# System Sizing Model—Simulation Model of the Service

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**Abstract** The model estimates the number of vehicles of a fleet that are necessary to meet the expected requests, as well as the estimated number of bays needed to ensure the temporary parking of the vehicles in use or charging at any time. The model allows to reproduce the service trend during a typical day, simulating the pickup requests at each station and the trip of each vehicle from the pickup to the return station; the model monitors the number of vehicles at every station, therefore allowing an estimate of the minimum number of bays per station and of the number of vehicles in order to satisfy the expected requests.

## 1 Context of the Model in the Service Configuration

This model aims at estimating some crucial values to measure the extent of the car sharing service, e.g. the number of vehicles required to set-up a fleet and the number of bays required for every pickup point (station), as a function of the characteristics to be given to the service (configuration parameters).

As explained in chap. 14, the values calculated from the present sizing model are then applied to the financial—economic model to evaluate the economic sustainability of the service. Furthermore, the sizing model allows to estimate the total number of km covered by the vehicles of the fleet. These data are essential for the subsequent sub-models to estimate the variation in vehicle congestion and in polluting and climate-altering emissions.

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The main model inputs are the number and location of stations and the O/D matrix of users, which is calculated from the previous sub-models of demand analysis and creation of O/D matrices, as well as some important service configuration parameters.

The core of the model, developed in MATLAB language, allows to reproduce the service time trend during a typical day, by simulating the pickup requests at each station and the trip of each vehicle from the pickup to the return station. The model monitors the number of vehicles at every station at any time, thus calculating the minimum number of bays per station and the number of vehicles necessary to satisfy the requests.

A prefixed percentage of electric vehicles to be included in the fleet can be imposed to input parameters: in this case, the model estimates the number of additional vehicles required with respect to the same service using traditional vehicles due to the time used for charging.

The increasing significance of the diffusion of electric vehicles required a variation in the base sizing model, as described in detail in Sect. 3. It considers an entirely electric fleet, and analytically and dynamically simulates the service operation with electric vehicles, also taking into account the dynamics of charging and running down of vehicle batteries.

## 2 Model Description

The fleet and bays sizing procedure consists of two sequential phases:

- a first preliminary phase, which calculates the O/D matrix of the actual trips to be simulated in the following phase. It starts from the users' O/D matrix and considers the number of average trips per user and the target share of pickup requests that the operator aims at satisfying. In this phase, the matrix of the distance between the several stations is also calculated;
- a second phase, which uses a dynamic and microscopic simulation model of the vehicle sharing service, in order to reproduce its daily operation and therefore to calculate the total km covered and the number of necessary vehicles and bays.

The simulation model of the second phase is dynamic and microscopic because:

- it can simulate the daily trend of the service over a typical day, with a time step of 1 min;
- it simulates the trip of each vehicle from one station to another (pickup from the station of origin and return at the station of destination), considering for each trip its starting and final position, the time taken and the km covered.
- each station is simulated separately by monitoring:

- the time trend of the number of vehicles available;
- the pickup requests (with a contextual check that a vehicle is available) and the return requests, which are stochastically extracted from a predefined demand pattern that is defined in the preliminary phase.

The next Sect. 2.1 describes in deeper detail final and intermediate inputs and outputs of the sizing model. Section 2.3 examines more closely the most significant methodological and procedural aspects of the model.

## 2.1 Input

The model mainly requires two input data sets, which characterize the service in terms of offer and demand. Data inputs are specified in detail in the following table.

| Definition | Source | Notes | Values |
|---|---|---|---|
| Number ($N_{stations}$) and location of stations | Configuration parameter | Offer parameter: pickup and return points in the area that is covered by the service. These data greatly depend on the service comprehensiveness, in relation to the extent of the area where the service is offered | Variable based on the configuration alternative |
| Space flexibility (1w or 2w) | Configuration parameter | Offer parameter: possibility to return the car either to any parking area (1w) or only to the same pickup point (2w) | Values expressed as 1 (1w) or 0 (2w) |
| Average length of the route in 2w mode | Work hypothesis | Demand parameter: it is used to randomly generate the duration of a single trip | Only active in 2w mode |
| Average duration of intermediate stops in 2w mode | Work hypothesis | Demand parameter: it is used to randomly generate the stopping time of a single trip | Only active in 2w mode |
| Type of vehicles (%FEV) | Configuration parameter | Offer parameter: it represents the desired percentage of electric vehicles out of the total fleet | Percentage value, which varies based on the alternative |
| Probability to find a vehicle available (%VEH) | Configuration parameter | Offer parameter: it indicates the percentage of the demand of trips that the service manager wants to satisfy | Percentage value, which varies based on the alternative |
| Users' O/D matrix | Model of creation of O/D matrices | Demand parameter: potential users travelling between the several stations of the system | $M_{O,D\_users}$ |
| Users-trips coefficient | From the literature | Demand parameter: it represents the daily number of trips per user. It allows to estimate the number of users' trips | $coeff_{us/tr}$ |

