A Framework For Modelling the Design and Operation of Shared Vehicles Systems

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GENERAL BACKGROUND

Three major system innovations have transformed transportation in the past two centuries with profound and far-reaching impacts (Shaheen, 1999). First came the widespread adoption of interurban rail in the mid 1800s, several decades later came the introduction of electric urban rail, and then automobiles in the early 1900s. Railroads transformed the nature of business, electric-rail transformed collection of neighborhoods into metropolitan regions, and finally the automobile transformed lifestyle with maximum comfort and convenience in personal mobility. These innovations not only shaped transportation but also much more of our economy and society (Shaheen, 1999).

In the modern world of rapid change, it is remarkable how profoundly the motor vehicle has revolutionized society, and economy (Shaheen, 1999). Providing large mobility benefits, private automobiles have become deeply entrenched, continuing to increase their share of travel, even in countries with high fuel and vehicle taxes, dense land use pattern, and high quality transit services. Indeed, private vehicles now account for about 80 percent of all motorized passenger travel in virtually all OECD (Organization for Economic Cooperation and Development) countries (Shaheen et al, 1998). This sweeping transformation of travel from collective conveyance to private vehicle generates large benefit on mobility and flexibility but also large costs including higher energy consumption, severe congestion, air pollution, noise pollution, accident, and other related impacts (Shaheen, et al, 1998). Public space in cities is increasingly dominated by cars, both in moving and parked, which are preventing other activities that are the lifeblood of the city from taking place. These spatial problems cannot really be solved by technical fixes (Shaheen, et al, 1998).

Shaheen, et al (1999), in their paper mentioned that transportation services and activities could be conducted more efficiently. But they are not, information about alternative modes and services is not well matched to travelers' needs, public transit is either unavailable or inconvenient, and private vehicles are not the economic match to all mobility needs. In order to encourage a change, a 'new form of urban mobility' called *carsharing* or *shared vehicle system* has recently evolved in many cities in Europe, North America, and around the world (Bernard and Collins, 1998).

SHARED VEHICLE SYSTEMS: DIFFERENT FORMS AND CONCEPTS

The Conventional Carsharing Concept

The conventional carsharing concept originated in Europe about twenty years ago (Barth and Shaheen 2002). It is based on the premise that individuals/households do not need to own or lease cars on a long term basis in order to maintain access to goods, services, jobs, etc., thereby allowing individuals to more freely make transportation mode choice decisions (Cousins, 1998). Members of the CSO can reserve the vehicles in advance; on the actual date and time of the rental, the user gains access to the vehicle, carries out their trip, then returns the vehicle back to the same location (station) they originally accessed the vehicle from (Barth and Shaheen, 2002). This kind of trip is known as "two-way" or "round" trip and the system known as *round trip shared vehicle system* (RTSVS). Vrtucar, Ottawa, ON, Canada; Car Share Co-op, Victoria, BC, Canada; Flexcar, Washington, DC, USA are the examples of conventional or co-op type neighborhood carsharing or shared vehicle systems.

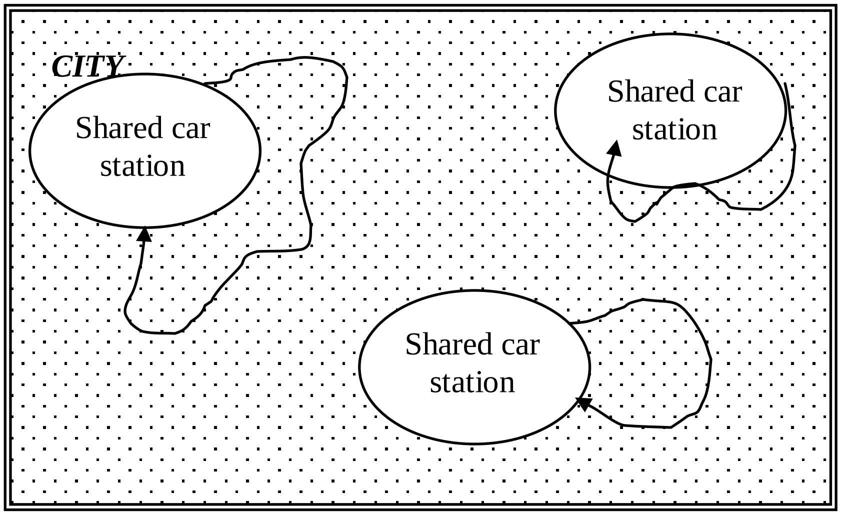

Figure 1 Conventional carsharing model (adapted from Barth and Shaheen, 2002)

The Station Car Concept

The station car concept is another new form of shared vehicle urban mobility system (Bernard and Nerenberg, 1998). Station cars are normally electric vehicles (EVs) driven to and from mass transit stations by transit riders as shown in Figure 2. While away from the transit station, they can be used for any type of short trip (Bernard et al, 1998, 1999). Therefore, by definition, station car system is a form of short-term-auto-rental (STAR) system similar to conventional carsharing system but usually consists of multiple stations. The concept of station car system originated in the United States and some programs have been implemented in Europe (Barth and Shaheen, 2002). CarLink I, and CarLink II of the University of California at Davis, USA, are smart intelligent station car type shared vehicle systems (Shaheen, et al., 1998, 1999).

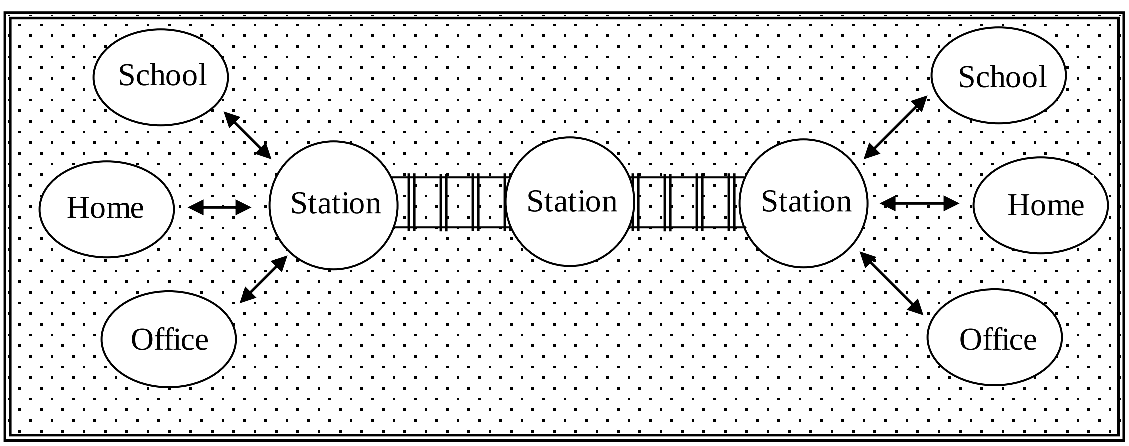

Figure 2 Station car model (adapted from Barth and Shaheen, 2002)

According to the National Station Car Association (NSCA), USA, when fully implemented, station car system will become a mobility system, as ubiquitous as a utility, changing the transportation paradigm of many metropolitan area households (Bernard and Nerenberg, NSCA, 1998). Each mobility system will be designed to support the specific transportation needs of each community.

