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Performance Assessment of an Urban Collective Cars System

Jennie Lioris * Regine Seidowsky ** Habib Haj-Salem *** and
Jean-Patrick Lebacque ****

* *IFSTTAR, GRETTIA, Paris (e-mail: jennie.lioris@ifsttar.fr)*

** *IFSTTAR, GRETTIA, Paris (e-mail: regine.seidowsky@ifsttar.fr)*

*** *IFSTTAR, GRETTIA, Paris (e-mail: habib.haj-salem@ifsttar.fr)*

**** *IFSTTAR, GRETTIA, Paris (e-mail:
jean-patrick.lebacque@ifsttar.fr)*

Abstract: A constrained optimization framework of an autonomous urban transport system, associated with reduced rates, is presented. A decentralized management is considered where prior seat reservation is not a prerequisite for the system functioning. Well-adapted vehicle itineraries based on the current demand and vehicle state are constructed. The event-driven system dynamics characterizing the non-deterministic features of the corresponding complex mathematical problem, encourage for a discrete event system approach. The implied stressing needs of a comprehensive study, will be achieved by intense simulations. Various strategies, related to real time controls and system dimensioning as well, are studied. A methodology appraising the system performance is introduced where the resulting system behaviour is evaluated in terms of client waiting time, detours, vehicle occupancy, travel times etc. Moreover, optimal parameter tuning is discussed underlying the importance of reasonable trade-offs for achieving the desired performance. Thus, involving optimisation, operational research methods and simulation techniques a significantly efficacious well-operating system can be achieved, providing the best suited configuration for any demand level and geometry. Utilising previously wasted vehicle capacity may reduce costs for both vehicles and clients while forms an ongoing attempt to control extended traffic congestion, air pollution, energy consumption etc.

Keywords: Demand responsive transportation; discrete event systems; asynchronous behaviour; Monte Carlo simulation; performance evaluation; parameter optimisation

1. INTRODUCTION

An operational transportation structure can only improve all challenges faced when considering a competent city activities and improved quality of life. Public transit often appears inadequate to satisfy urban mobility encouraging the use of private cars and resulting in constantly growing traffic density. Alternative structures associating public and private transportation, prohibition or imposing tolls for entering the city centre, have been put forward, remaining partial solutions requiring the driver willingness to bear additional costs to ensure comfort and convenience. Systems like car sharing do not necessarily diminish the passenger to vehicle ratio often followed by a poor spatial distribution (greater concentration on high-demand destinations) unless additional constraints are imposed obliging users to return them to specific stations. For a very long time, carpooling has been presented as a prestigious economical transit mode but it still holds many disadvantages. Passengers have to administer their own arrangements for defining mutually acceptable predefined pick up points and timetables, inevitably time consuming tasks.

Demand Responsive Transport (DRT) is getting increasingly popular. So far, in many existing schemes various restrictions are presented (fixed routes, advanced booking), Tao (2007), Fu (2002), London Dial a Ride, Kunaka (1996)

often at the disposal of elderly or persons with restricted mobility.

This work presents an optimised DRT system, imposing the minimum number of constraints to customers. It is destined to all commuter types, providing independent mobility and travel conditions similar to the ones of the private car at a low cost for both vehicles and passengers. Such a model was initially studied by Fargier and Cohen (1971) and this research is an advancement of their work. The related transportation problem is characterised by complex dynamics, belonging to the class of discrete event system, (DES). The system evolution is ruled by the occurrence of asynchronous events over time, solely responsible for generating state transitions. Explicit modelling of the nondeterministic behaviour is required often through the inclusion of appropriate stochastic model components. Moreover, the involved complexity requires a combination of mathematical techniques and effective processing of experimental data for efficacious system performance. Thus, discrete event simulations allowing a deep understanding of the system behaviour together with appropriate mathematical theory will lead to an optimal control of the system evolution.

