Automatic Bottleneck Detection Based on Traffic Hysteresis Phenomena: An Application to Paris Highway Network

Oscar Sánchez[1] and Omar Mekkaoui[2]

[1] Facultad de Ingeniería Universidad Autónoma del Estado de México
Cerro de Coatepec s/n, Ciudad Universitaria, 50130, Toluca, Estado de México, Mexico
osanchez@uaemex.mx
[2] THEMA-Université de Cergy-Pontoise, 33, Bd du Port, 95000, Cergy, France
Omar.mekkaoui@eco.u-cergy.fr

Abstract. This paper refers to the problematic that the phenomenon of traffic hysteresis induces from a macroscopic overview. Firstly, the document presents a topological analysis of traffic hysteresis in two levels of variation: density and flow. The referred analysis takes into account temporal and spatial components of the phenomena and is based on empirical data obtained from a freeway bottleneck configuration. Secondly, a mathematical model supported on the basic traffic equation is formalized in order to describe the phenomenon of hysteresis. The econometric adjustment of the model follows this stage with a discussion about the possible extensions of this model. Finally, the proposed model is applied to the A-14 highway and presented later on. Thereafter, some implications of the hysteresis phenomenon are discussed on the basis of economical planning and evaluation of transport systems.

1 Introduction

Several mathematical models and techniques have been proposed with the purpose of formalizing the relation between different macroscopic variables of traffic, such as speed, flow and concentration. This formalization related to the empirical studies and the inclusion of external factors that impact traffic stream has lead us into a paradigm renewal about the relation that those variables maintain over the years (e.g. see [1]).

The restating of paradigms merges from different circumstances that have an impact on the relationship vehicle-infrastructure-driver. (a) The technological advance that implies infrastructure improvements as well as vehicle performance inducing less wheel friction, and enhancing high speed stream. (b) The adaptability nature of drivers that guide them to take more risks, particularly, in the reduction of vehicle-to-vehicle safety margin. The process of constant renewal is important due to the fact that most of the planning, socioeconomic, and infrastructure management studies lie on such paradigms. Following this renewal process, this document not only revises the previous overview about hysteresis, but also includes spatial and temporal factors. The first ones are related to the configuration of the infrastructure while the second ones relate to the variation of the demand. Is precisely bottleneck infrastructure that induces queue formation as well as the traffic phenomenon known as traffic hysteresis (see [2]). The proposed approach is empirical and consists generally, in analyzing such phenomenon by using macroscopic traffic data and the relations of their basic

T. Böhme et al. (Eds.): IICS 2004, LNCS 3473, pp. 236–251, 2006.

equation. A theoretical treatment of hysteresis based on a microscopic approach can be revised in [3] or [4].

Diagram flow-concentration is particularly used in model building that embodies different stages of hysteresis. The development of such models is supported firstly, in the analysis of the flow-time (*q-t*) diagram characteristics as well as the speed-time (*u-t*), flow-speed (*q-u*) and flow-concentration (*q-k*) diagrams applied to an urban bottleneck road configuration in the Parisian A-14 Highway. Secondly, the model is based on the characterization of hysteresis phenomenon stages through the flow-speed and flow-concentration diagrams. These two model components, retaken on section 2, were described in [5] and are essential to characterize the four phases of hysteresis (section 3) in which the assumption is, a linear behavior tendency in each of them by simplicity. On the knowledge of these considerations, the analytical solution to the model is simple. However, its complexity lies on the identification of break points tendencies between two consecutive phases. In order to solve this difficulty two econometric techniques are proposed. The first one is a hypothesis trial based on Chow's test that allows the identification of tendency rupture (section 4). The second one is a structural econometric model often applied in time series estimation. Due to the fact that the amount of processing information required to adjust the model is elevated, an algorithm, for the first approach, is proposed (section 5) to find break points of each hysteresis stage. This last tool is considerable to identify or surveying conflictive road sections (black points) in dense congested or highly demanded networks. This conflictive section identification allows to detail studies to reduce or eliminate external effects of congestion heading the transport system to a more efficient performance level.