Multiple Station Shared Vehicle System Concept

It has been envisioned that the ultimate development or future matured form of the carsharing or shared vehicle system is the one in which the cars are used between stations, major activity centers, where the system consists of more than two stations and called multiple station shared vehicle system (MSSVS) as shown in Figure 3. Therefore, in an MSSVS, a car can be taken from one station/depot and returned to the same or another station (Barth and Shaheen, 2002). Hence the system will experience both one-way and round trips. The underlying concept of vehicle use, fleet management, and usage cost is similar to conventional carsharing system.

Most of the carsharing services, including station cars, are priced in similar way (Katzev, Richard, 1999). The subscribers or members pay a monthly/annual subscription to the host CSO, and a charge for each trip by hour and/or distance (Cousins, S.H., 1998). This means that all the fixed costs of car ownership and use are transformed to variable or perceived costs. The mobility service providers are usually responsible for parking, maintenance, licensing, insurance, and other infrastructure (i.e., charging facilities, ITS technologies) costs (Bernard and Collins, 1999).

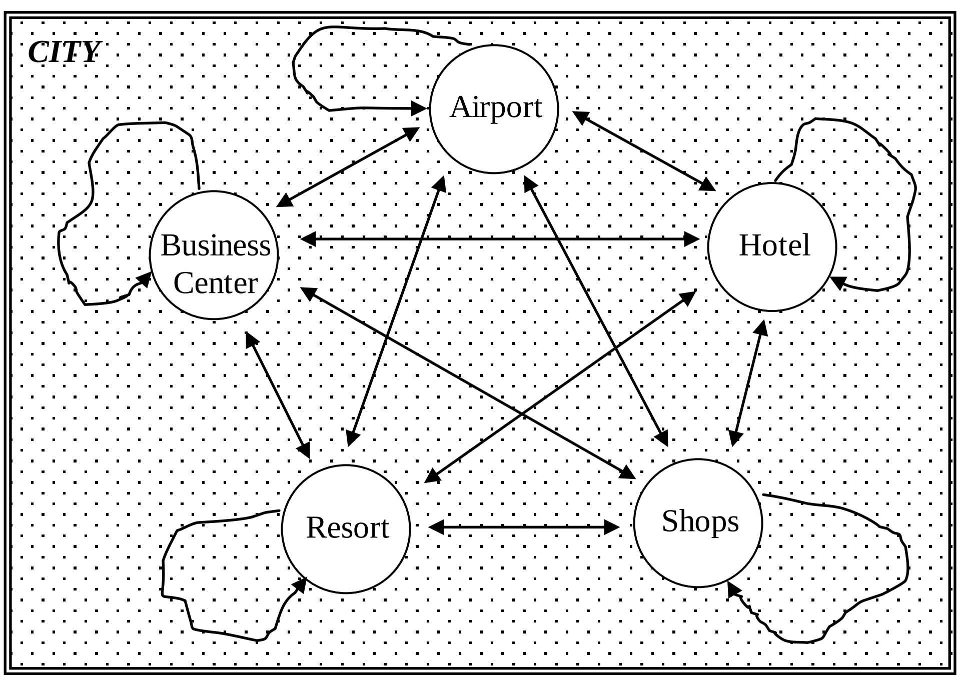

Figure 3 Multiple station shared vehicle system model (adapted from Barth and Shaheen, 2002)

Shared Vehicle Systems Operations

From the definition and classification of shared vehicle systems in the previous sections, it is observed that three models of such system are presently in operation. The three classes, identified and defined in the previous sections, include; 1) conventional carsharing model, 2) station car model, and 3) multiple station shared vehicle system model. The degree of complexity of the operations of these three different forms of shared vehicle systems is not same. Review of the literature shows that the operations of shared vehicle systems could be best characterized by the following system components:

1. Trip registration procedure,
2. Vehicle access procedure,
3. User trip procedure (if applicable), and
4. Vehicle relocation procedure (if applicable).

In conventional carsharing system, the service providing organization owns fleets of vehicles that their user pool can access throughout the day. Vehicles are placed in neighborhoods, apartment buildings, etc. A user either reserves a vehicle in advance or simply walks up to an available vehicle. Reservations are generally made by telephone to a system control center or through Internet (Cousins, S.H., 1998). The keys are typically obtained through a *common lock box*, and then the vehicle can be used for a period of time as set by the CSO. At the end of the trip, the vehicle is returned to the original station and hence the trips are round trips, and the mileage is recorded.

The second form of carsharing system is the station car as shown in Figure 1.2. In this case, users can access station cars at both ends of their commuting route(s). At each end, a car could be used for trips throughout the day. For registration and vehicle access, various types of techniques are presently in use, ranging from access to key through *common lock-box* to *smartcard* technology (Shaheen, 1999). Although the operation of station car system is similar to that of conventional carsharing system, all four system operation components are present in the station car operations.

The ultimate form of shared vehicle system is the multiple station shared vehicle system (Barth and Shaheen, 2002). In this form of shared vehicle system, vehicles are used among multiple stations to go from one activity center to another. In this form of shared vehicle system, the trips are more likely to be oneway each time (Barth and Todd, 1999). Because there are many more oneway trips, in a multiple station scenario the number of vehicles can quickly become disproportionately distributed among the stations with respect to the station demand at a particular time of the day (Barth and Todd, 1999).

