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Simulation and Dynamical Analysis of Freeway Traffic*

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Abstract - *This paper discusses the problem of modelling and simulation of traffic systems, and presents the traffic simulator SITS (Simulator of Intelligent Transportation Systems). The SITS is based on a microscopic simulation approach considering different types of vehicles, drivers and roads. A dynamical analysis of several traffic phenomena is then addressed.*

Keywords: *Intelligent transportation systems, Simulation and modelling.*

1 Introduction

Nowadays we have a saturation of the transportation infrastructures due to the growing number of vehicles over the last five decades. This situation affects substantially our lives particularly in the urban areas, while people needs, to move rapidly between different places. The results are traffic congestion, accidents, transportation delays and larger vehicle pollution emissions. The difficulties concerned with this subject motivated the research community to center their attention in the area of ITS (Intelligent Transportation Systems).

ITS applies advanced communication, information and electronics technology to solve transportation problems such as, traffic congestion, safety, transport efficiency and environmental conservation. Therefore, we can say that the purpose of ITS is to take advantage of the appropriate technologies to create “more intelligent” roads, vehicles and users [1]. Computer simulation has become a common tool in the evaluation and development of ITS. The advantages of this tool are obvious. The simulation models can satisfy a wide range of requirements, such as: evaluating of alternative treatments, testing new designs, training personal and analyzing safety aspects.

Bearing these facts in mind, this paper is organized as follows. Section 2 discusses the state-of-the-art of modelling and simulation of ITS. Section 3 describes briefly the microsimulation model SITS. Section 4 presents simulation results related with the dynamic behaviour of a traffic system. Finally, section 5 presents some conclusions and outlines the perspectives towards future research.

2 Modelling and Simulation

In this section we give an overall view of the development of simulation models in road traffic planning and research, which is considered as the most prevalent in the transportation community. However, it should be noted that there are many other simulation models available for use in aviation, railroad and maritime transportation.

The traffic simulation models can be classified according to various criteria, namely, the scale of independent variables, the representation of the processes and levels of detail [2].

The classification according to the level of detail with which the traffic system is represented by the model can be divided in Microscopic, Mesoscopic and Macroscopic. The Microscopic simulation model describes both, the space-time behaviour of the system’s entities (*i.e.* vehicles and drivers) as well as their interactions at a high level of detail (individually). The Mesoscopic model represents most entities at a high level of detail, but describes their activities and interaction at a lower level of detail. The Macroscopic model represents entities and describes their activities and interactions at a low level of detail.

Presently, most traffic system simulation applications are microscopic in nature and based on the simulation of vehicle-vehicle interactions [5].

Microscopic traffic simulators are simulation tools that emulate realistically the flow of vehicles on a road network. Micro-simulation is used for evaluation prior to, or in parallel with, on-street operation. The main modelling components of a microscopic traffic simulation model are: an accurate representation of the road network geometry, a detailed modelling of individual vehicles behaviour and an explicit reproduction of traffic control plans. With these components it is possible to deal with ITS systems, like adaptive traffic control systems, automatic incident detection systems, dynamic vehicle guidance systems and advanced traffic management systems. The recent evolution of the microscopic simulators has taken advantages of the state-of-the-art in the development of object-oriented simulators and graphical user interfaces. There are a considerable number of developed microscopic simulation models. The SMARTEST project identified 58 of these models of which 19 are listed on Table 1.

Table 1- Types of models

Urban	Motorway	Combined	Other
HUTSIM	AUTOBAHN	AIMSUN2	ANATOLL
MICSTRAN	FREEVU	CORSIM	PHAROS
NETSIM	FRESIM	INTEGRATION	SHIVA
PADSIM	MIXIC	PARAMICS	SIMDAC
SITRA-B+	SISTM	TRANSIMS	

The type "other" models have been designed with specific objectives like modelling of the tactical level of driving and testing of intelligent vehicle algorithms. They provide a detailed roadway environment for a simulated robot-driving vehicle, to evaluate the safety and comfort conditions of a line of cars or to simulate strategies. In the sequel we give an overview of two of the micro simulation tools listed on the table 1.

SMARTEST is one simulation modelling project that covers the different areas of ATMS. It is applied to road transport European scheme tests and is the result of European Union research project. This project uses mathematical simulation modelling for dynamic traffic management problems. AIMSUN2 (Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks) [6] is one of the SMARTEST's software tool based on a microscopic simulation approach, which reproduces real traffic conditions in an urban network. It provides a detailed modelling of the traffic network, distinguishing between different types of vehicles and drivers, modelling incidents and conflicting manoeuvres.