2 Traffic Hysteresis

In this section an empirical and inductive procedure is followed in order to introduce the hysteresis concept. Pursuing this goal, in first place, the theory of traffic stream based on a macroscopic approach for describing different traffic regimes is pointed out. In second place, and based on empirical data, the temporal variation of macroscopic traffic variables, such as flow and speed, presented in a bottleneck configuration structure are analyzed. Finally, the theoretical and empirical elements are put together to prove hysteresis phenomenon presence in diagrams *q-u* and *u-k*.

2.1 Relating Macroscopic Variables, Traffic Regimes and Hysteresis

The macroscopic relation of traffic was first introduced by Wardrop in 1952 [6] and after reformulated by Gerlough and Huber in 1975 [7]. The relation could be valid when variables of traffic are treated as a continuous or discrete variable (see respectively [8] and [9]). In the discrete variable case:

$$q_i = \overline{u}_i \overline{k}_i . \tag{1}$$

In which q represents vehicular flow measured in the i point of a transversal section. Variables $\overline{u}_i$ and $\overline{k}_i$ represent, average speed and concentration respectively (see [10] or [11]). Several studies have tried to determine the relation between two out of the three variables of this equation. Empirical studies (e.g. [9]) show that the diagram flow-speed indicates four regimes to measure traffic congestion (see [8]), which are shown in diagrams *q-u* and *k-q* on figure 1.

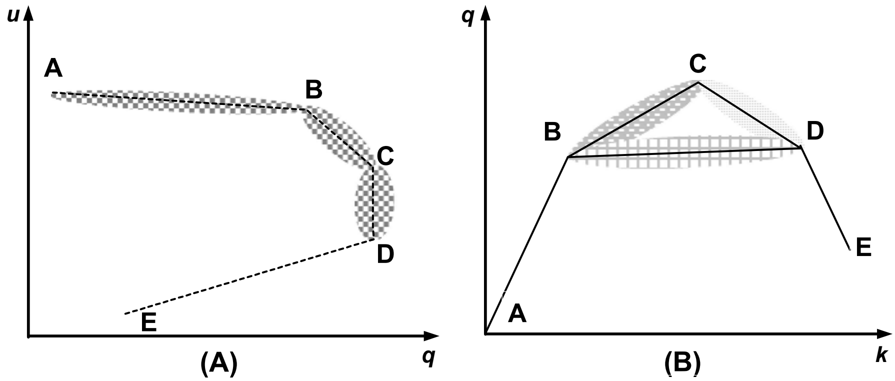

Fig. 1. Saturation regimes for flow-speed (a) and flow-stream (b)

2.1.1 Uncongested Regime

This regime known also as not congested [9], is formed by two stages: (a) *free flow*. It occurs when demand is relatively low. The number of vehicles in the infrastructure is reduced and motorists drive at a desired speed; (b) *Car following*: during this stage, infrastructure endures a crescent vehicular volume without reaching its full capacity. Drivers are restricted by front vehicles and cannot drive at the desired speed. During first stage (segment A-B on figure 1a), average speed varies around top speed limits. This tendency prolongs for an important interval of stream. During the second stage (segment B-C on figure 1a), speed begins to decrease and the transition regime is reached. slope line in *q-u* and *k-q* diagrams identifies uncongested regime.

2.1.2 Transition Regime

It is also known as discharged queue stages. At this stage infrastructure receives maximum traffic and discharges it according to its capacity. When this level is reached, an additional incorporation of vehicles leads into the formation of queues (peak hour). Once the demand begins to diminish (after peak hours), infrastructure begins to discharge queues (segment C-D on figure 1.a). The phenomenon of hysteresis takes place in this regime. This phenomena means that the trajectory followed by the traffic variables (i.e. *q-u* or *q-k* relationship) during the loading phase of the infrastructure is not the same as in the unloading one. Diagram *k-q* on figure 1.b shows this phenomena. In the limits of car-following regime (point C on figure 1.b) a tendency rupture between the represented segments B-C and C-D appears. Indeed, while the B-C segments reflects that flow and concentration level increase, the C-D segment shows an increasing on the concentration (induced by an increasing demand) along with a diminishing on flow levels. In the limit of D a new tendency rupture appears. This is due to the absence of more traffic (the hyper saturated regime will be reached if more traffic arrives to the infrastructure). The infrastructure begins to unload in a different trajectory this time. The last situation is indicated in figure 1b by segment D-C (whenever there is more traffic, the supersaturated system will be shown). Theoretically and empirically ([5] and [12] respectively) it had been shown that traffic hysteresis is not only motivated by the increasing or decreasing of demand. But also because of the recurrent congestion in peak hours (i.e. that induced by vehicle interaction) as well as the not recurrent one (e.g. blocking, accidents, bad weather, temporary reduction of infrastructure capacity).