## 2.2 Output

Model outputs may be divided into intermediate (obtained at the end of the preliminary phase and necessary to feed the actual service simulation model) and final ones, which can subsequently be used by other sub-models (economic–financial model, estimate of emissions and congestion).

Intermediate outputs are:

- **Matrix of distances** ($M_{distances}$): it represents the matrix of the distances between the stations of the configuration. It is calculated by means of an optimal routing algorithm;
- **Matrix of desired** ($M_{O,D\_desired\_trips}$) **and actual** ($M_{O,D\_carried\_trips}$) **trips**: the first matrix represents the demand of desired trips. It is calculated starting from the $M_{O,D\_users}$ matrix that is modified by means of the users-trips coefficient. The second matrix represents the number of actual trips: it differs from the previous one because not all the desired trips can be run, but only a share corresponding to the probability to find a vehicle available. The two types of matrices are hourly and the sum of the matrices defined for each time slot of the day gives the number of total (desired and actual) trips of one day.

Final outputs are:

- **Number of vehicles** ($N_{vehicles}$) that must make-up the fleet and be available at the start of the daily service at each station, in order to satisfy the percentage of requests defined by the parameter "probability to find a vehicle";
- **Number of bays** ($N_{bays}$) that must be provided at each station to park the maximum peak of vehicles that is expected during the day at a station, and therefore guarantee the possibility to park all the vehicles that are temporarily not used at any time of the service;
- **Total number of daily km covered** ($KM_{CS}$) by all the vehicles of the service resulting from the sum of the km covered for each trip that is simulated by the model.

## 2.3 Operations

Some of the most important theoretical and operational aspects of the simulation of the vehicle sharing service are described below, thus making the operation of the developed model more comprehensible.

### 2.3.1 Calculation of the Matrix of the Distances Between Stations

Knowing the road distance between each couple of stations of the vehicle sharing service is fundamental for the simulation model, in order to correctly estimate the km covered by the vehicles and the time between the pickup of the vehicle at the origin and its return at the destination.

A graph of the road network of the city of Milan, which was provided by AMAT (Agenzia Mobilità Ambiente e Territorio—Mobility and Environment Agency of Milan), was used to define the distances, with the indication of the length of each road link. Dijkstra's algorithm[1] was used to calculate the minimum-length route $l_{s1s2}$ between each couple of stations s1, s2 belonging to the set S that includes all the stations of the configuration under consideration.

The matrix of the distance ($M_{distances}$) is therefore obtained, where the distance between generic stations s1 and s2 results from $l_{s1s2.}$ This matrix is not symmetric, because the graph associated with AMAT's road network is antisymmetric as it takes into consideration road directions.

### 2.3.2 Calculation of Desired and Actual Trips

Starting from users' origin/destination matrices ($M_{O,D\_users}$), which are generated from the model of creation of O/D matrices, the matrix of desired trips ($M_{O,D\_desired\_trips}$) is calculated by applying a coefficient. It is defined from the literature [enter a reference] and indicates the average daily number of trips generated per user ($coeff_{us/tr}$):

$$M_{O,D\_desired\_trips} = M_{O,D\_users} \cdot coeff_{us/tr}$$

It is now possible to calculate the actual trips matrix ($M_{O,D\_carried\_trips}$) by subtracting from the desired trips matrix the share of trips that are not satisfied due to the unavailability of a vehicle, and which must not be considered in the following phase of service simulation.

The matrix of actual trips is therefore defined as:

$$M_{O,D\_carried\_trips} = M_{O,D\_desired\_trips} \cdot \%VEH$$

where %VEH is the configuration parameter expressing the probability to find a vehicle available.