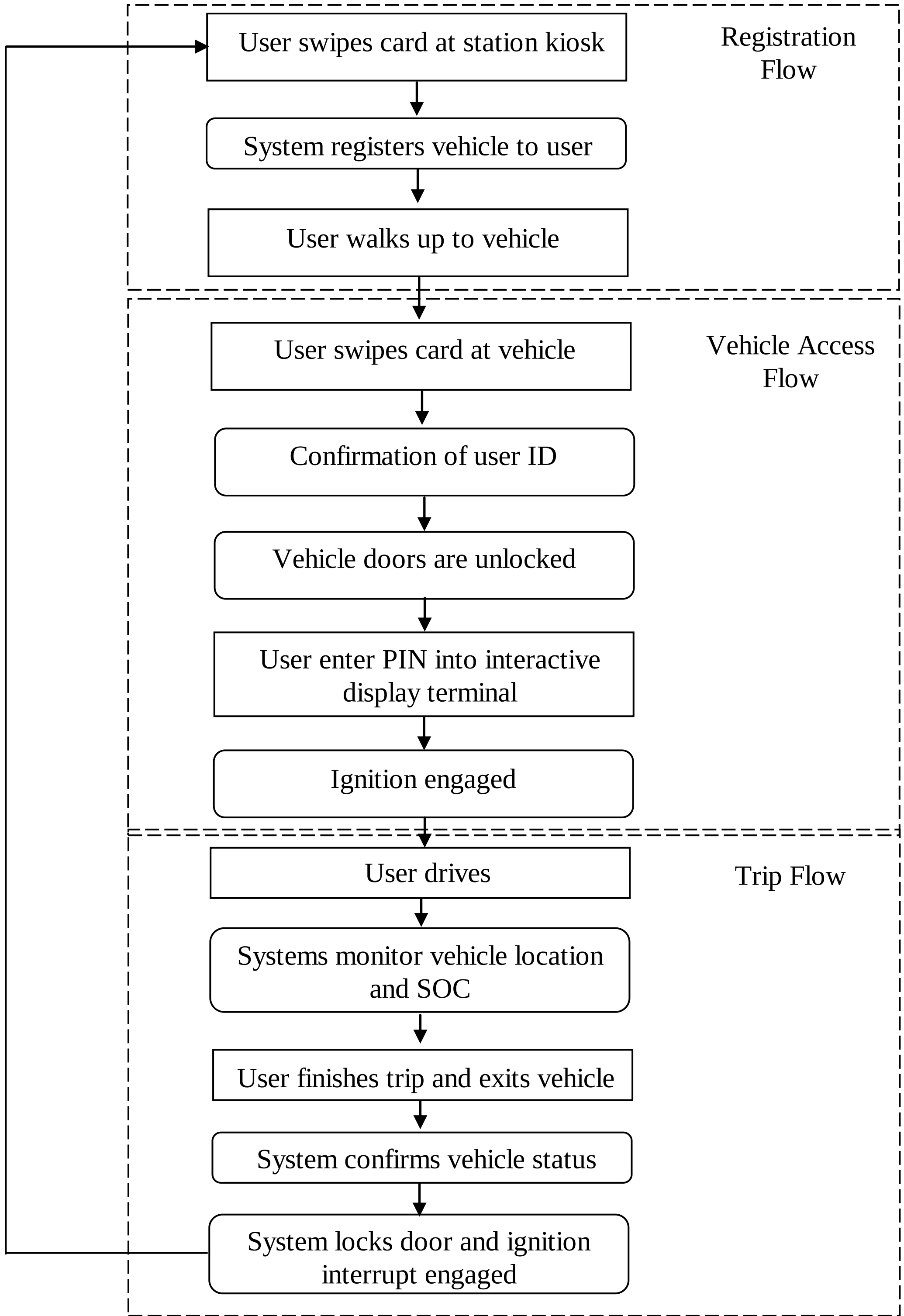

Figure 4 Multiple station shared vehicle system operation and user interaction flowchart (adapted from Barth and Todd, 2000)

Consequently, it is indeed necessary to relocate vehicles periodically during operation to bring balance in vehicle distribution or at the end of operation to meet the next day demand at each station (Barth and Todd, 1999). For these reasons, a multiple station shared vehicle system operations comprise of trip registration, vehicle access, user trip procedure, and vehicle relocation processes. These components should be analyzed and designed consistently and enriched with appropriate ITS technologies to make the system efficient, user-friendly, and manageable (Barth, M. and Todd, M., 1999). Figure 4 illustrates the system and user interaction flowchart of a multiple station intelligent shared vehicle system, comprised of trip registration, vehicle access, and user trip procedure. The monitoring of vehicle distribution and vehicle state-of-charge and relocation activity are not included in Figure 4.

RECENT MODELLING EFFORTS AND APPROACHES: LITERATURE REVIEW

Introduction

Recent modelling efforts on shared vehicle system design and operation are scarce. Notable examples are *Intelligent Community Vehicle system* of College of Engineering, Center for Environmental Research and Technology, University of California at Riverside, CA, USA, "Praxitele Project" in Saint-Quentin, France, and the "Kyoto Public-Car System" in Kyoto, Japan (Barth and Todd, 1999; Arnaldi et al, 1998; Nakayama et al, 2001). Liu, Sinha, and Fricker undertook an earlier effort in 1983 at Purdue University, Indiana, USA.

Barth and Todd (1999) at University of California at Riverside developed a process-oriented, discrete-event simulation model with an application of queuing theory to network. Liu et al (1983) also developed simulation model at Purdue University using discrete-event simulation technique. John P. Miller (1982) developed a self-drive vehicle system, similar to the shared vehicle system concept, model at Carleton University, Ottawa, Canada.

Barth and Todd's Multiple Station Shared Vehicle System Simulation Model

The multiple station shared vehicle system (SVS) simulation model developed by Barth and Todd at the University of California at Riverside (UCR) was applied to a hypothetical community, Coachella Valley, CA, USA. The studied SVS system consisted of six stations, selected through comprehensive travel demand survey and analysis. The model was a discrete-event simulation model and based on application of queuing theory to networks. The simulation model consists of three major components: (1) the stochastic trip generator, (2) the traffic simulator, and (3) evaluation of the results. The model block diagram is shown in Figure 5.

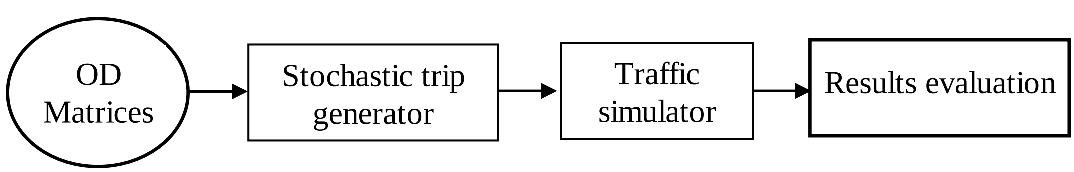

Figure 5: Model block diagram (Bath and Todd, 1999)

The origin-destination (OD) matrices are the hourly travel demand between stations. The travel demand profile was developed considering the seasonal and weekday variations. A year is divided into three seasons i.e., peak, mid-peak, and off-peak and a week was divided into two periods i.e., weekdays (Monday-Thursday) and weekend (Friday-Sunday). From the available technical paper (Barth and Todd, 1999), it can be observed that six sets of hourly trip matrices, with OD information, for six peak-day periods were used as input to the stochastic trip generator model.

Regarding the travel demand, the study estimated and used the daily travel demand of the hypothetical site based on the surveys done by some local agents. The distribution of the group or party size is shown in the travel demand data (Barth et al, 1997). In the developed model, the authors (Barth and Todd) did not mention the party size as a variable. It is assumed that the modelling effort did not consider party size as a variable in each arrival.

