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Simulation and Dynamic Management of Highway Traffic Flow: Application to Ramp Metering

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--***ABSTRACT***--

The abstract: The works presented in this paper exploits the advantages of simulation tools for the regulation of road traffic. The illustration is made through the implementation of a ramp metering using the ALINEA ***(Asservissement Linéaire d'entrée Autoroutière)*** *strategy to ensure a maximum throughput. The studied site includes a section of a freeway with real data. Simulation results show a clear improvement in traffic conditions using the ALINEA regulation strategy.*

Keywords*-Traffic Regulation, Simulation, ALINEA, Ramp, Congestions.*

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I. INTRODUCTION

Traffic conditions on urban and interurban road networks are becoming increasingly difficult every year. Studies conducted in recent years show an increase in recurrent congestion and a terrifying augmentation in greenhouse gas emissions (expressed in tons of CO_2) with a harmful impact on the quality of life of citizens.

In order to improve road traffic conditions without widening the existing roads, it quickly became apparent that there is a need to establish models whose objective is multiple, as shown in the following figure:

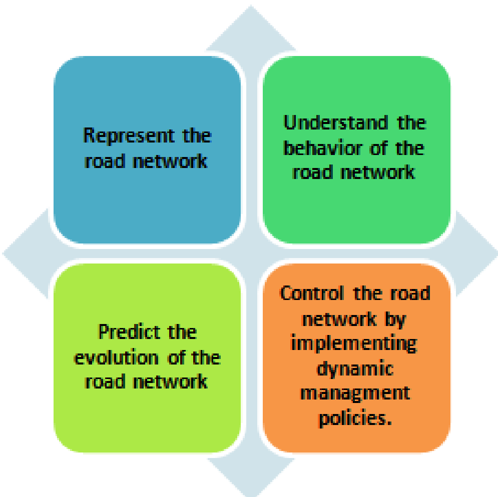

Fig.1: Objectives of the models

A range of simulation tools has been developed based on these models in order to help road network operators to better manage road traffic.

The usefulness of simulation in the field of road traffic was felt given the lack of analytical methods and the need to perform tests and evaluation of proposed actions before their application.

The purpose of this article is to present the importance of simulation tools for road traffic management, discussed in section 2. Section 3 is devoted to the regulation of road traffic. The implementation of the ALINEA strategy for ramp metering and the results are discussed in section 4. Finally, conclusions and perspectives are given in section 5.

II. SIMULATION OF ROAD TRAFFIC FLOW

The traffic phenomena are very complexes resulting from a supply-demand system; these phenomena have been studied since many years to allow mainly the control this system [1, 2, 3, and 4].

It is a question of identifying and forecast these phenomena in order to be able, among others, to anticipate them in order to manage them as well as possible. We distinguish forecasts short, medium and long time forecasts. the short term makes it possible to control the flows (dynamic re-allocation, ramp metering, etc.) and to provide near-real-time or forecast traffic information , the medium term to provide forecast information , the long term makes it possible to redefine the infrastructures and to influence the demand (urban plan, highway plan).

Traffic Analysis and Simulation[5]

Studies on the identification of road traffic phenomena and on the understanding of both individual and collective behavior are pursued using a number of investigative means. Studies are conducted on the road, on track and more recently in the laboratories with simulators. These studies are carried out by observing the behaviors "from outside" (via equipment in sensors of the infrastructure) or "from inside" of the vehicle (embedded measurements).

Measurements of "outside" behaviors do not describe the specific activities of drivers, but rather the results of these activities in interactions with the road environment. The "embedded" measures of behavior make it possible to collect finer indicators relating to the dynamics of the driver's actions in relation to changes in his environment. Measures "from the outside" are less "explanatory" and are limited when it comes to deepen the cognitive aspects of driving. Finally, the "external" studies brought a statistical and mathematical vision of the traffic, then rather characterized as a flow. "Internal" studies, more recent because they require a certain technology, have led to a so-called self-centered vision of traffic, characterized by the interaction of the elements of the system: users, infrastructures and operators (for example: highway management companies).