TRANSIMS (Transportation Analysis and SIMulation System) models are used to create a virtual metropolitan region by the complete representation of the region's individuals, their activities, and the transportation infrastructure. The trips are planned to satisfy the activity patterns. After that, TRANSIMS simulates the movement of individuals across the transportation network. So a virtual world of travellers is created, which mimics the travelling and driving behaviour of real people in the region. The models "simple car-following" and "lane changing logic" are based on cellular automaton technique. This technique is based on a discrete approach where the road and street network is build from elements that can accommodate only one vehicle at a time unit. In this cellular automaton approach the vehicles move by jumping from the actual element to a new one according to rules describing the driver behaviour while maintaining the basic physics laws present in vehicle movements [4].

3 The SITS simulation package

SITS is a software tool based on a microscopic simulation approach, which reproduces real traffic conditions in an urban or non-urban network. The program provides a detailed modelling of the traffic network, distinguishing between different types of vehicles and drivers and considering a wide range of network geometries.

SITS models each vehicle as a separate entity in the network according to the state diagram showing in figure 1. Therefore, are defined five states {1-aceleration, 2-breaking, 3-cruise speed, 4-stopped, 5-collision} that represent the possible vehicle states in a traffic systems.

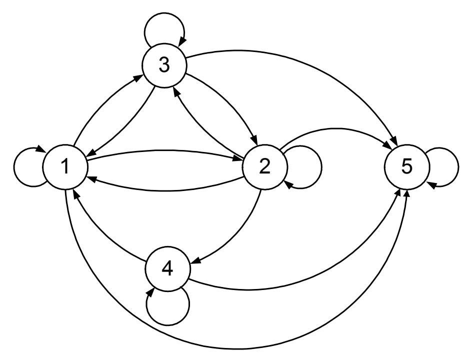

Figure 1 - SITS state diagram (1-aceleration, 2-breaking, 3-cruise speed, 4-stopped, 5-collision)

In this modelling structure, so called State-Oriented Modelling (SOM), every single vehicle in the network has one possible state for each sampling period. The transition between each state depends on the driver behaviour model and its surrounding environment. Some transitions are not possible; for instance, it is not possible to move from state 4 (stopped) to state 2 (breaking), although it is possible to move from state 2 to state 4.

At this stage of development the SITS considers different types of driver behaviour model, namely car following (where drivers follow their leaders and try to match their speed), free flow (where each driver tries to attain its own desired speed) and lane changing logic. Furthermore, SITS allows also the analysis of signal control devices and different road geometries considering road junctions and access ramps.

The simulation model adopted in the SITS is a stochastic one. Some of the processes include random variables such as, individual vehicle speed and input flow. These values are generated randomly according to a pre-defined amplitude interval.

The main types of input data to the simulator are the network description, the drivers and vehicles specifications and the traffic conditions. The output of SITS consists not only in a continuously animated graphical representation of the traffic network but also the data gathered by the detectors, originating different types of printouts.

SITS tracks the movements of individual vehicles to a resolution of 10^{-2} sec and uses five different colours to represent the individual vehicle states; namely, stopped (red), acceleration (green), breaking (yellow), cruise speed (blue) and collision (black), as represented on figure 2.

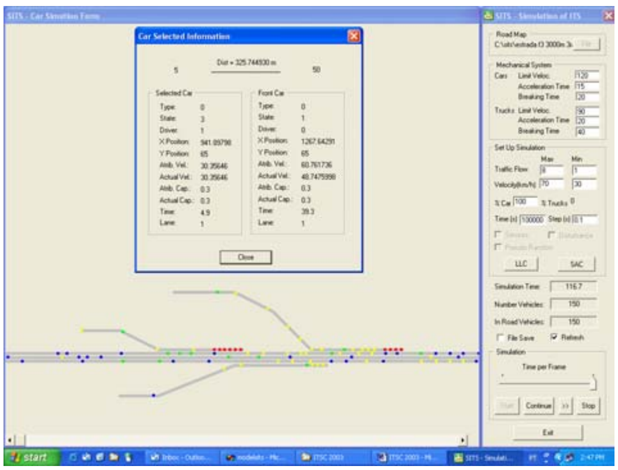

Figure 2 – SITS animated graphical representation

4 Simulation results and dynamical analysis

In the dynamic analysis are applied tools of systems theory and automatic control. In this line of thought, a set of simulation experiments were developed in order to estimate the influence of the vehicle speed $v(x,t)$, the road length (l) and the number of lanes (k) in the traffic flow $\phi(x,t)$ at the road coordinate x and time t. In fact, traffic flow is a non-linear and time variant system but, in the sequel, it is shown that the Fourier Transform can be used to analyse the system dynamics.