The next of the paper is organised as follows: §2 formalises the decision problem and discusses the utilised controls.

§3 and §4 illustrate the system performance under the simulated scenario. §5 presents a methodology for adjusting parameter values. Finally, §6 summarises the main conclusions of this study.

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2. CONTROLLING THE SYSTEM

A system comprised of a network, clients wishing to join particular destinations and a related set of vehicles in service is considered. At any time, a prospective customer appearing at a network node searches for a potential vehicle able to serve a specific destination. Whenever that is not possible, the client according to his/her preferences either decides to join a queue for a limited period or quits the system. Similarly, cars bring passengers to their destinations while they are also interested in new passengers. Non-served clients, idle cars or an increased number of detours penalise the system performance. No advanced seat arrangement is required while an optimised passenger assignment to a particular vehicle accompanied by well adapted itineraries will reduce all related costs for both vehicles and clients.

Client Acceptance Algorithm to a given vehicle

Problem Definition: A vehicle with a given number of passengers aboard having an itinerary (destinations sorted according to the visiting order) encounters a new client. A decision should be taken whether the new client should be accepted in which case the new car itinerary must be provided.

Hereafter, a client decision algorithm is presented, however different versions of controls can be developed and evaluated. One of the strong simulation points is that it reproduces precisely the system behaviour without the risk consequences of a poor decision making.

Notations

- n_0 : present vehicle position;
- t_0 : meeting time;
- n_c^d : the destination of the candidate client;
- $\delta(a, b)$: the duration of the direct travel from node a to node b ;
- $L = \{n_1, n_2, \dots, n_m\}$: vehicle itinerary at t_0 ;
- $\ell_1 = \{x(1), \dots, x(|\ell|)\}$: a possible tour of visiting all nodes in $\ell = L \cup \{n_c^d\}$;
- $t(k)$: is the predicted arrival time at node $x(k)$, element of ℓ_1 ;
- $p(x(k))$: the number of disembarking passengers at node $x(k)$;
- s : the diversion threshold accepted by each passenger proportionally to the direct travel;
- t_i^o, n_i^o, n_i^d : the entry time, the origin and destination node of passenger i respectively;
- t_j^p : the predicted arrival time at destination $n_j \in L$
- t_j^{lim} : the deadline for arrival at node $n_j \in \ell$ where

$$t^{\text{lim}}(j) = \begin{cases} \max\left(t_j^p, \min_{i \in d^{-1}(j)} (t_i^o + s \times \delta(n_i^o, n_i^d))\right) & \text{if } n_j \in L, \\ t_0 + s \times \delta(n_0, n_c^d) & \text{if } n_j = n_c^d \text{ and if } n_c^d \notin L. \end{cases}$$

The underlying idea is that for each passenger the diversion threshold must not be exceeded proportionally to his direct travel. But at the same time it may be impossible to satisfy that constraint due to delays for doing various operations at nodes, past stochastic arrival times etc.

We are seeking to minimise the sum of the predicted arrival times by taking into consideration the number of disembarking passengers at each node.

Inactive Vehicle Management

A station node should be chosen for an empty vehicle and an associated maximal parking period. If no client is found within this time, the vehicle makes a new request for updating the previously taken decision. The choice of the parking node is provided by a probability law involving the distance of present vehicle position and the station node while considering the client arrival intensity of the candidate node.

3. SYSTEM ASSESSMENT

3.1 Data

Within this section the utilised reformulated data are presented since the real information can not be easily provided for publication. Nevertheless, the study is not going to be influenced and the intended proposed methodology remains valid, since under different data different numerical values will be resulted.

3.2 Operating area

The employed network is inspired by the Paris plan comprised of 288 nodes and 674 edges as shown in Figure 1. Travel times may vary during an implementation representing varying traffic conditions.