[1]Dijkstra, E. W. (1959). "A note on two problems in connexion with graphs". Numerische Mathematik 1: 269–271. doi:10.1007/BF01386390.

In the case, 2w the origin and destination of trips coincide (the user must return the vehicle to the pickup point). O/D matrices are therefore used by simply extracting the total trips that started from each station, without considering the information on the destination.

### 2.3.3 Method to Define the Vehicles of the Fleet

During the service simulation phase, each station is provided with a counter of the vehicles available, which is set to zero at the start. This setting allows to instruct the model to calculate the vehicles needed "inversely" with respect to the real situation: at the initial instant of the simulation, it is fictitiously supposed that there are no vehicles available. Only at the instant when a pickup is requested a vehicle is "generated", which immediately leaves the station to simulate the trip required and travels towards the target station. Even at the following instants, every time a pickup request cannot be satisfied with the vehicles that were previously entered in the simulation (e.g. if the pickup station at that time does not have any parked vehicle or has a lower number than the requests), a new vehicle is generated.

Each station is actually provided with two specific counters: the first monitors the present vehicles (which are therefore available for pickup) at the station at a general instant *t* of the simulation ($N_{virtual\_available\_vehicles,t}$); the second counts the vehicles generated from the beginning of the simulation (time 0) until the general instant *t* of the simulation ($N_{generated\_vehicles,t}$). The final value of this counter (at the end of the period of simulation of the daily service) exactly represents the number of vehicles needed to satisfy all the pickup requests made during the whole daily service ($N_{vehicles}$), which must therefore be at the station at the instant the service starts.

If the simulated configuration includes a prefixed percentage of electric vehicles in the fleet (expressed by a greater value than zero of the configuration parameter % FEV), the previously calculated value $N_{vehicles}$ will be increased by using a multiplicative coefficient in order to consider the downtime necessary to recharge the electric vehicles.

This coefficient considers that for each vehicle driving time unit, during which the battery runs down, a corresponding time unit is required to recharge the power that is used up. During this time, the vehicle must not be used.

The total running downtime depends on the number of km covered per time unit (and therefore on the journey average speed) and on the total range of the battery. The total recharging time depends, besides on the range of the battery, also on the recharging speed, which in turn depends on the technology used.

As already mentioned, a variation of the model was developed to analytically and dynamically simulate the charging and running down process of vehicles, see Sect. 3.

### 2.3.4 Simulation of Pickups at the Stations of Origin

For each station, the model provides a list of pickup requests, defining the exact time when the requests will occur. The following procedure is hereby applied:

- for each hour of service operation (24 h in the simulated configuration), the corresponding trips demand is considered. It is differentiated according to the pickup station and derived from the previously calculated matrices of actual trips ($M_{O,D\_carried\_trips}$);
- within each hour, the total pickup requests for each station are randomly spread along the 60 min of the time slot, thus defining the exact minute when the model must take into consideration each trip request. This random distribution is modified at each run that is carried out by the model for each simulated configuration (10 runs are expected for each configuration, as explained in deeper detail below);
- for each station and time step of the simulation (minute), the pickup request is compared with the fleet at the station and handled as follows:
- with vehicles available ($\mathrm{N}_{\mathrm{virtual\_available\_vehicles,t}\,>\,0}$), the model reserves a vehicle that is already at the station;
- without vehicles available ($\mathrm{N}_{\mathrm{virtual\_available\_vehicles,t}\,=\,0}$) the model "generates", as previously described, a new vehicle, thus increasing by a unit the counter of generated vehicles ($\mathrm{N}_{\mathrm{generated\_vehicles,t}}$), and moves it to its destination;
- at each pickup, the counter of vehicles ($\mathrm{N}_{\mathrm{virtual\_available\_vehicles,t}}$) available at the station is decreased by a unit. However, in case a new vehicle is generated, the same counter is previously increased by a unit, just as the counter of generated vehicles ($\mathrm{N}_{\mathrm{generated\_vehicles,t}}$). Basically, a vehicle is virtually generated, made immediately available for pickup and then immediately picked up.