The first group of experiments considers a one-lane road (*i.e.*, $k = 1$) with length $l = 1000$ m. Across the road are placed $m = 21$ sensors equally spaced. Therefore, sensor 1 (S_1) is placed at the beginning of the road (*i.e.*, at $x = 0$) and the last sensor (S_{21}) at the end (*i.e.*, at $x = l$). The Transfer Function (*TF*) between two sensors is calculated for a traffic flow at the beginning of the road $\phi_1(t) \in [1, 8]$ vehicles s^{-1} and a vehicle speed $v_1(t) \in [30, 70]$ km h^{-1}, that is, $v_1(t) \in [v_{av} - \Delta v,\ v_{av} + \Delta v]$, where $v_{av} = 50$ km h^{-1} is the average vehicle speed and $\Delta v = 20$ km h^{-1} is the maximum speed variation. These values are generated according to a uniform probability distribution function.

Figure 3 shows the polar plot of the *TF* $G^1_{21,1}(s) = \Phi_{21}(s)/\Phi_1(s)$ between the traffic flow at sensors S_{21} and S_1 on the one-lane, where $\Phi_i(s) = \mathcal{F}\{\phi_i(t)\}$ ($i = 1, 21$). It can be observed that the result is distinct from those usual in systems theory revealing a large variability. Moreover, due to the stochastic nature of the phenomena involved different experiments using the same input range parameters result in different *TF*s.

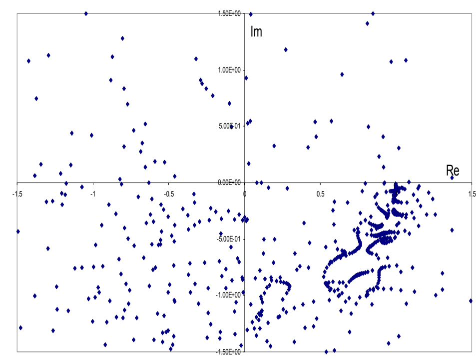

Figure 3 - Polar plot of the *TF* $G^1_{21,1}(s)$ for one experiment with $\phi_1(t) \in [1, 8]$ vehicles s^{-1} and $v_1(t) \in [30, 70]$ km h^{-1}. ($v_{av} = 50$ km h^{-1}, $\Delta v = 20$ km h^{-1})

This phenomenon makes the analysis complex and experience demonstrates that efficient tools capable of rendering clear results are still lacking. Moreover, classical models are adapted to 'deterministic' tasks, and are not well adapted to the 'random' operation that occurs in systems with a non-structured and changing environment.

In order to overcome the problems, alternative concepts are required. Statistics is a mathematical tool well adapted to handle a large volume of data but not capable of dealing with time-dependent relations. Therefore, to overcome the limitations of statistics, it is adapted a new method [3], that takes advantage of the Fourier transform by embedding both tools.

In this line of thought, the first stage of the new modelling formalism starts by comprising a set of input variables that are free to change independently (*ivs*) and a set of output variables that depend on the previous ones (*ovs*). In a traffic system the *ivs* and *ovs* are defined as $\phi^k(x_i,t)$ and $\phi^k(x_j,t)$, that is the traffic flows at positions x_i and x_j, respectively, at time t and for the k^{th} lane ($k = 1,2,3\ldots$).

The second stage of the formalism consists on embedding the statistical analysis into the Fourier transform through the algorithm:

i) A statistical sample is obtained by carrying out a large number (n) of experiments having appropriate time/space evolutions. All the *ivs* and *ovs* are calculated and sampled in the time domain.

ii) The Fourier transform is computed for each of the *ivs* and *ovs.*

iii) Statistical indices are calculated for the Fourier spectra obtained in *ii).*

iv) The values of the statistical indices calculated in *iii)* (for all the variables and for each frequency) are collected on a 'composite' frequency response entitled Statistical Transfer Function *(STF)* of each *TF*.

The previous procedure may be repeated for different numerical parameters (*e.g.*, traffic flow, vehicle speed, road geometry) and the partial conclusions integrated in a broader paradigm.