Simulation models derived from these two traffic approaches have thus emerged: some simulate the traffic using models based on mathematical equations; the others simulate the traffic using computer models of interactions between autonomous entities.

Road traffic is a dynamic problem associated with complex processes that cannot easily be described analytically [6]. To a large extent, these processes are characterized by the interaction of several components of the system, called entities. The number of parameters is important and the interactions are complex. The simulation models implemented undertake to realistically mimic the behavior and interactions of real entities (cars, trucks ...) in order to reproduce as closely as possible the behavior of the system: road traffic.

Simulation is today an effective tool for the analysis, reproduction and prediction of a wide variety of problems, difficult to study by other means too expensive or dangerous. This tool is now in current use; it has been favored by the democratization of new computer techniques and the emergence of new material technologies (Figure 2).

Fig.2: Examples of Traffic Simulation Tools (AIMSUN©, PARAMICS©)

III. TRAFFIC REGULATION

The challenges of traffic management

Limiting the possibilities of extending the road network today requires optimizing the use of existing networks. In addition, road traffic generates a significant set of nuisances of all types that must be mitigated:

➢ Loss of time related to the congestion phases.

➢ Road insecurity.
➢ Environmental impacts: noise pollution, greenhouse gas emissions, local air pollution.

Dynamic traffic management tools can help optimize networks and reduce road noise by:
✓ Maximizing flow and limiting congestion.
✓ Delaying or constituting an alternative to extensions / extensions of the network.
✓ Promoting a better sharing of current roads, especially to promote public transport.

Observation on our road networks:

- Network not able to sell peak traffic volumes, as shown in the figure above: in non-regulation mode, we notice the traffic demand exceeds the capacity of the road network.
- Need to reduce congestion volumes ...
- ... and the cost of their externalities

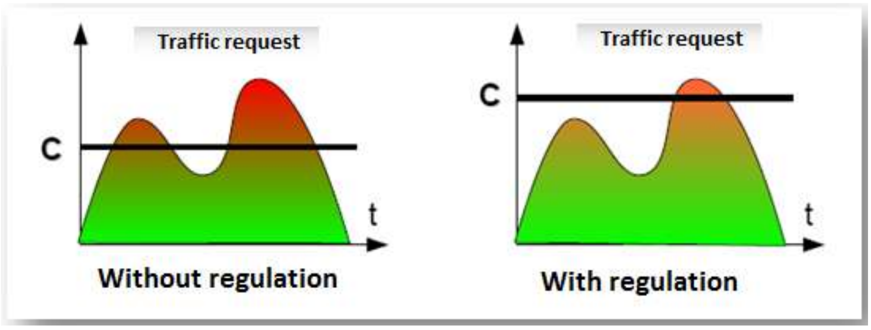

Fig.3: Traffic demand, with and without regulation

So the major objective of the regulation is to increase the capacity of existing networks by using dynamic regulation strategies, such as speed regulation, access control, dynamic management of channels, etc.

The objectives of ramp metering

Before defining the main objectives of ramp metering, we first define congestion, and to do this we need to define the relationship between demand and capacity of a pathway. We have seen in the first part that a portion of the way can be presented by a fundamental diagram which illustrates the rate of occupation as a function of the flow, as shown in the following figure.

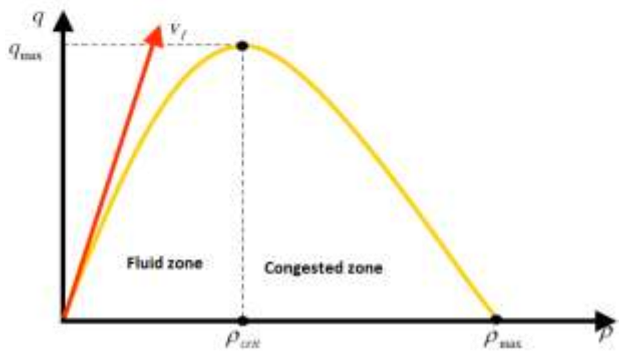

Fig.4: The fundamental diagram

The fundamental diagram shows that before reaching the maximum flow rate, which corresponds to the critical occupancy rate, we have a fluid flow of vehicles. Beyond this critical point, we have a saturated state: it is congestion.