Approximately 15,400 clients are generated per hour according to a centripetal demand geometry (movements from the periphery towards the city centre). The maximal client waiting time at the origin node is of 10 minutes. The acceptable client detour threshold w.r.t. direct travel is taken equal to $s = 1.9$. Each vehicle has 5 available passenger seats and 3,744 vehicles are employed. The maximal stationary time of each idle vehicle is of 15 minutes. The employed scheme (demand intensity and the number of vehicles in service) reflects the actual situation in Paris. The involved centripetal demand geometry corresponds to the early morning hours, when population moves from the suburbs towards the city center.

4. SINGLE DETAILED SIMULATION ANALYSIS

4.1 Checking Client Arrival Rates

Statistics drawn for the simulation run with theoretical values are compared. Figure 2 illustrates verification the

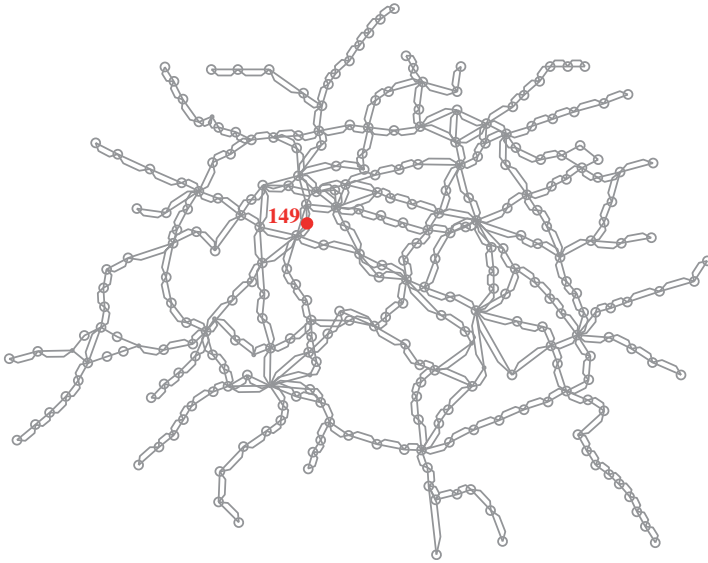


Fig. 1. Paris plan

employed demand. For every node i , the total number of clients appeared during the simulation divided by the simulation length is the y -coordinate whereas λ_i is the x -coordinate (288 points) corresponding to the client intensity at node i .

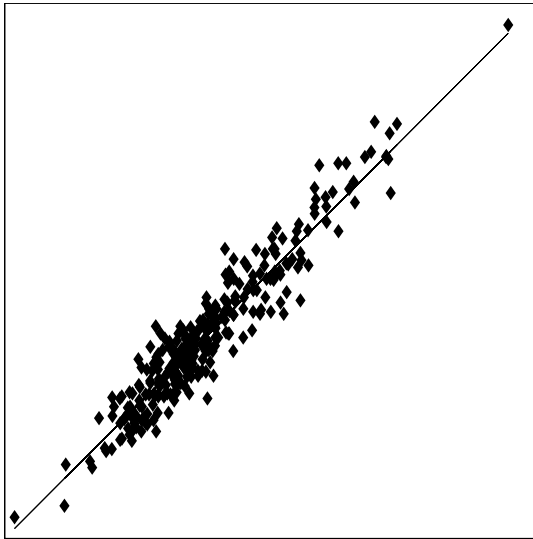


Fig. 2. Demand Verification: parameter λ_i

4.2 Abandonment

Customers quit their origin node after 10 mins from their arrival time, if no suitable vehicle is found during this period. The average abandonment rate for this simulation is 1.33%. This rate can be examined per node, revealing some *critical nodes* which can then be further and more carefully analysed.

4.3 Waiting Times and Queue Lengths

Global Statistics

The average waiting time of clients (who finally embarked in a vehicle) for the whole network is of 97 seconds (including the dialog duration) with a standard deviation of

99 seconds. Figure 3 represents the histogram of the client waiting times. The distribution is roughly exponential.