The Kyoto Public-Car System's Simulation Model

Nakayama et al (2001) developed their simulation model for multi-station 'Kyoto Public-Car System' using genetic technique (GT) algorithm to configure the operation of the system and search for optimal management configuration in Kyoto, Japan. The motivation behind the "Kyoto Public-Car" system was to search for a new system in order to use EVs for daily travel demand in the City Center of Kyoto. Owing to increased concern for Global Warming caused by greenhouse gases such as the 'tailpipe' CO_2 gas emission, and the characteristics of the trips, the concept of shared vehicle system based on EVs appeared logical.

The Kyoto Public-Car System - The system consists of five stations and a fleet of 35 EVs. All vehicles are 2-seater type, which implies that each trip is composed of ≤ 2 passenger(s). The land use in Kyoto is dense and mixed, streets are narrow and auto occupancy rarely exceeds two. Therefore, it is implied that 2-seater vehicles are suitable for all trips. The Kyoto Public-Car System features are summarized as follows:

1. Ultra-compact 2-seater EVs equipped with GPS and in-vehicle information system
2. Advanced fleet management by two manufacturers
3. Unmanned checkout and return (check-in) using ITS technologies
4. Both one way and round trips are allowed

Formulation of the Simulation Model - Nakayama et al (2001) mentioned that shared vehicle system is premature in Japan. It is desired that as many people as possible should use the system. The decision variables incorporated in the model include, (1) Total number of vehicles in operation, the fleet size ≤ 35, (2) Whether to permit uneven distribution, (3) Number of users/members, and (4) Composition of members based on socio-economic characteristics.

The Simulation Model -A *periodic scan approach* was implemented in simulation, which simulated the states of the EVs at every scanning period. The states of the EVs are defined in terms of two variables: 1) the locations of EVs, and 2) battery state-of-charge (SOC). Genetic technique algorithm was used to implement the model. The model flowchart is shown in Figure below.

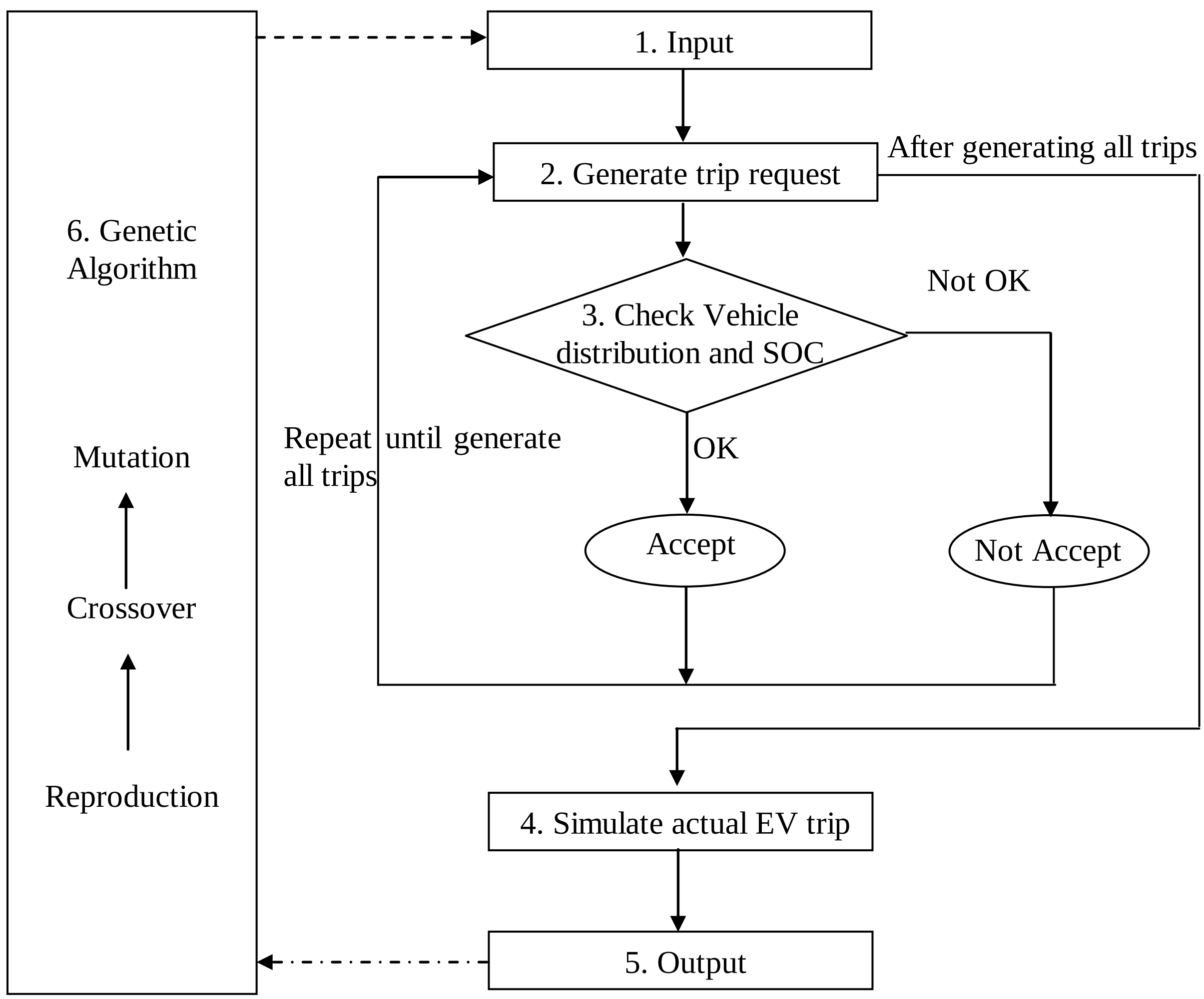

Figure 6 Model Flowchart, Kyoto Public-Car system

Travel Demand Data - The travel demand database that was used to develop the simulation model was derived from the reservation or trip request observed over a period of 12 days just after the Kyoto Public-Car system commenced its operation. The number of stations, their locations, and the number of parking slots at each station are kept fixed in each case. Nothing is mentioned about the trip travel time, its estimation method, and party size of individual trips.

Simulation Models For French Praxitele Trial Project

Arnaldi et al (1998) developed simulation models for French Praxitele Trial project in Saint-Quentin, France. The Praxitele project was charged with designing a new kind of transportation system in a suburban environment, which consisted of a fleet of electric public cars (EV). The project recognized that the realization of such a system requires experimentation regarding the behavior of autonomous vehicles, platooning with a lead driver-control vehicle, in the urban environment. To perform an authentic simulation of a real environment composed of a large set vehicles different models were developed. These models include: (1) geometric model of the environment, (2) mechanical simulation, (3) motion control model, (4) drivers model, (5) sensor model, and (6) visualization model.