2.1.3 Hypercongested Regime

In this regime, flow and speed decrease, but concentration continues to grow. This tendency prevails until all vehicles remain immobile during a certain time interval (segment D-E figure 1a). At his moment, average speed is null, concentration is the highest and the flow null. This system is completely unstable; it is also called "within a queue" and should be treated carefully in planning studies (see discussion on this topic in [5]).

2.2 From Empirical Studies to Hysteresis Morphology

The goals in this case study are multiple. (a) Validate and select the obtained data on the field about recurrent and not recurrent congestion. (b) Analyze the repercussion of demand variation over the basic equation relations through a dynamic perspective (adding time variable to the whole analysis). (c) Study each and all different stages of the blocking phenomenon (i.e. beginning, propagation and disappearing), the formation and propagation of waiting lines in relation to time (demand variation), and space (corridor configuration).

2.2.1 The Case Study

The case study corresponds to a section of the urban highway A-14 tunnel located in the La Défense sector (Northwest Paris). Such two lane section is 1.4 kilometers long (segment 1-5 in figure 2) and channels traffic which runs towards either Porte de Paris-La Défense or to the Boulevard (Boulevard Périphérique) coming from the Norwest suburbs. Two ramps inside the tunnel allow vehicles in and out towards Paris and Puteaux respectively. At the tunnel exit (section 5 in figure 2) a pair of kilometers ahead, a traffic light system regulates the entering of traffic towards Paris. This road section is equipped with five loops that automatically register (measurement section) traffic flow and speed (transversal section 1-5 in figure 2) every five minutes. The analyzed information takes into consideration include 5-days from 6 to 23 hours of registering during the months of January and March 1998.

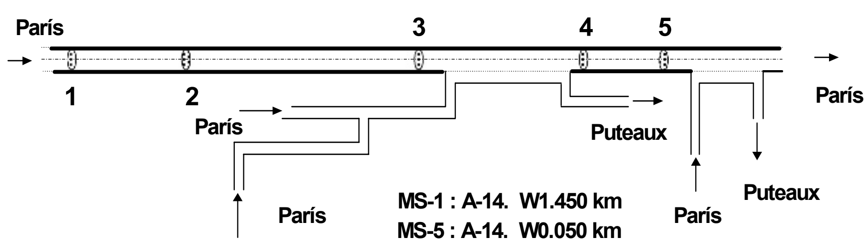

Fig. 2. Location and configuration of observation points (MS) in A-14 French Highway (La Défense sector)

2.2.2 Impact of the Temporal and Spatial Factors over Flow-Speed Relationship

The configuration of the studied section shows, a priori, that traffic conditions in the Measurements Sections (MS) are not equal. Therefore, the resultant macroscopic relations will reflect different traffic phenomenon (see [9]). In section 3-5, for example there is shown vehicles transference, and the stream continuity previous to section 3 is disturbed. Similarly happens in section 5. Indeed when we observe flow and speed variation along the day at MS-5, we will notice recursive reduction of the average speed during peak hours (from 8:00 a.m. to 9:12 a.m. in the morning and from 19:00 to 20:12 in the afternoon (see figure 3). Moreover, a slight diminishing on stream can also be seen (the variation tending to decrease is more important in the morning than in the afternoon). If macroscopic traffic stream theory states that in a hypercongested regime flow decreases with speed: why does the flow remain constant when speed decreases? Not recurrent congestion and vehicle interaction are the cause of speed reduction. As mentioned before, at the latest part of section 3 (section 3-5) there is a stream transfer zone due to ramps. Anytime the traffic is higher, the transference is more intense: downward vehicles in section 5 stay blocked longer time intervals and their average speed reduces. After passing the transfer section, vehicles running into Paris could be stopped: the regulation system imposed by the red light on the traffic lights. This kind of delay is more likely to appear in peak hours due to the fact that the quantity of vehicles waiting for the green light increases; thereafter, a queue is formed and propagated downward section 5-3 inducing new blocking zone. In order to verify this hypothesis, a look on average speed and flow variation should