### 2.3.5 Simulation of Trips

When a pickup is simulated at a certain station of origin and at a certain time instant, the model will define:

- the trip destination:
  - in the case 1w, it is defined by means of a random extraction based on the probability distribution provided by O/D matrices $M_{O,D\_carried\_trips}$ (once the origin of the trip is prefixed, this matrix allows to calculate the percentage distribution of trips with respect to the several possible destinations);
  - in the case 2w, the destination coincides with the origin.

- the length of the trip:
  - in the case 1w, once the origin and destination of the trip are known, the length is calculated by means of the matrix of distances ($M_{distances}$) that is previously calculated;
  - in the case 2w, it is randomly generated from an exponential probability distribution whose average is the input parameter "average length of the route in 2w mode".
- the duration of the trip:
  - in the case 1w, it is calculated from the length of the trip, by considering a constant journey speed on all road links, however depending on the time slot (lower speed in rush hours with heavier traffic);
  - in the case 2w, the distance is calculated as in the case 1w, however summing an intermediate stopping time ($T_{parking}$) that is randomly generated from an exponential probability distribution whose average is the input parameter "average duration of intermediate stops in 2w mode".

### 2.3.6 Simulation of Returns at the Stations of Destination

For each simulated trip, based on the journey simulation described above, the model handles the return to the selected station of destination as follows:

- the vehicle used is returned at a time instant that is calculated by adding the duration of the trip to the instant of the pickup from the station of origin;
- the counter of the vehicles available at the station of destination ($N_{virtual\_available\_vehicles,t}$) is increased by one unit.

### 2.3.7 Definition of the Necessary Number of Bays

The number of bays per station that is necessary to park the vehicles must be calibrated according to the maximum peak of parking requests occurring over the time span of the daily service.

In order to calculate the number of bays that are necessary for each station ($N_{bays}$), once the main simulation is concluded, the model repeats for the second time the simulation that was already carried out according to the following criteria:

- in this case, the number of real vehicles that are available at each station at the beginning of the service (time 0) is not set to zero, but it is equal to the need of vehicles that was previously calculated ($N_{real\_available\_vehicles,0} = N_{vehicles}$);

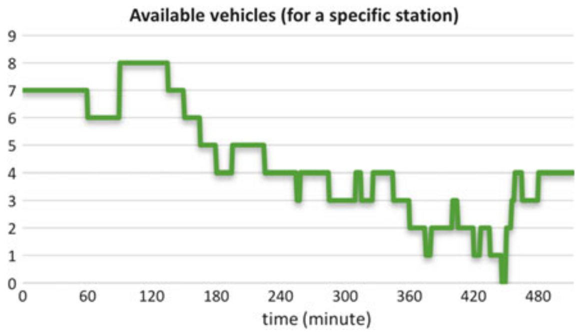


**Fig. 1** Example of trend during the period of simulation of the number of real vehicles that are available at a pickup station

- the number of pickups and returns at each station for each time step $t$ is already defined in the main simulation (the simulation is being repeated, no new one is generated);
- for each simulation time step $t$, the model calculates the real vehicles that are available at the station ($N_{real\_available\_vehicles,t}$) starting from the vehicles that were available in the previous time step ($N_{real\_available\_vehicles,t-1}$), then subtracting the vehicles picked up in the time step $t$ and adding the vehicles returned in the same time step $t$. Figure 1 shows the trend of the number of real vehicles that are available at a specific station during the simulation period.

The number of necessary bays ($N_{bays}$) therefore results from the maximum number of real vehicles available at the station at each time instant $t$ of the simulation period [0..$T$]:

$$N_{bays} = \max_{t \in [0..T]} N_{real\_available\_vehicles,t}$$

### 2.3.8 Use of Several Runs for Each Simulated Scenario

As already mentioned, each configuration under evaluation is simulated by means of several runs of the model (10 runs). In each run some data inputs, e.g. the minutes when the actual pickup requests occur and the destination of the several journeys, are different because they are randomly generated from a proper distribution of probability.

For each simulated configuration, the average values of the several model outputs are extrapolated with respect to the 10 runs.

This allows to take into account the variations in users' behaviour that may naturally occur during the real operation of the service, thus avoiding the risk of sizing fleet and bays based on peculiar cases that may prove extreme and do not represent an average working condition.