To implement the above set of models into a unique system, a simulation platform was designed. The main task devoted in this effort was to develop a virtual urban environment with selected transportation network in simulation and study the operations of Praxitele vehicles (electric public cars) and their motion control algorithm with information from virtual sensor.

A Model of Car Availability in Car Sharing Scheme of Different Sizes

With the same view in mind that a car can be used more efficiently and could improve its productivity, Associate Professor H.S. Cousins developed a model based on the theory of binomial probability at the International Ecotechnology Research Centre at Cranfield University, Cranfield, Bedfordshire, UK (Cousins, 1998). In his model, the effect of different car sharing scheme/system sizes and failure rate (number of times a vehicle will not be available when needed) against fleet size for a given travel demand was formulated. The system size is defined as the number of users and/or stations in the car sharing system. The underlying concept was a cooperative type shared vehicle system in which all the trips were round trip type.

The model was capable to develop information on the number of cars needed to meet a given demand at different level of booking failure or level-of-service (LOS) ranging from 5 to 20 percent. The study did not mention any systematic pattern of the demand and its variations. A one-hour peak period, the 18:00h of the day, was used in the analysis. None of the major system variables including the vehicle sizes and mix, trip distance, trip duration or travel time, party size of each trip are clarified properly.

Simulation Analysis of A Mobility Enterprise System's Operation - Purdue University, Indiana, USA

Liu, Sinha, and Fricker (1983) developed a simulation model for a hypothetical "mobility enterprise" with their earliest effort in 1983 at Purdue University, Indiana, USA. They found that approximately 80% of the urban trips are short trips with one or two passengers. Most of these trips can be accommodated by vehicles smaller than subcompact cars. Therefore much of the capacities of household cars are wasted. Vehicle ownership pattern is thus not contingent upon the basis of "average use". They thought, if it is possible for a household to own a vehicle best suited to its member's most frequent travel needs and to have easy access to special purpose vehicles (SPV) from a cooperatively held pool of vehicles, much of this waste could be eliminated.

The Mobility Enterprise Design Concept - Liu et al thought that the automobile productivity improvement that can be achieved by a mobility enterprise, same as shared vehicle system, comes from better matching one's trip requirements to the vehicle characteristics. The basic theory or principle under the mobility enterprise is to ensure access of each member to a Minimum Attribute Vehicle (MAV) for mostly work trips as well as access to a wide range of Special Purpose Vehicles (SPV).

The Mobility Enterprise System Simulation Model - The underlying objective was to simulate the operations of the mobility enterprise in cooperative driving concept and to carry out experiments in laboratory. The model was a discrete-event simulation model, which was developed employing a proven simulation language known as SLAM. A total of thirteen events, as shown in the model flow chart, were included in the simulation model.

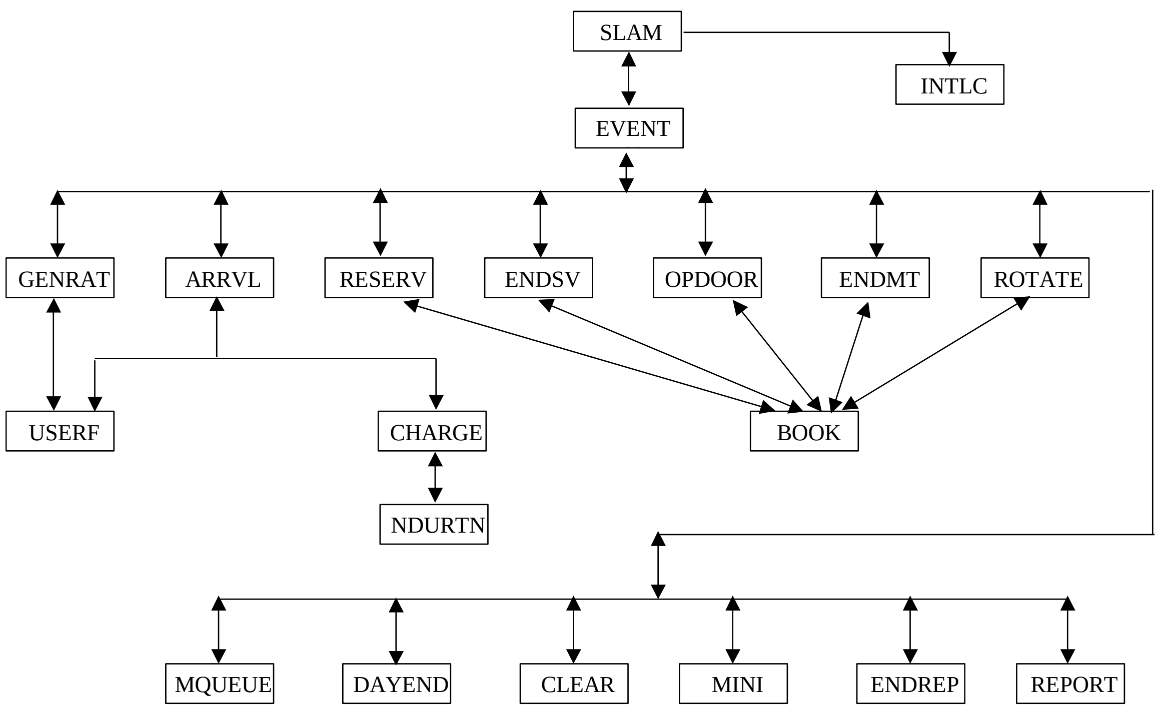

Figure 7 Simulation Model Flowchart, Liu et al (1983)

The entire operation of the mobility enterprise, including the leased and shared fleet, was included in the model. Although the model addressed various system design variables such as fleet size and mix, pricing and reservation schemes, maintenance, and organization structures; it was lacked by the variables including, demand pattern, party size, and others.

The Use of Electric Vehicles (EVs) in CFB Ottawa's Base Taxi Fleet–A Comparative Cost Study

John P. Miller carried out this research as an M. Eng. thesis at Carleton University, Ottawa, Canada, in 1982 under supervision of Prof. Ata M. Khan. This study examined a self-drive taxi system as an alternative to the base taxi system that was in operation at Canadian Forces Base (CFB) Ottawa, in support of duty personnel of the Department of National Defense (DND). The study assumed that the self-drive system must meet 100% of the travel demand in order to be an alternative to the base taxi system. The modelling methodology for the system is not described in detail in the thesis but the findings of the model, such as the required fleet size to meet the total travel demand of the duty personnel, relocation need etc, are included.