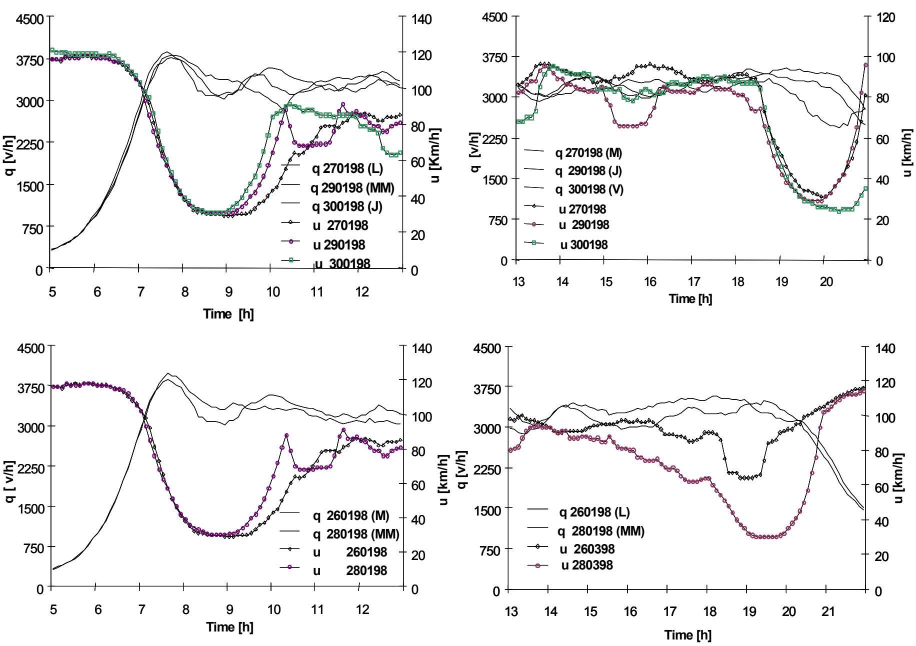

Fig. 3. Stream variation and average speed along the day (P0 5, 2 lanes)

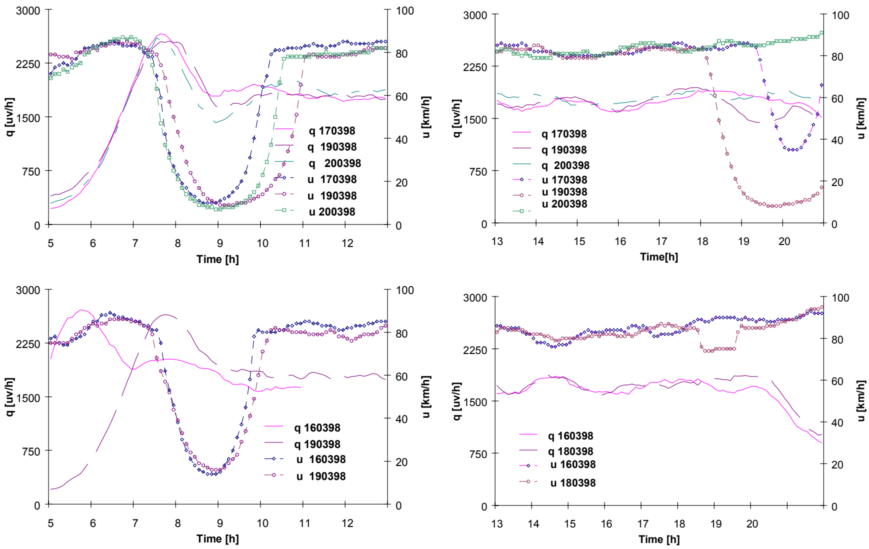

Fig. 4. Speed-flow diagrams and traffic hysteresis (PO 1, 2 lanes)

be taken to a section beforeMS-5. In the MS-1, for example, we have on the one hand, at the beginning of the day, the flow is not high (2500 v/h, see figure 4). However, the same speed reduction phenomena appear even in infrastructures of constant capacity (2 lanes road as in section 5). Consequently, one may conclude that vehicle interaction hardly contributes to speed reduction. On the other hand, the beginning of speed reduction in section 1 and 5 is out of step (about 30´ minutes in the morning). This out of step time corresponds to the queue propagation time generated by access infrastructures (ramps), which work as bottleneck; as well as by the traffic lights.