To illustrate the proposed modelling concept, was repeated the previous simulation for a sample of $n = 2000$ and it was observed the existence of a convergence of the *STF*, $T_{21,1}^{1}(s)$, as show in Fig. 4

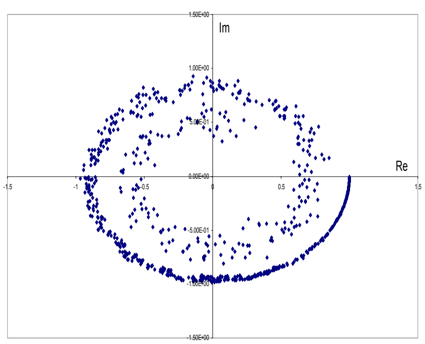

Figure 4 - The *STF* $T_{21,1}^{1}(s)$ for $n = 2000$ experiments with $\phi_1(t) \in [1, 8]$ vehicles s^{-1} and $v_1(t) \in [30, 70]$ km h^{-1} ($v_{av} = 50$ km h^{-1}, $\Delta v = 20$ km h^{-1})

Based on this result we can approximate numerically the *STF* to a third order system with time delay, yielding the approximate expression:

$$T_{21,1}^{1}(s) = \frac{e^{-\tau s}}{\left(\frac{s}{p}+1\right)^{3}} \qquad (1)$$

The pair of parameters (τ, p) varies with the average speed v_{av} and its range of variation Δv, the road length l and the input vehicle flow ϕ_1. Figures 5 and 6 show τ and p versus Δv for $v_{av} = 50$ km h^{-1}, respectively.

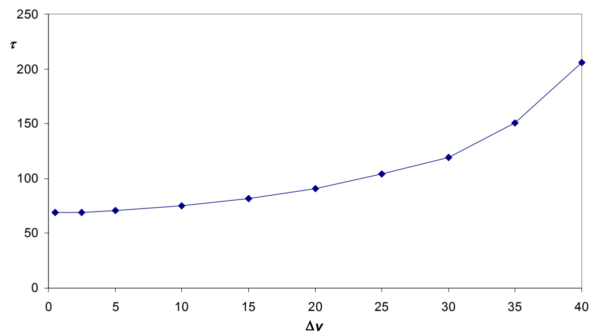

Figure 5 – Time delay τ *versus* Δv for an average vehicle speed $v_{av} = 50$ km h^{-1}, a one-lane road and $\phi_1(t) \in [1, 8]$ vehicles s^{-1}

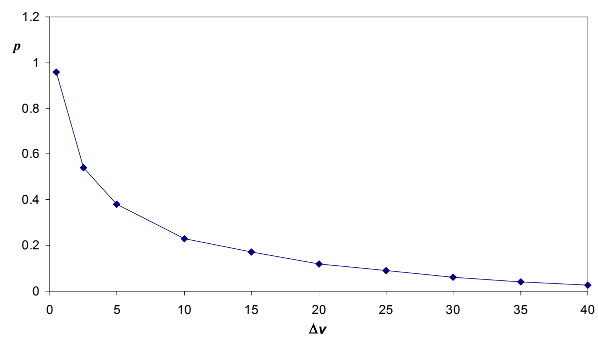

Figure 6 - Pole p *versus* Δv for an average vehicle speed $v_{av} = 50$ km h^{-1}, a one-lane road and $\phi_1(t) \in [1, 8]$ vehicles s^{-1}

It is interesting to note that:

$$(\tau, p) \rightarrow \begin{cases} (\infty, 0) & \text{when } \Delta v \rightarrow v_{av} \\ \left(\frac{l}{v_{av}}, \infty\right) & \text{when } \Delta v \rightarrow 0 \end{cases} \qquad (2)$$

These results are consistent with our experience that suggests a pure transport delay $T(s) \approx e^{-\tau s}$ ($\tau = l/v_{av}$), when $\Delta v \rightarrow 0$, and $T(s) \approx 0$, when $\Delta v \rightarrow v_{av}$ (because of the existence of a blocking cars, with zero speed, on the road).

On the other hand, figures 7 and 8 show τ and p versus v_{av} for $\Delta v = 20$ km h^{-1}, respectively.