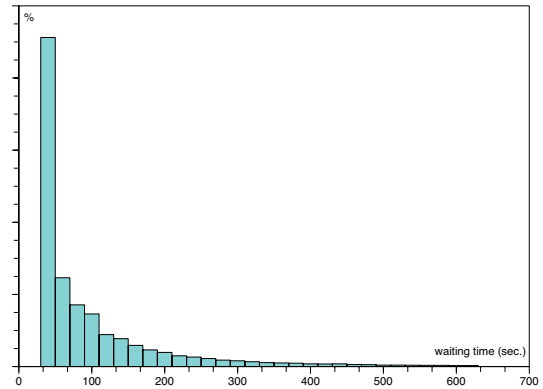


Fig. 3. Waiting Time Histogram

4.4 Queue Lengths

- The overall average client queue length is 1.54 and the per-node analysis shows a strong correlation with waiting times.
- The analysis can be focussed on particular nodes on demand (e.g. analysing critical nodes).

4.5 Measuring System Reliability

- The histogram of the *diversion ratio*, depicted in Figure 4, is evaluated as the ratio of the client effective trip duration over the direct trip duration (evaluated by the average distance from the client origin to client destination node by the shortest path — matrix δ). The average diversion ratio is equal to 1.54 with standard deviation of 0.39.
- For the *total diversion ratio*, illustrated in Fig. 5, the initial waiting time is included at the numerator of the ratio. The average total diversion ratio is equal to 1.64 with standard deviation of 0.40.

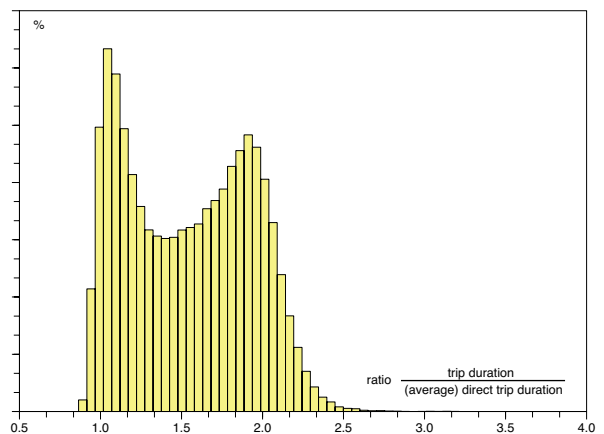


Fig. 4. Histogram Trajectory Detour

4.6 Car Activity

Number of clients served. For the 8 hour performed simulation, vehicles carried from 2.63 to 5.13 clients per hour with an average of 3.77 clients per hour.

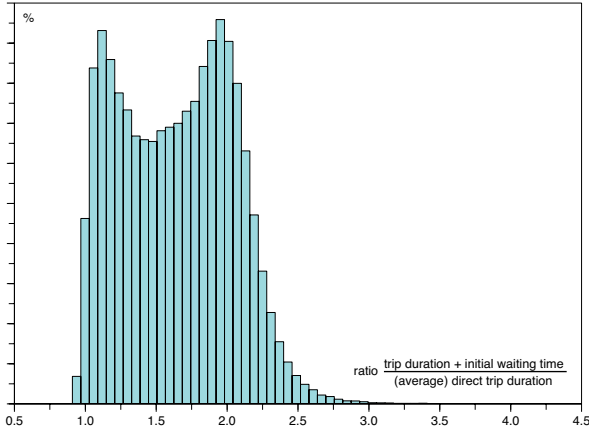


Fig. 5. Histogram Total Trajectory Detour

Average number of vehicle passengers

In average, vehicles carry 2.16 passengers (individual values range from 1.29 to 3.15). Figure 6 resumes the number of vehicle passengers and the percentage of time during which vehicles were occupied by the related customer number. As one can see, within the current the total available vehicle capacity was utilised only during 5% of the total time. What allows for a high service quality.