It is also noticeable that the reduction in average speed has, above all, an exogenous and not recurrent nature due to the fact that it is not presented neither systematically nor in frequency (i.e. no speed variation on March16, 17 and 18 in the afternoon) or in magnitude (i.e. speed variation on March 17, 19 and 20 in the afternoon). Let us see how this situation is reflected in the case of the basic diagram.

2.3 Basic Diagrams and Hysteresis

Few studies have analyzed in a detailed way the implication of traffic hysteresis in terms of stream conditions. In [12], all macroscopic traffic relations in the previously mentioned A-14 section Highway are analyzed (see section 1.2). Figure 5, extracted from the herein analysis, shows the way in which traffic conditions evolve along the morning in MS-5. Diagram flow-speed values display a great dispersion in the transition regime. Between 7:00-7:54 the flow decreases same as speed. Between 8:00-8:54 flow tends to decrease but speed starts increasing. This effect is reflected in the basic diagram *k*-*q* due to the loop alike trajectory described by the data. All this leading us to the phenomenon of traffic hysteresis: concentration values (obtained through equation 1) during the loading phase of the infrastructure (the flow between 7:00-7.54 h) do not correspond to the ones from the unloading phase (the flow between 10:00 - 12:54). The variation on traffic concentration is explained by the formation of queues as well as by demand variation (number of cars arriving to highway). Let us have in mind that transfer zone and traffic light systems eliminate continuum flow causing queues at peak hours. When peak hour start (after 7:00), a few vehicles are delayed (low concentration 40-60upc/km). As time goes by demand increases to its top limit, the number of blocked vehicles grows and the lines grow too (between 7:00 -7:30) Demand starts diminishing as well as blocked vehicles in the line (unload phase between 9:00-12:54). At this moment concentration levels are the lowest respect to loading phase. Once queue formation in MS-5 has been displayed, what effect provokes its propagation? Figure 6, a very illustrative view of macroscopic relations in section 1 brings some answers to this question. Firstly, we confirm that loading and unloading phases of transition regime are more evident, which at the time indicates that queue from section 1 is more important. Vehicles remain blocked for a longer time interval; therefore their average speed is much more reduced. Secondly, notice that the quantity of vehicles passing trough section 2 is inferior to those passing through section 5. Basic diagram also reflects the dichotomy of the transition regime so hysteresis is much more marked. Indeed, the propagation of waiting lines has a notable influence on hysteresis appearing, which at the time marks the so mentioned dichotomy. Bottleneck starts queue formation, that is a fact, but it is also a fact that those lines are propagated downward inducing vehicles to be blocked during a longer time period, therefrom their average speed is much more reduced. As a consequence of such phenomenon, vehicle stream in downward sections would be inferior to the stream in next to bottleneck sections.

The previous analysis states that intrinsic factors on the phenomenon of congestion have an impact on hysteresis intensity. However, there are external factors that lead into its formation such as: adverse weather conditions, not recurrent congestion presence (infrastructure maintaining or accidents), infrastructure configuration, road signs, traffic regulation devices, infrastructure location, etc. The evaluation of these factors influence on hysteresis goes beyond the scope of this analysis and will be matter of new studies. As for now, we will only limit this document to propose a model to characterize the different phases of the already described phenomenon.

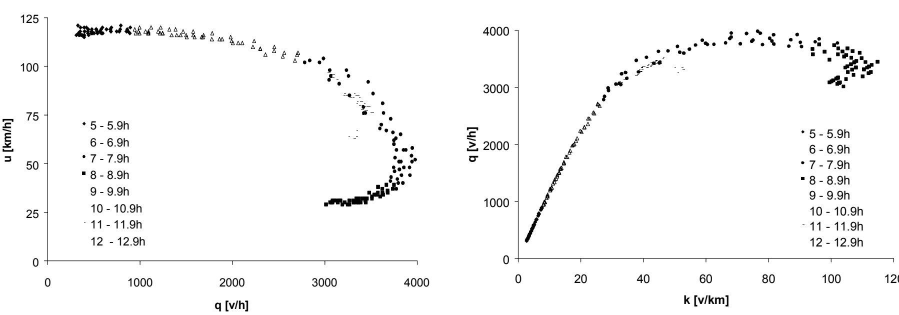

Fig. 5. Traffic hysteresis in *q-u* and *k-q* relations in MS 5 of study studied section