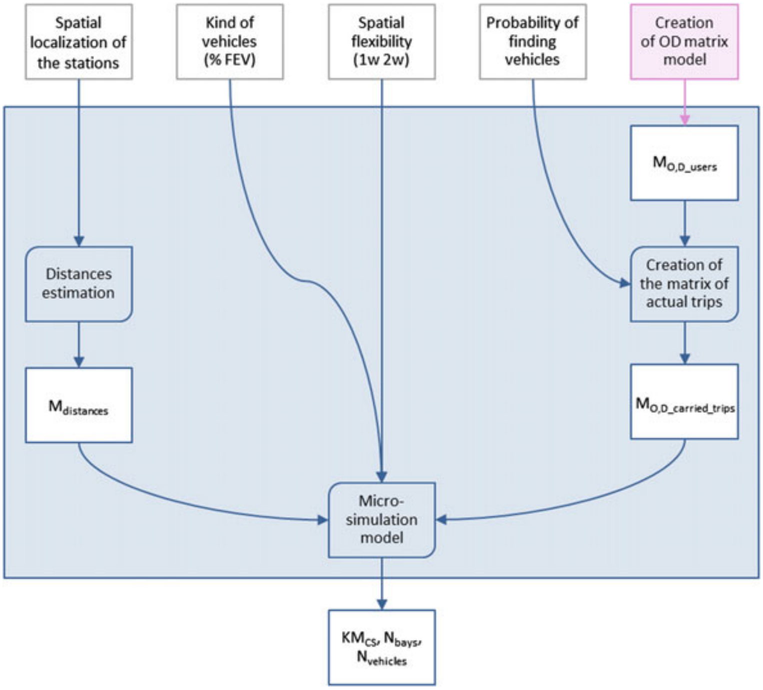


**Fig. 2** Scheme of the sizing model (in sky blue)

However, the model also extrapolates the minimum and maximum values of the several outputs obtained in the 10 runs. The range of a possible variation in the sizing values can therefore be estimated, thus clarifying the level of uncertainty that characterizes the results (Fig. 2).

## 3 Dynamic Simulation of Electric Vehicles Fleet

In the developed model that was described above, the fleet sizing with electric vehicles was estimated by using a multiplicative coefficient that allows to consider the additional time necessary for the electric recharging, therefore the need for a greater fleet with other service configuration parameters being equal.

In order to simulate this aspect at its best, a variation of the main model was developed. It can be used with entirely electric fleet and allows to simulate real charging and running down processes during the service, and to obtain a more precise estimate of the number of necessary vehicles.

This variation of the model requires the input of some additional and/or more precise configuration parameters with respect to the base model:

- **total range**: maximum number of km that the vehicle can cover after a complete battery charging cycle; it depends on the type of vehicles used;
- **recharging time**: the time necessary for a complete recharging cycle; it depends on the type of vehicles and on the recharging station used;
- **minimum range threshold**: the residual range of a vehicle (in km). Below this threshold, the user must be prevented from using a vehicle to avoid the risk of running down during the trip.

With respect to the base model, further theoretical and operational aspects are introduced during the simulation phase:

- for each simulated vehicle a counter is added, which monitors in every instant the charge of the vehicle (residual range in km);
- in the return phase:
  - vehicles having a lower charge than the minimum threshold of range cannot be used; if no vehicles are charged enough, the model will generate a new vehicle by increasing the relating counter ($N_{generated\_vehicles,t}$);
  - if there are several vehicles available having a higher charge than the threshold, the model will reserve the vehicle with a higher level of charge;
- in the return phase, the counter of the vehicle residual range is updated by subtracting the total km covered during the just concluded trip;
- in the stopping phase, at each simulation time step the counter of the residual range of each vehicle in charge is progressively increased as a function of the recharging speed; the residual range cannot obviously exceed the total range of the vehicle.

## 4 Conclusions

The simulation model developed that is described in this chapter represents an effective instrument for the correct sizing of a vehicle sharing service having certain characteristics that are predetermined by the manager (configuration parameters). The dynamic and microscopic approach applied, as well as the capacity of the model to simulate the real dynamics of the handling of the fleet vehicles, allow an accurate estimate of the vehicles and bays necessary to properly provide the required characteristics of the service. The same outputs given by the simulation model are important for the extended evaluation model of the service, as they provide essential elements to evaluate the financial–economic sustainability as well as to estimate the impacts on traffic and on polluting and climate-altering emissions.