Methods of regulating an access

We can restrict the flow of incoming vehicles on a mainline by:

✓ Modifying the path of access to decrease its capacity.
✓ By arranging the access by devices allowing to channel the incoming vehicles such as the marking on the ground…

- ✓ Put in place fires that will periodically interrupt the flow of incoming vehicles. The setting up of its lights is manual and is controlled by a local clock adapted to the traffic conditions.
- ✓ Setting up fires adapting in real time to traffic conditions, correlated to a device for controlling access queues.

The last regulatory solution seems to be the most optimal solution. However, other solutions can also have beneficial effects. Only the analysis of cases, traffic conditions, existing equipment and economic conditions will determine the most optimal solution.

The objective of access control is to regulate ramp flows by traffic lights in order to preserve the capacity of the freeway, thereby limiting the appearance of traffic lights. Congestions in the vicinity of the accesses. Existing strategies break down into two types: fixed fire strategies where the value of the fire cycle is calculated offline using historical data [7] and adaptive strategies where the fire cycle is calculated using real time [8].

For adaptive strategies, there are two types: isolated and coordinated. Isolated strategies use real-time measurements only in the vicinity of controlled access [9], whereas the command generated by coordinated strategies takes into account all traffic conditions on the axis or network. regulated using all the real-time measurements of the regulated area.

IV. REGULATING A RAMP ON A HIGHWAY

In order to maintain the capacity and the fluidity of the freeway represented in the figure below, the principle of access control is to maintain the density ρ_s (in number of vehicles / km / lane) on the main section close to the critical density ρ_{cr}, corresponding to an optimal use of the capacity offered by the freeway.

This control acts by means of the traffic lights, on the input flow of the rampq_r (in number of vehicles / h). In other words, one acts on the flow of the ramps in order to stabilize the density of the traffic on the principal way. Mainstream segment.

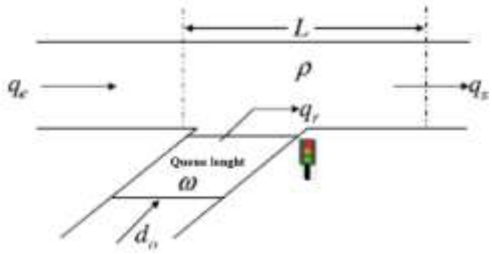

Fig.5: Freeway Section with Ramp

A. Description of the simulated site

The simulated network consists of the A25 freeway network in the direction of Lille in France. The total length of the simulated network is approximately 5 km (see the figure below).

Fig.6: Site description

The freeway network is equipped with electromagnetic loops, which will make it possible to measure traffic flow and speed. And also we have an operating system that supports real-time data collection and storage in a database of searchable traffic.We present the studied site in the form of the following figure:

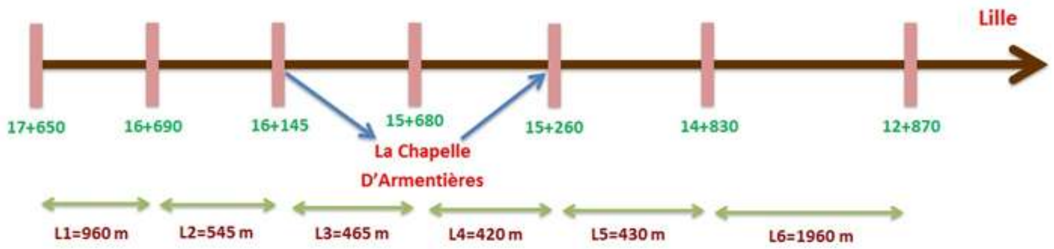

Fig.7: simulated site schema

L_i: The length of each segment. It represents the length between two data sensors.

