1 of such random variables each with an identical distribution as specified above.

We also have to consider vehicles arriving in the future. In this case, only the interval t+1 would be relevant and the arrival point of such a vehicle must be (x_b, y_b) AND must choose path 1 AND with the same destination choices.

$$s_{t+1} \sim B(\frac{\lambda}{2}, \frac{y_e}{N^4})$$

Hence, random variable s_1, representing the number of compatible rides using path 1 will be the sum of these random variables. Given that all these Binomial distributions have the same probability of success and these random variables are independent, the distribution of s_1 will be as follows:

$$s_1 \sim B(\lambda(x_b + \frac{1}{2}), \frac{y_e}{N^4})$$

Similarly, the number of compatible rides using the second path (dashed line in Fig. 6) can be derived as s_2. In this case, we need to replace x_b by $N - y_b$ and y_e by $N - x_e$, which results in the following:

$$s_2 \sim B(\lambda(N - y_b + \frac{1}{2}), \frac{N - x_e}{N^4})$$

The desired random variable s is the sum of these two:

$$s = s_1 + s_2$$

Given that all x and y random variables have identical and independent uniform distributions with the mean of $N/2$, and the mean value of Binomial distribution for large n and small p is np, then the expected value of s for all passengers, denoted by μ will be:

$$\mu = \frac{\lambda(N+1)}{2N^3} \approx \frac{\lambda}{2N^2} \qquad (1)$$

In the above expression, N^2 is a measure of the area of the city *in units of distance that corresponds to the acceptable waiting time of passengers*.

Using Poisson approximation of the Binomial distribution, which would be reasonable for this problem (large n and small p), we obtain the distribution of mean number of successful rides for passengers as:

$$P(s) = e^{-\mu} \frac{\mu^s}{s!}$$

From the above, we can see that, on average, the probability of finding no suitable ride is:

$$P(s=0) = e^{-\mu}$$

Hence, the desired probability of finding a successful ride will be:

$$p_s = 1 - e^{-\mu}, \text{ where } \mu \approx \frac{\lambda}{2N^2} \qquad (2)$$

For example, consider a city roughly the size of Sydney (30 x 30 km) with 1M vehicles arriving on roads during the peak period. Let the total duration of peak period be 100 minutes and 10% of drivers to have donated their trips to the transport commons. Assume a grid size of 1x1 km^2 corresponding to waiting time of around 1-2 minutes for typical city speeds. In this case p_s would be approximately 43%. With 20% trip donations, this is raised to almost 70%.

A. Assumptions and discussion

The assumption of total independence and uniform distribution of destinations is probably a worst-case scenario. On the other extreme, consider a situation when everyone is travelling to a single destination, such as the centre of city. Using the same steps as before we can derive the expected number of successful rides for this case as:

$$\mu = \frac{\lambda(N+1)}{N^2} \approx \frac{\lambda}{N}$$

In this case, even if 1% of trips were donated to the transport commons, the probability of success would have been around 97%, and with 3%, the probability would be almost 100%. (Note, however, that the accuracy of our approximations is diminished for these estimates.) The real world situation is likely to be somewhere between these two extremes.

In the above derivation, we assumed that the passengers are willing to wait at most one time interval. We can use the same procedure to derive the probability of success if the waiting time was 2 or more. We leave the formal derivation for the future but will present some results on the impact of waiting time in the next section.

The above derivation did not impose any constraints on the number of passengers per vehicle. As the proportion of passengers to drivers increases, there will come a time when the probability of success is reduced due to this capacity limit. Nevertheless, assuming a capacity limit of 2 or 3 passengers per vehicle, the transport commons can provide a valuable service to a large number of residents with almost no infrastructure investment. In the above example, 20% of drivers could carry in excess of 250K passengers during the peak period.

IV. Simulation Results

To verify the analysis and explore other situations, we have developed a simulation of 30x30 size grid city as described in the previous Section. In Fig. 7, the probability of success is plotted against a range of arrival rates from $\lambda = 100$ to $\lambda = 1800$, which based on equation (1) corresponds to $\mu = [0.05, 1.0]$. As can be seen, the analytical model closely matches the simulation results but somewhat overestimates the probability of success. This discrepancy may be because the analysis considers a very long peak period with many vehicles already on the road upon arrival of a passenger.

Fig. 8 shows the cumulative distribution of success if the passengers were willing to wait. As can be seen for $\mu = 1$ almost all passengers will find a ride within 20 waiting periods.

Fig. 9 shows a scenario where passengers and vehicles are equally likely to choose one of five possible destinations representing major business or commercial centers. The improvement of the probability of success in comparison with Fig. 7 is substantial.

V. Conclusions

In this paper we introduced the concept of transport commons and described a possible system architecture for its implementation. We developed an analytical model to determine the probability of obtaining a ride from the transport commons by passengers. The results of the analysis as well as simulation study, demonstrate that transport commons is capable of providing a practical base for a dependable public transport service.

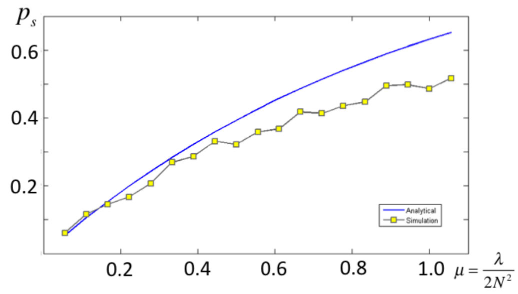

Fig. 7: Probability of success as a function of μ

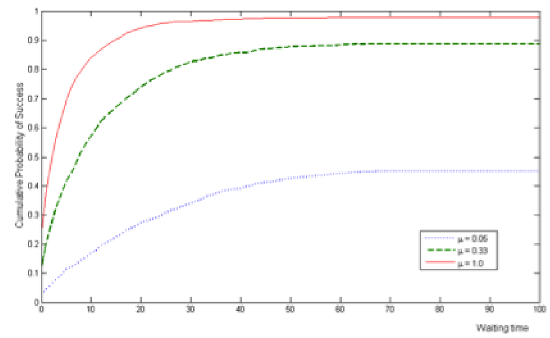

Fig. 8: Impact of waiting time on probability of success

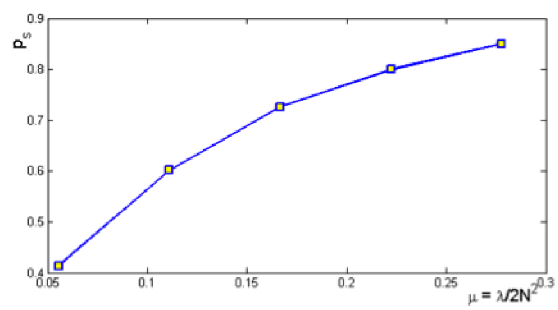

Fig. 9: Probability of success with five destinations

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