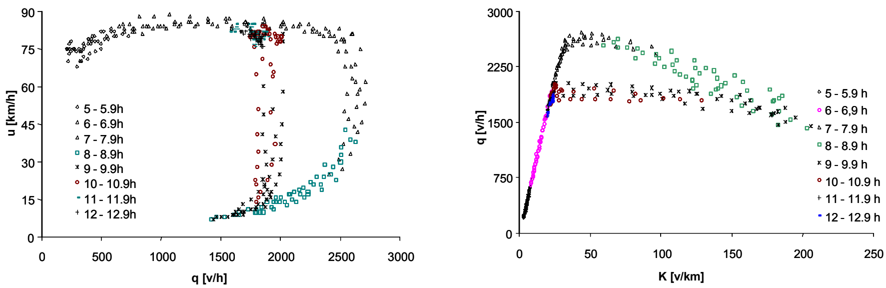

Fig. 6. Traffic hysteresis in q-u and k-q diagrams in MS1

3 The Proposed Models

The proposed model does not correspond directly to the macroscopic relations shown in section 2 due to the fact that congestion process is considered to be formed both by the uncongested regime and the transition regime. (cf. Section2) Actually, supersaturated or hyper-congested regime [13] represents in anyway a second level of hysteresis, which may be linked to not recurrent congestion presence (accidents, maintaining or infrastructure building) and that will be matter of future investigations. So far, the present model limits itself to the study of recurrent congestion effects parting from the flow-concentration relation. The following paragraphs make a description about the way in which the already mentioned traffic regimes (see section 2.1) have been characterized.

3.1 Modeling Traffic Regimes

Consider the basic diagram shown in figure 7. In this diagram hysteresis has been represented by two regimes: uncongested regime(*segment O-F-S*) and transition regime(segment *S-H-F)*, as well as the tendency break points *F, S* and *H.*

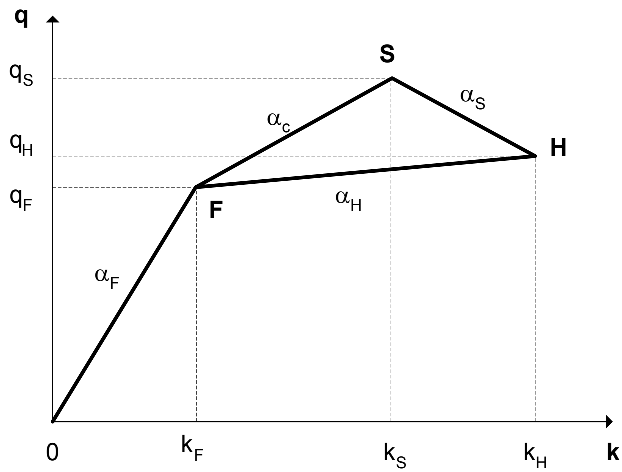

Fig. 7. Modeling Traffic hysteresis characterization in basic diagram (k-q)

3.1.1 Uncongested Regime

As indicated in section 2.1, the flowing regime takes two phases: steady stream or free flow and strained stream or car following. Steady stream corresponds to segment *O-F* and can be characterized by slope line α_F. During that phase there is a proportional increment in both concentration and stream that ends up in *F* point associated to stream q_F and concentration k_F. Such point means a frontier (break point) that marks the tendency rupture that starts the new strained stream stage (segment *F-S*). In this stage, there still is a proportional stream and concentration increasing though in a slower ratio (in relation to steady stream), which is defined by the slope α_C. In a strained stream condition, infrastructure continues receiving traffic until it reaches its capacity limit (critical point S defined by q_S and k_S). This occurs when a new tendency rupture takes place and the free flow regime becomes transition regime.