B. Summary description of the traffic model

We used the METANET program, based on a second-order macroscopic model. METANET represents a network in the form of an oriented graph composed of links corresponding to the freeway sections. Each link has uniform characteristics (i.e., with no entry or exit ramps and no major changes in its geometry).

Changes in the characteristics of the link or in the geometry of the road (appearance of an entry or exit ramp) are identified by the introduction of a node. Each link is divided into segments of length L_i.

C. The parameters used

The critical densityρ_{cr}, the parameter a and the free speed v_f, come from the fundamental diagram of May:

$$V_e(\rho_i) = v_f.\exp\left(-\frac{1}{a}\left(\frac{\rho_i}{\rho_{cr}}\right)^a\right) \qquad (1)$$

ρ_i : The density of the segment i.

We used the following relationships to calculate the values:The law of conservation:

$$\mathbf{rho(k+1) = rho(k) + \frac{T_s}{L}(q_{in} - q_{out} + q_r)} \qquad (2)$$

$$\mathbf{q = rho * v * \lambda} \qquad (3)$$

T_s : The step of the simulation.
L : The length of the section studied the place where the congestion will form.
λ : Number of lanes. In our case, we have$\lambda = 2$.

The main way

→If $\rho < \rho_{cr}$ (ρrepresents the density of the segment).
We will calculate the flow of the main track using the following equation:

$$\mathbf{offre = V_e.\rho_i.\lambda} \qquad (4)$$

ρ_i : The density of the segment i.
V_e : The equilibrium speed.

$$\mathbf{V_e(\rho_i) = v_f.\exp\left(-\frac{1}{a}\left(\frac{\rho_i}{\rho_{cr}}\right)^a\right)} \qquad (5)$$

$$offre = v_f.\exp\left(-\frac{1}{a}\left(\frac{\rho_i}{\rho_{cr}}\right)^a\right).\rho_i.\lambda \qquad (6)$$

→Else if $(\rho = \rho_{cr})$

$$offre = q_{max}.\lambda \qquad (7)$$

And if $\text{demand} = d + \frac{w}{T_s}$

$$q_e = min(offre, demand) \qquad (8)$$

The on-ramp: We have the following relation which links between the calculated r (which is our control variable) and the flow q_r.

$$\mathbf{q_r = r.\hat{q}_r (9)}$$

And

$$\mathbf{\hat{q}_r = min(\hat{q}_{r,1}, \hat{q}_{r,2}) \qquad (10)}$$

Such as :

$$\hat{q}_{r,1} = d_0 + \frac{w}{T_s} \quad (11) \mathbf{\hat{q}_{r,2} = q_{sat}. min\left(1, \frac{\rho_{max} - \rho}{\rho_{max} - \rho_{cr}}\right) \qquad (12)}$$

Queue of the ramp: is calculated using the following equation:

$$\boldsymbol{w(k+1) = w(k) + T_s[d(k) - q_r(k)] \qquad (13)}$$

D.Description of ALINEA Strategy

ALINEA (Asservissement Linéaire d'entrée Autoroutière) is an isolated ramp metering strategy. It is based on the control theory of linear systems. ALINEA's operation consists in maintaining the density on the downstream section of the convergent in the vicinity of its capacity. The chosen set point is close to the density
Critical is an optimal use of the capacity offered by the freeway.

The command law ALINEA is written:

$$\boldsymbol{r(k) = r(k-1) + K_p(\rho_{cr} - \rho_s(k)) \qquad (14)}$$

This control strategy calculates a rate r included in the interval$[r_{min}, r_{max}]$.
$K_p = 70$ veh/h : Gain ALINEA.
The latter is subject to constraints:

✓ If the calculated green time is less than the minimum green time, it is reduced to the minimum green time.
✓ If the calculated green time is greater than the maximum green duration, it is reduced to the cycle time (retraction of red).