LESSONS LEARNED

From the foregoing literature it is obvious that the models developed at Purdue University and University of California at Riverside (UCR) are similar in modelling concept and used discrete-event simulation technique. They differ in system concept that they simulated. Models developed at Purdue University did not provide details about the customer arrival pattern, party size, vehicle availability and/or distribution, relocation need, and dealt with cooperative type shared vehicle system. It also lacks in detail about the method of trip generation. The concept of the self-drive taxi system for CFB Ottawa was similar to a multiple stations shared vehicle system but the model lacked in detail and produced significantly different results from that of Barth and Todd model. Other two modeling efforts, Kyoto *Public-Car* system model and Prof. Cousins's *car availability model*, are different either in system concept or modeling concept or both. The *Praxitele Trial* project simulation model developed by Arnaldi et al is different by modelling context.

Based on this literature review, it can be concluded that scope exists to develop improved and more realistic simulation model of the shared vehicle systems by considering additional variables. A complete set of variables, including party size, travel time, vehicle mix, vehicle-to-parking ratio would lead to more realistic design and operation model. An improved model could help in gaining insights that are not yet explored and enhance the design and operations of shared vehicle systems. It also could enhance the likelihood of sustainable development of this new innovative and potential transportation system and the urban transportation for 21st century in North America, Europe, and other parts of the world.

AN IMPROVED MODELLING FRAMEWORK

Introduction

The main purpose of this chapter is to outline the step-by-step description of the framework to develop an improved shared vehicle system simulation model. As identified through the comprehensive research, the complete methodological framework is guided by the following three tasks:

1. Shared vehicle systems definitions, their potentials, and identification of design and operational problems
2. Lessons learned from the review of the recent modelling efforts
3. Structuring the new modelling approach

A brief overview of the classification of the shared vehicle systems is provided. The definitions of different forms of shared vehicle systems are gathered from the available literature and presented in detailed form. The literatures on recent modelling efforts are also reviewed.

The remaining tasks of the modelling framework are described in the following sections.

Structuring the New Modelling Framework

The available literature on shared vehicle systems modelling is extremely insufficient in North America as well as elsewhere in the world. Among the literature, notable efforts are identified and explained in the previous Chapters. Barth and Todd (1999) used discrete-event simulation technique to develop simulation model for their shared vehicle systems named "*Intelligent Community Vehicle System* (ICVS)" and UCR *IntelliShare*. On the other hand, Nakayama et al used genetic technique (GT) algorithm with periodic scan approach (interval oriented, fixed increment in time advance) to model shared vehicle system operations for Kyoto Public-Car System in Kyoto, Japan.

In their models, Barth and Todd used hourly OD matrices for six peak days from peak, mid-peak, and off-peak seasons weekdays and weekends to optimize the vehicle-to-trip ratio in satisfying the user average waiting time or number of relocation or both. The total daily demand was not considered. Although a complete distribution of the party sizes for a given 24-hour demand for a particular season is illustrated in the report, the party size of the arrival at each time was not taken into consideration in the modelling effort.

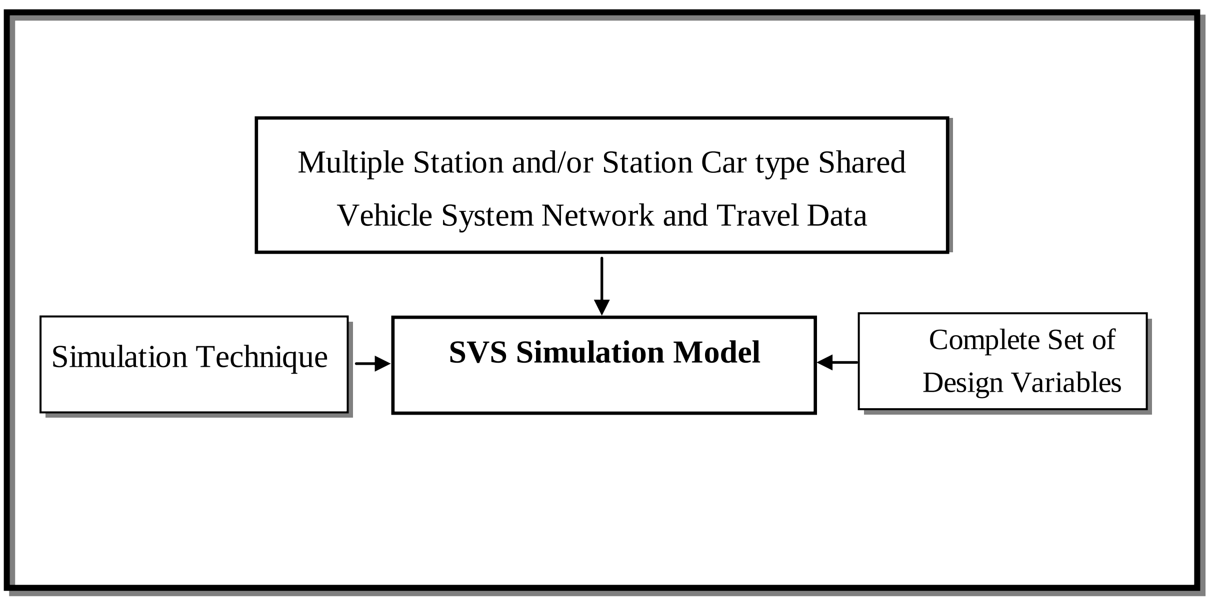

Figure 8 Conceptual Modelling Framework for Shared Vehicle Systems

Nakayama et al optimized checkout rate per vehicle and determined optimal vehicle-to-user ratio for "Kyoto Public-Car System". In the report they mentioned that parking was not considered as a design variable and kept constant due to some constraints in arranging additional parking slots. In addition, the model did not take into account some important system variables such as travel times and method of estimation, pattern of customer arrival, party size in each arrival and parking-to-vehicle ratio. A conceptual Modelling framework is depicted in Figure 8.

Demand-Supply Interaction in Shared Vehicle Systems Operations - The efficient operation of shared vehicle systems is dependent on the availability of vehicles when a user wants to use one. The combined management of the vehicle availability and party size of each arrival/trip with the available vehicle fleet could significantly improve the shared vehicle system operation efficiency and productivity of the vehicles. The steps that may follow in modelling (as Figure 8) demand-supply interaction in shared vehicle systems, focused on multiple station and station car type shared vehicle systems, operations are summarized as follows:

1. Identification of design variables and measures of performance (MOP) indicators
2. Formulation of dynamic database system and travel demand profile
3. Selection of a complete set of design variables and development of a possible set of case scenarios
4. Considering system efficiency (how efficiently the system is operating) as the objective function under each scenario model and optimize the system design and operations.