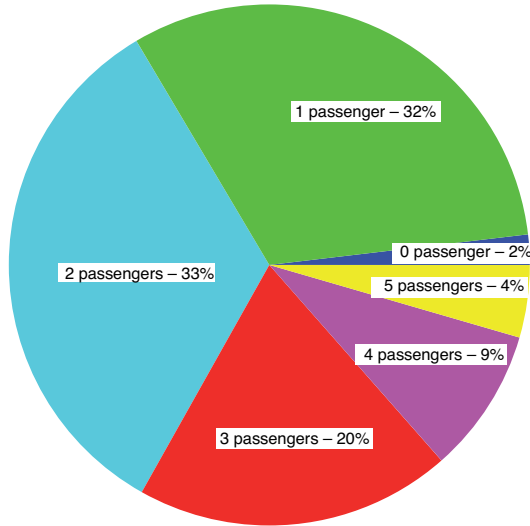


Fig. 6. Taxi Occupancy

Vehicle Activity

As Figure 7 illustrates cars

- circulate on network links for the 88% of the time,
- are stopped at nodes for interacting with passengers during 9% of the time,
- are parked at an empty state for the 3% of the time.

5. PARAMETER TUNING

Two important parameters are integrated into the study of “collective cars” performance:

- the threshold s which limits diversion in the decision algorithm related to the client acceptance or rejection by a given vehicle

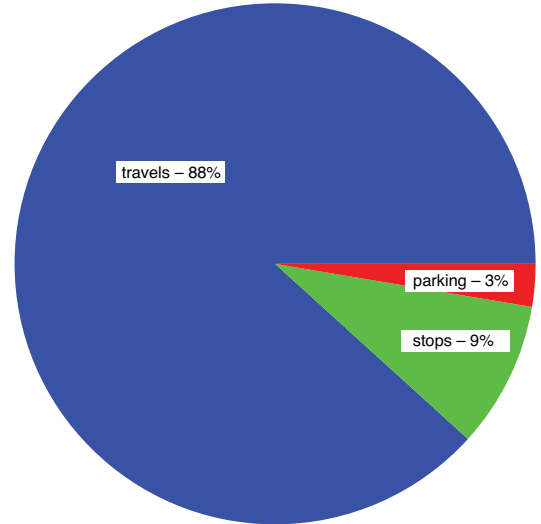


Fig. 7. Vehicle Activity

- the number n of vehicles in service.

These two parameters have an impact on almost all statistical indicators we may observe through simulations.

5.1 Service Quality Indicators (SQI)

Three classes of statistical indicators, characterising the system behaviour, can be defined:

- (1) SQI strongly positively correlated with each other. For this category, it suffices to retain only one statistical measure. This is the case of the *customer waiting time* and the *client queue length* at a node.
- (2) SQI which are independent and can only be directly observed. Thus, clients who have not found an appropriate vehicle during their maximal waiting period are only reflected by the *abandonment rate* since they left the system prematurely.
- (3) In addition, some indicators are conflicting and therefore they must be monitored simultaneously in order to achieve a reasonable trade-off: for example, increasing n will obviously improve all service quality indicators from the client point of view. At the same time, the average taxi activity will be reduced, which in return will increase all related costs and consequently fares.

Choice of SQI

During this study, the following three indicators are retained:

- x : the average *abandonment rate* over the whole network
- y : *minus* the average *number of clients transported* per taxi during a 8 hour simulation
- z : the average *total diversion ratio*.

- Indicator z is related to clients who effectively reached their desired destination. It incorporates *two* service quality indicators: the *initial client waiting time* and the *amount of diversion* of their effective journey compared to the direct trip.
- x accounts for the clients who finally gave up the system.

- Both previous measures certainly improve (i.e. *decrease*) as the number of taxis in service n , increases; therefore, $-y$ should be monitored to relativize this improvement. The *minus sign* has been included in order that, for all three indicators x, y, z , “better” is equivalent to “smaller”.