During our simulations, the duration of the cycle is equal to $C = 40$ seconds, with a duration of green and orange lights of 35 seconds maximum. The minimum duration of red is 5 seconds in normal operation. These durations, used by the operators, seem appropriate since they minimize the stops on the ramps. Users are constantly moving in the queue to the traffic light. Thus, the following constraints are taken into account:

✓ Cycle time: 40 seconds.
✓ $Vertmin = 15$ seconds (10 seconds of green + 5 seconds of orange), so $rmin = 15/40 = 0.375$.
✓ $Vertmax = 35$ Seconds (30 seconds of green + 5 seconds of orange), so $rmax = 35/40 = 0.875$.

E. The values of the parameters used

ρ_s	The density in the intersection section between the ramp and the highway.
v_s	Average speed.
q_s	The average flow.
q_e	The input rate in this section. This quantity is also called the demand on the main track.
w	The length of the queue in number of vehicles.
q_r	The flow authorized to enter the main track.
T_s	The step of the simulation.
q_{sat}	The saturation flow of the ramp.
ρ_{max}	The maximum density on the main track.
ρ_c	The critical density of the main track.
d_0, d	The request on the ramp (the data is extracted from an Excel file).
q_{max}	The maximum flow of the main track.
The data used are from 22/03/2013 from 06:00 to 10:00.	
In the interest of realizing a case study close to reality, we have assumed that 10% of the flow of segment No. 3, is released by the exit ramp.	

TABLE 1: The parameters used

F. The results of the simulation

After the application of the ALINEA command, the following figure shows the evolution of the density without control, with the ALINEA command and the critical density.