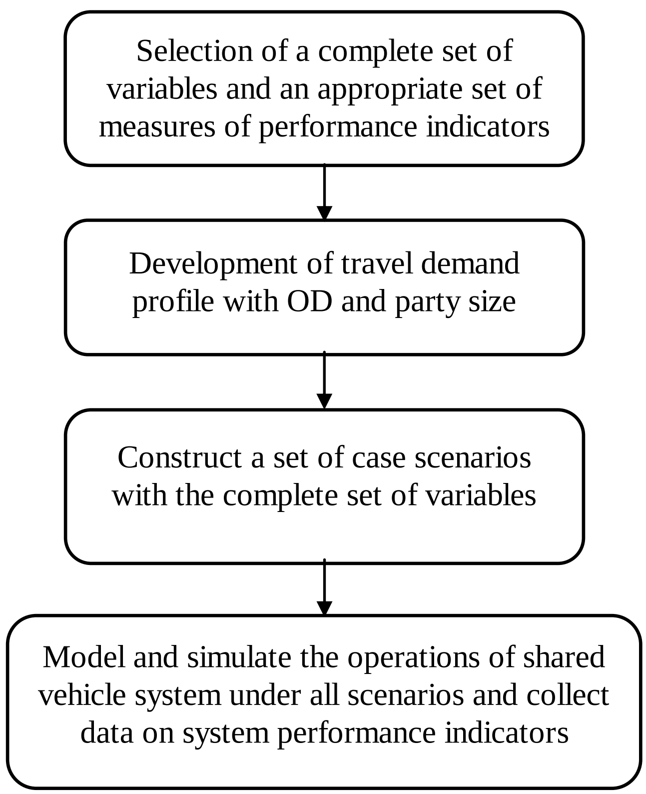

Figure 9 Steps in demand-supply interaction modelling process

In this paper only the first three steps are covered without the case scenario. The demand-supply interaction of a multiple station or station car type shared vehicle system could be illustrated as in Figure 9.

Methodology for Design Variables Selection - From the available literature it is observed that the operation of the shared vehicle system is highly sensitive to the system attributes that include: accessibility, vehicle availability, characterized by user or customer wait time, and vehicle distribution, characterized by number of vehicle relocations. These attributes are direct functions of system variables including user pool or number of users, travel demand, diurnal demand pattern/variation, party size, vehicle fleet size and mix, vehicle-to-trip ratio, number of available parking slots or vehicle-to-parking ratio, network traffic conditions, user acceptable maximum wait time, and others when the system is of multiple station type for a given number of stations within the system. In the case of round trip type system, the system efficiency depends on variables including system size in terms of number of members, demand pattern, vehicle-to-user ratio, acceptable failure rate and/or maximum acceptable wait time, and accessibility. These system variables constitute a complete set of common decision variables. This means that these variables are common for any kind of urban and/or land use form. Hence the variables and factors that should be considered in the design and operations of any multiple station shared vehicle system could be identified as follows:

1. Number of stations
2. Travel demand and its distribution among stations with respect to time of the day
3. Number of parking slots at each station (parking-to-vehicle ratio)
4. Party or group size in each arrival or trip
5. Vehicle fleet size (in terms of vehicle-to-trip ratio) and its composition (mix)
6. The road network and its traffic condition with respect to congestion as trip travel times in the area/community where the car sharing system is in operation
7. Distribution of vehicles at each station beginning of each day operation
8. Average acceptable waiting time and queue length
9. Vehicle relocation needs and criteria
10. Composition of the users' socioeconomic condition
11. Urban form and densities
12. Other transportation services, availability, and integration with carsharing

The above whole set of variables and factors may be aggregated into the following two subsets/groups:

1. Variables/factors that have a direct influence on shared vehicle systems design and operations in any market segment, include variables 1 to 9, and
2. Variables/factors that have site or market specific influence on shared vehicle system design and operations include variables 10 to 12 in the list above

Formulation of Dynamic Database and Travel Demand Profile - The demand estimation, in terms of origins and destinations (OD) and time variation, is the most resource consuming but fundamental task in transportation systems study, analysis, design, evaluation, and strategic planning. The viability of any transportation system and/or service is inherently dependent on the demand-supply balance. In the case of shared vehicle systems, demand is random and varies widely among stations and with respect to time. It is a dynamic attribute of the system with respect to time and space, and produces enormous task to meet this demand by a given number of vehicles supplied at various stations. In the design of any system if the estimated demand or loading pattern and its nature (say variation and/or distribution) are not realistic the total system design definitely will produce false results. In the design of shared vehicle system we should follow the same philosophy to determine travel demand with its variations and party size distribution in time and space as realistically as possible.

In its simplest form and to be a true representative of larger systems we may consider a multiple station shared vehicle system consisting of three stations as shown in Figure 10.

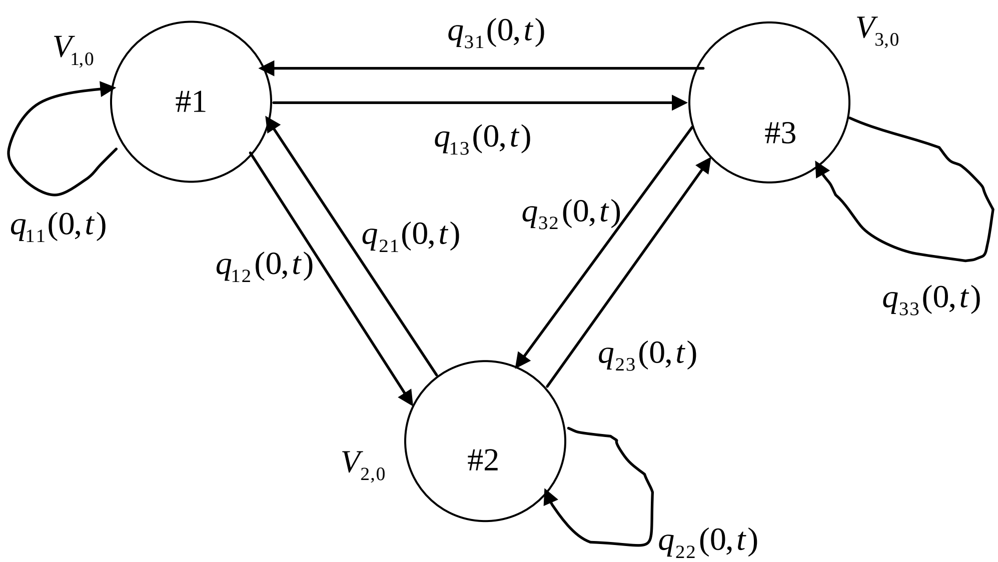

Figure 10 Real-Time travel demand and vehicle distribution at stations

The variables are defined below:

$V_{i,0}$ = number of vehicles at the beginning of operation of any day at station i; for $i = 1,2,3$

$q_{i,j}(0,t)$ = number of trips generated or realized from station i to station j during time 0 to t; for $i = 1,2,3$ and $j = 1,2,3$.