5.2 Methodology Adjusting Parameter Values

As previously discussed, three SQI measures x, y, z are chosen depending on two parameters s and n . We seek values of these parameters inducing values of x, y, z as small as possible. Hence, all reachable values of x, y, z lie on a 2D-surface in a 3D-space. A point has to be chosen lying on the lower left-hand border of this surface. This choice is not unique (Pareto optimality) and reflects the relative importance assigned to each indicator. Nevertheless, when two surfaces corresponding to two different situations (e.g. two geometries of demand) can be compared with respect to the positions of their lower left-hand borders, one can ascertain which one is the most favourable for the performance of the system.

In what follows, a methodology of analysis comparing two demand geometries is illustrated.

5.3 Comparison between Centripetal and Centrifugal Demands

A series of simulations is implemented for two demand geometries, a centripetal and a centrifugal demand, when varying values of s and n . In Figure 8 the red (lower) surface corresponds to the centripetal demand while the green surface is associated with the centrifugal demand. Both demands are of the same intensity and amount of imbalance (they correspond to reversed travels of clients from origins to destinations).

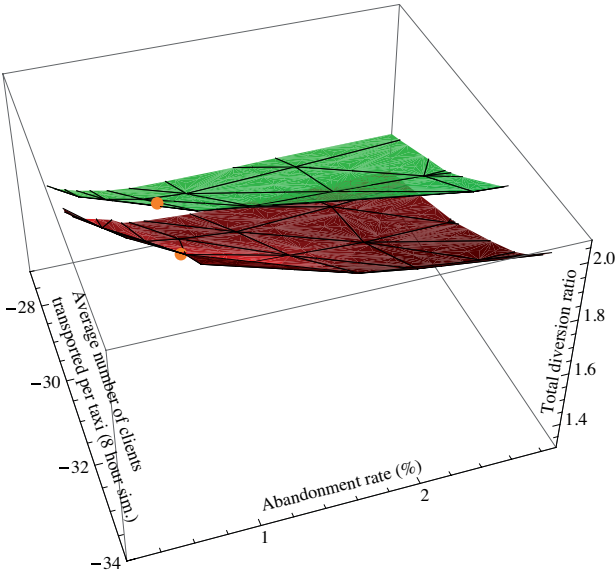


Fig. 8. Centripetal-Centrifugal 3D demands

For each of the two scenarios, a particular point on the corresponding surface is chosen in such a way that two of the three coordinates of those points are equal. We search for a difference over the third one. In order to facilitate the study, Figure 9 will be utilized illustrating a

2D representation of the surfaces in the (x, y) plane while the z coordinate is represented by its level curves. The level curves are indicated in square boxes in Figure 9.

The points chosen on each surface are located on the level curve 1.7 (that is, both achieve an average total detour ratio of 1.7) and they also both achieve a global abandonment rate (x coordinate) of 1%. However, the corresponding average number of transported clients per vehicle y is greater with the centripetal geometry (about 30 clients for simulations corresponding to 8 hours of real time) than with the centrifugal (only about 28.5). This is consistent with the fact that more vehicles are needed with the centrifugal demand to achieve those performances (3,910 versus 3,744). Finally, a different value of s is also needed: 1.98 versus 2.1.