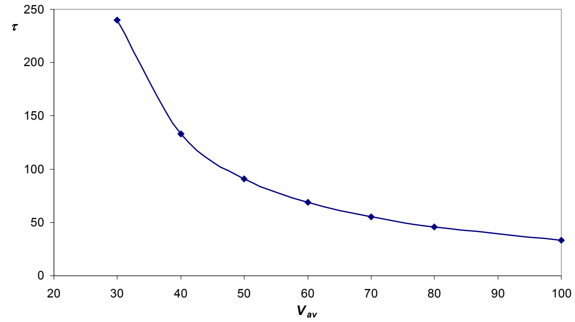

Figure 7 - Time delay τ *versus* v_{av} for an range of variation $\Delta v = 20$ km h^{-1}, a one-lane road and $\phi_1(t) \in [1, 8]$ vehicles s^{-1}

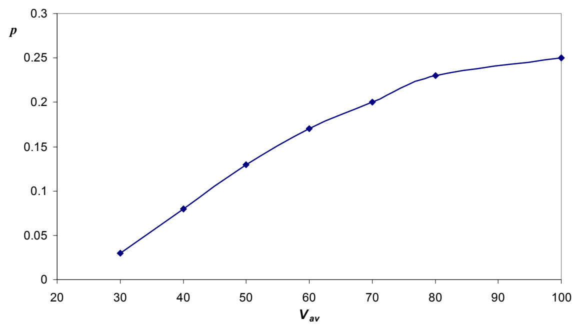

Figure 8 - Pole p *versus* v_{av} for an range of variation $\Delta v = 20$ km h^{-1}, a one-lane road and $\phi_1(t) \in [1, 8]$ vehicles s^{-1}

In this case we have:

$$(\tau, p) \rightarrow \begin{cases} (\infty, 0) & \text{when } v_{av} \rightarrow \Delta v \\ (0, \infty) & \text{when } v_{av} \rightarrow \infty \end{cases} \tag{3}$$

which has a similar intuitive interpretation. Based on these conclusions further experiments, considering multi-lane roads, are presently under development.

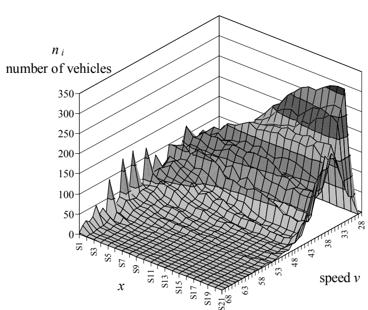

Figure 9 - Number of vehicles n_i *vs*. speed v and sensor position x, for a one-lane road and $\phi_1(t) \in [1, 8]$ vehicles s^{-1} $v_1(t) \in [30, 70]$ km h^{-1}

In a second set of different experiments it is analysed the interference between vehicles travelling on the same lane. The relation between the numbers of following vehicles n_i, the sensor coordinate x and the speed v is shown in Fig. 9.

It can be observed that, the vehicles interfere with others in the same lane because they have different speeds. This results in a diminishing in the speed of the faster vehicle if the one preceding it is a slower one.

A complementary perspective (Fig. 10) for the analysis of the traffic flow along the road, can be quantified through the entropy $H(x) = \frac{1}{N}\sum_i f_i \ln(f_i)$, where $f_i = n_i/N$, $N = 2048$ is the total number of vehicles used in the simulation and n_i is the absolute frequency.

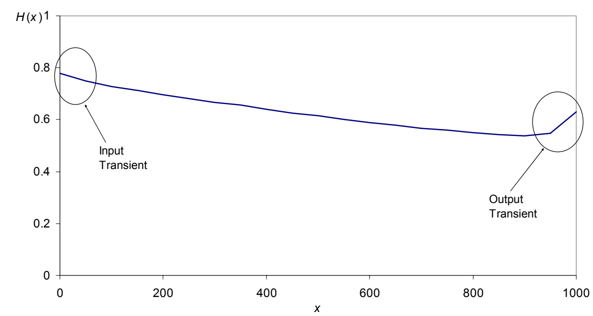

Figure 10 - Entropy $H(x)$ of the traffic velocity *vs.* the position x for a road with length $l = 1000$ m and vehicle speeds in the range $v_1(t) \in [30, 70]$ km h^{-1} and $\phi_1(t) \in [1, 8]$ vehicles s^{-1}

The entropy decreases along the road because the faster vehicles have to diminish their speeds to match the speed of the slower vehicles. Figure 10 also identifies two transients, namely the input and output transients.