The total number of trips generated at station #1 during time interval 0 to t (unit of the time could be minute or hour) could be calculated as follows:

$$T_1(0,t) = q_{11}(0,t) + q_{12}(0,t) + q_{13}(0,t),$$

or $T_1(0,t) = \sum_{1}^{3} q_{1j}(0,t)$ ....(4.1)

where $T_1(0,t)$ – is the total number of trips generated at station 1 and destined to stations j (j = 1,2,3) during the period 0 to t.

If the system consists of n number of stations or depots then the above expression could easily be generalized as follows;

$$T_i(0,t) = \sum_{j=1}^{m} q_{ij}(0,t), \text{ for i = 1, 2, 3,….n} \quad \text{...(4.2)}$$

where $T_i(0,t)$ is the total number of trips generated at station i and destined to stations j (j = 1,2,3…m) during the period 0 to t. In the case of multiple station shared vehicle system m = n.

Knowing the number of trips realized and arrived at station i from other stations within the time interval 0 to t, we can use the above models/logics to dynamically update the vehicle database and distribution to make decisions for vehicle relocation need. A typical real-time travel demand matrix for a time period t_k (k[th] hour of the operation day) within the operation period that includes trips among all stations within the system is shown in Table 1.

Table 1: Typical travel demand matrix with ODs of k[th] operation hour that includes trips between all stations

$TripFrom\ i/j$	1	2	3	.	.	.	n-1	n
1	$q_{1,1}$	$q_{1,2}$	$q_{1,3}$				$q_{1,n-1}$	$q_{1,n}$
2	$q_{2,1}$	$q_{2,2}$	$q_{2,3}$				$q_{2,n-1}$	$q_{2,n}$
3	$q_{3,1}$	$q_{3,2}$	$q_{3,3}$				$q_{3,n-1}$	$q_{3,n}$
….	….	….	….	….	….	….	….	….
n-1	$q_{n-1,1}$	$q_{n-1,2}$	$q_{n-1,3}$				$q_{n-1,n-1}$	$q_{n-1,n}$
N	$q_{n,1}$	$q_{n,2}$	$q_{n,3}$				$q_{n,n-1}$	$q_{n,n}$

Note: i and j indicate the origin and destination station for a particular trip

In this way, the total numbers of OD matrices have been reduced to the number of operation hours per day. These OD matrices together with party size, the network traffic conditions (measured in terms of trip travel time) with respect to congestion, and distance among stations could be used to model the shared vehicle systems design and operations.

Selection of Complete Set of Design Variables and Development of Case Scenarios - From the users point of view, the success of a shared vehicle system is dependent on getting a vehicle easily when they want to use one (Cousins, 1998). From operators or service providers' viewpoint, they wish to meet the users need from a minimum number of vehicle inventories. These aspects come together in the form of car:user ratio. The actual ratio is dependent on many factors - most importantly, the level of local services within the walking distance, public transportation quality, walking and bicycling facility, type of urban form, user demographics, trip purposes etc. However, the ratio is highly dependent on the size of the system, the user pool or demand itself (Cousins, 1998). A method is, therefore, required to reveal the interrelationships of the system variables and the system performance measures to develop meaningful scenarios including a complete set of decision variables. Therefore, variables and MOP selection information depicted in Table 2 and Figure 11 are used in this study.

Table 2 Variables and measures of performance (MOP) indicators selection

Recent Studied Models	Variable Considered in the Models	Selected Variables	Measures of performance (MOP)
UCR ICVS Model by Barth and Todd	➢ Number of stations ➢ Travel demand in trips, ➢ Fleet size	✓ No. of stations ✓ Travel demand in trips ✓ Fleet size	➢ Vehicle-to-trip ratio ➢ User wait time ➢ Number of relocations
Kyoto Public car model by Nakayama et al	➢ Number of stations ➢ Travel demand by users ➢ Fleet size ➢ Users socioeconomic composition	✓ Number of stations ✓ Fleet size	➢ Vehicle-to-user ratio ➢ User wait time
Variables and MOP carried over for this thesis research study		✓ Number of stations ✓ Travel demand in trips ✓ Vehicle-to-trip ratio (Fleet)	✓ Vehicle-to-trip ratio ✓ User wait time ✓ Number of relocations

Note: ✓ - Considered as more important ➢ - Considered in previous studies

A complete set of variables could be determined using the following variable selection logic.

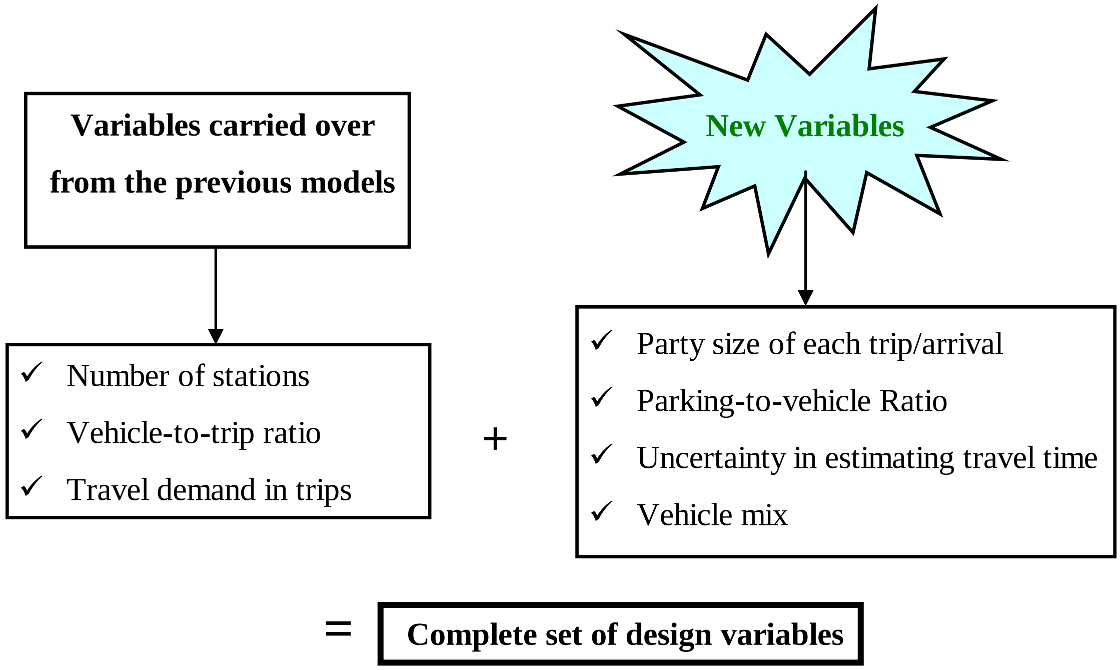

Figure 11 Complete set of variables

Conclusion

A comprehensive review of the recent carsharing systems modelling effort have been completed. Pitfalls in selecting system variables that are crucial for shared vehicle system design and operations modelling are identified. Finally, a methodology for identifying a complete set of design variables in modelling shared vehicle system is developed.

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