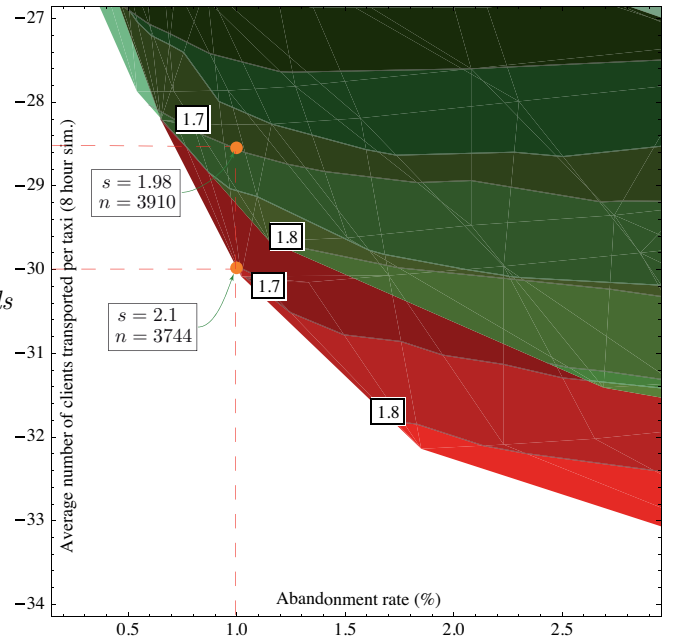


Fig. 9. Centripetal-Centrifugal 2D demands

One can conclude that the centripetal geometry of demand in a network having a topology inspired by the Paris metro plan, tending to accumulate vehicles towards the city center, is more favorable than the centrifugal one, which tends to disperse taxis toward the suburbs. Obviously, other topologies may lead to different conclusions (work not included in this paper).

6. CONCLUSION-FUTURE WORK

An efficient transportation mode is often perceived as an important support contributing to the numerous requirements of urban productivity. Public transport often is inadequate for daily metropolitan mobility and private car remains consumer’s first choice preserving confort and convenience. Therefore, cogestion is implied accompanied by difficult driving conditions and consequently raised accidents rates. Classical taxis could be a successful solution if only they were more affordable. Exploitation of the vehicle capacity within an accessible flexible system could be a promising idea to be explored, reducing transportation costs, limiting congestion and energy consumption. Systems like car sharing do not necessarily diminish the

passenger to vehicle ratio often followed by a poor spatial distribution. Carpooling schemes require passengers to administer the related arrangements (inevitably time consuming tasks) while vehicle itineraries are not necessarily optimised.

This paper suggests an autonomous DRT system, reducing commuter fares while assuring a quick delivery to destinations. A decentralised approach is studied, requiring only local information where each vehicle management is optimised independently of the others. Some other principal differences from the existing structures consist in an autonomous system operation, no requirement for prior seat reservation is any more necessary while the entire network is served and not only some specific areas. The related transit problem is studied from a DES approach. Thus, association of Optimisation and Operational Research methods combined with advanced simulation techniques will lead to an optimal system functioning and desired trade-offs. Specific control designs allocate customers to vehicles while the vehicle itinerary is dynamically optimised every time its state changes. Moreover, management of empty vehicles improves the system productivity while additional car costs are diminished. Since a whole category of decision algorithms can be conceived (in addition to the ones proposed in this study) a methodology evaluating the system performance according to the currently utilised scenario is discussed. Hence, client and vehicle metrics are presented such as client waiting times, abandon rates and detours, vehicle occupancy and activity etc.

At present, more sophisticated control policies related to client acceptance are about to be developed taking into consideration the stochastic demand model.

Aiming at an optimised system performance, all vehicle decisions are provided by associated algorithms taking into consideration the current system state. A transportation mode involving fully autonomous electric cars, where information technologies will be incorporated coordinating vehicle control and decisions, tuning and timing trips, can increase operational efficiency. Such a vehicle structure would also contribute to a successful management when recurring and non-recurring congestion, safety (human error constitutes a major factor to accidents) while it controls additional energy consumption. Many successful demonstrations and studies, on fully autonomous electric cars, are conducted in the USA and Europe, Tesla Motors (2016), Report-UK (2015) while current research investigates the problem of efficient risk resolution. Since present traffic regulation still prohibits entry of fully autonomous vehicles in traffic, specific road infrastructure and geometry design could be envisaged amongst other eventual possibilities as a first step towards an efficacious, innovative and accessible future transport mode.

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