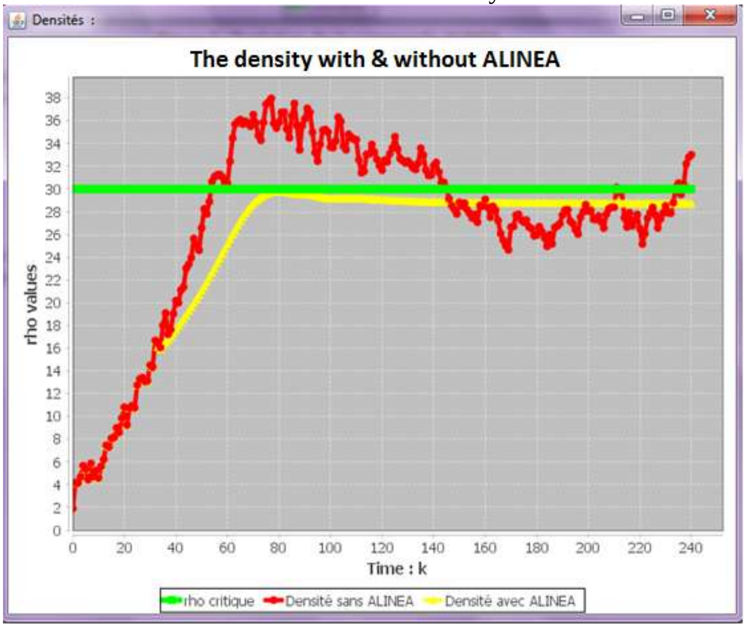

Fig.8: Evolution of density with & without ALINEA control

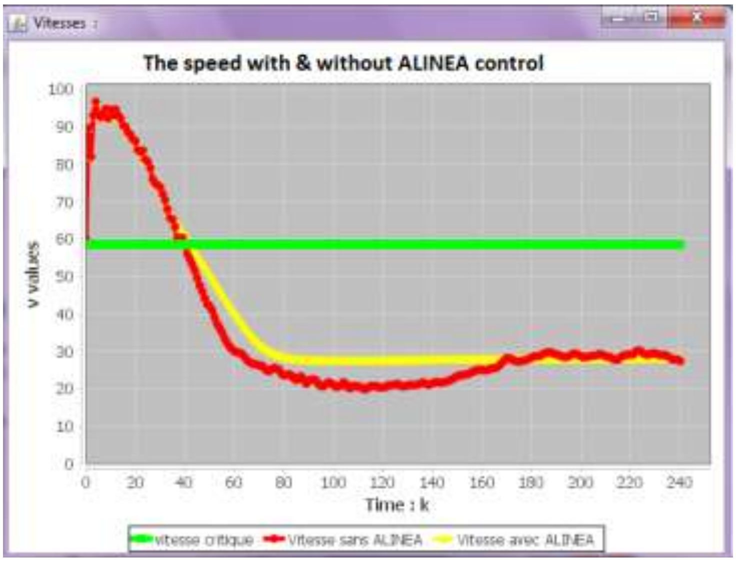

Fig.9: Evolution of speed with & without ALINEA control

We notice that after the application of ALINEA, we obtained the following results:

✓ The density obtained with ALINEA is strictly lower than the critical density, so according to the fundamental diagram seen previously, we will be in the fluid zone and we will never arrive at the congested zone.
✓ The speed obtained with ALINEA is higher than the speed without ALINEA; it means that we improve the speed of the vehicles.

During peak hours, there is significant demand. With the ALINEA command, you can stabilize the density around the critical value and increase the speed.

G. Criteria for evaluating control strategies

The evaluation criteria chosen for simulation and on-site correspond to those commonly used by operators. We distinguish:

Total Time Spent in Network (TTP) This is the total time spent by all vehicles in the system. This criterion includes the time spent on the highway plus the ramps. Expressed in (veh * h), the TTP is calculated according to:

$$TTP = T\sum_{K=1}^{K}\sum_{i=1}^{N}\rho_i\,(K)\Delta_i \qquad (15)$$

Total Travel Distance (TPD) This is the distance traveled by all vehicles in the system. It is expressed in (veh.km). The criterion (TPD) is calculated according to:

$$DTP = T\sum_{K=1}^{K}\sum_{i=1}^{N}q_i\,(K)\Delta_i \qquad (16)$$

Where qi is expressed in (veh / h) is the measured flow rate of the station (i). The other variables are the same as those of the TTP criterion.
Generalized average speed: This is the generalized average speed calculated from the knowledge of the indices: total distance traveled and the total time spent in the system. The criterion (Vm) is expressed in km / h and is given by $Vm \;=\; DPT\;/\;TPT$

Pollutant emissions CO: Among the pollutants, the criteria considered were restricted to the emission of carbon monoxide (CO). The exact calculation of its criteria is quite complex and requires a thorough knowledge of the fleet running on the network.

H. Results of the study in simulation

Comparaison pour la A25

Critères	Sans commande	ALINEA	GAIN %
TTP veh*h	437.9595099518...	404.83420293490...	7.563554681250...
Vmoy km/h	55.19654375613...	63.884632977657...	15.74027761575...
Emission CO	191367.3059703...	184982.77719380...	3.336269350808...

Fig.10: Comparison values

The total time spent by all vehicles in the system decreased by 7.6%, the calculated average generalized speed increased by 15.7% and we obtained a reduction of CO emissions by 3.4%.

V. CONCLUSION

The purpose of this article was to present the importance of simulation tools for road traffic management, and mainly we addressed the traffic regulation. In this context we have briefly defined the access control strategies and in particular ALINEA. And from the studied site, we presented and discussed the results obtained from the application of ALINEA on a ramp of a highway.

The integration of the ALINEA strategy into a multi-level multi-agent simulator is being implemented. Other work in progress is concerned with control with Model Free Control(MFC). The interest will be to compare the results of the two strategies.

The MFC has many advantages and that is probably what explains the industrial successes of today.

1) Its simplicity, a few lines are enough to expose the principles.
2) The number of synthesis parameters is very small. The corrector is synthesized once for all the regulations which brings to 2 the number of these parameters.
3) It has an intrinsic decoupling of the tracking dynamics (imposed by the reference trajectory) of the regulation dynamics (imposed by the corrector).
4) Any linear system, or not, is reduced to a pure integrating system whose sympathetic properties are well known in command.
5) Model errors, disturbances, defects ... are rejected in "block", i.e. we are not trying to distinguish their effects through models.

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