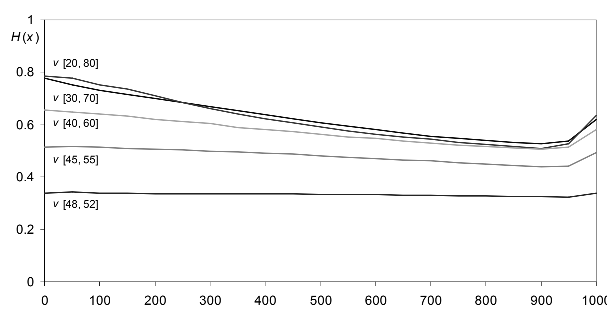

Figure 11 - Entropy $H(x)$ of the traffic velocity *vs.* the position x for a one-lane road with length $l = 1000$ m and average vehicle speed of $v_{av} = 50$ km h^{-1} with $\phi_1(t) \in [1, 8]$ vehicles s^{-1}

A third set of simulations analyses the entropy variation for different ranges of vehicle speed. Figure 11 shows the results for an average vehicle speed of $v_{av} = 50$ km h^{-1} in the ranges $v_1(t) \in [20,80]$, $v_1(t) \in [30, 70]$, $v_1(t) \in [40, 60]$, $v_1(t) \in [45, 55]$ and $v_1(t) \in [48, 52]$ km h^{-1} (*i.e.* $v_{av} = 50$ km h^{-1} and $\Delta v = \{30, 20, 10, 5, 2\}$).

It can be observed that, for small velocity ranges, the entropy remains almost constant and the transients are difficult to detect. This is justified by the fact that the vehicles have a small difference of speeds that originates a minimal interference among the vehicles. Also relevant are the rise of the output transient and the convergence of entropy, for larger velocity ranges.

In Fig. 12 is compared the variation of entropy $H(x)$ for roads with one and three lanes. At the beginning of the road the entropy has almost the same value for both cases, but for distances $x > 500$ m, the entropy for the one-lane road decrease faster than for the three-lanes case. This phenomenon occurs because, for a road with three-lanes, it is applied a lane change scheme that gives priority to the right lane. Moreover, in a three-lanes road, the entropy of the right lane is lower than the entropy of the left lane.

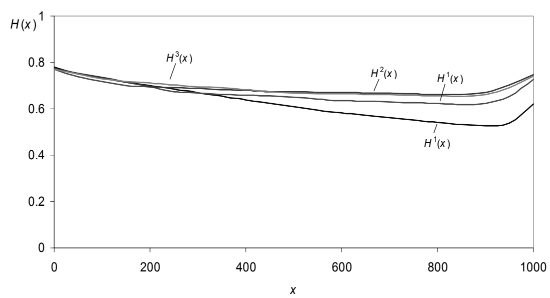

Figure 12 - Entropy $H(x)$ of the traffic velocity *vs.* the position x for one-lane and three-lanes roads with length $l = 1000$ m and $v_1(t) \in [30, 70]$ km h^{-1} and $\phi_1(t) \in [1, 8]$ vehicles s^{-1}

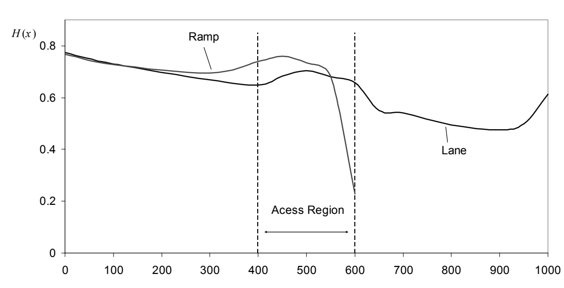

Figure 13 - Entropy $H(x)$ of the traffic velocity *vs.* the position x for a one-lane road ($l = 1000$ m) and an access ramp ($l = 200$ m), $v_1(t) \in [30, 70]$ km h^{-1} and $\phi_1(t) \in [1, 8]$ vehicles s^{-1} in both lanes

In a last experiment it is analysed the entropy $H(x)$ for a one-lane road with a ramp access (Fig. 13). We conclude that we have a strong variation mainly along the access region $400 < x < 600$, particularly the access ramp.

5 Conclusions

In this paper was described a software tool based on a microscopic simulation approach, to reproduce real traffic conditions in an urban or non-urban network. At this stage of development the SITS considers different types of driver behaviour model, namely car following, free flow and lane changing logic. On the next stage of development we will include better driver behaviour models and traffic safety models. Another important improvement is the inclusion of aspects such as, ramp-metering and signal control devices.

Several experiments were carried out in order to analyse the dynamics of the traffic systems. The results of using classic system theory tools point out that it is possible to develop traffic systems, including the knowledge gathered with automatic control algorithms. In his line of thought it was also presented a new modelling formalism based on the embedding of statistics and Fourier transform.

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