3.1.2 Transition Regime

Starting from *S* point, infrastructure capacity is exceeded and the quantity of vehicles running continues to grow (saturation phase). Queue is considerable now and starts propagating themselves downwards. At this moment, total of vehicles running out of the analyzed section diminish. However, concentration continues growing with a slope α_S. Concentration reaches its limit (*H* point, defined by k_H *and* q_H) marking the beginning of the phase nominated as hysteresis in which traffic diminishes (indicated by the decreasing of concentration), as well as flow a α_S ratio. Provided additional cars do not enter to the section, infrastructure will continue unloading until reaching its critical point *F* representing the frontier between steady and strained stream. Due to the intensity of hysteresis phenomenon observed in diagram *q-k* on the empirical studies, it had been considered that the transition process among regimes might be estimated by using a straight line. Nevertheless even though intensity is more important, the described principles would be valid as long as not lineal curves are employed.

3.2 Identifying Break Points

In the proposed model, the identification of initial/terminal points of each hysteresis phase is characterized by a regular increasing of flow and concentration. In first stage, the congestion first stage is represented by a regular increment of these variables until the arrival of their limits, point in which a difference in growing tendencies between steady and strained stream phases (*F* point in figure 7) can be distinguished. Afterwards, in the saturation phase, concentration may continue increasing, but infrastructure is not able to unload the quantity of vehicles that run into it anymore. Subsequently, queue formed and flow decreases (section *S-H*, figure 7). Finally, in the hysteresis phase, when demand levels decrease, the intensity of vehicles running into is lower in relation to the preceding phase. The vehicles remaining blocked in waiting lines start abandoning infrastructure, action that reduces both stream and concentration, but at more inferior rates than in the preceding stage. This way, the characterization of the described model could be outlined by identifying the infrastructure's initial points of the demand state: loading and unloading vehicles.

3.2.1 Traffic Stream Loading State

It is characterized by positive variation in concentration between two consecutive intervals of time *t,* and is conformed by the steady stream and strained stream phases of the non-congested regime as well as by the saturation phase of the transition regime. Taking into account the linear hypothesis which links break points with the geometrical relation from figure 1, it is possible to determine in an analytical way the slope variables and resultant stream for each of those phases. Table 1 summarizes the result from that operation. It is important to mention that in free flow regime, regime u_F represents the maximum circulation speed observed.

3.2.2 Traffic Stream Unloading State

The characteristic of this state is the negative variation of the concentration along two consecutive instants. The hysteresis phase within the transition regime and the steady stream within the flowing regime form it. As in the previous state, results are shown in table 2 and were obtained by considering geometrical relations in figure 7.

Table 1. Analytical values of the loading stream state

Phase	*Condition*	*Validity*	*Slope*	*Flow*
Uncongested (F)	$\frac{\Delta q(+)}{\Delta k(+)} > 0$	$0 \le k_j \le k_F$	$\alpha_F = \frac{q_F}{k_T}$	$q_j = u_F k_j$
Transition (T)	$\frac{\Delta q(+)}{\Delta k(+)} > 0$	$k_F < k_j \le k_S$	$\alpha_T = \frac{q_S - q_F}{k_S - k_T}$	$q_j = q_T + \alpha_F (k_j - k_T)$
Congested (S)	$\frac{\Delta q(-)}{\Delta k(+)} < 0$	$k_S < k_j \le k_H$	$\alpha_S = \frac{q_S - q_H}{k_S - k_H}$	$q_j = q_H + \alpha_S (k_H - k_j)$

Table 2. Analytical values of the unloading stream state

Phase	*Condition*	*Validity*	*Slope*	*Flow*
Hysteresis(H)	$\frac{\Delta q(+)}{\Delta k(-)} < 0$	$k_T < k_j \le k_H$	$\alpha_S = \frac{q_T - q_H}{k_T - k_H}$	$q_j = Min\{q_T, q_H\} + \alpha_H Min\{k_T + k_H\} - k_j$
Uncongested (F)	$\frac{\Delta q(-)}{\Delta k(-)} > 0$	$k_S \le k_j \le k_T$	$\alpha_F = \frac{q_T}{k_T}$	$q_j = u_F k_j$

4 Model Econometrics

Two models that could be implemented to adjust the proposed hysteresis model have been developed.

4.1 Identifying Breaks Points Based on Chow's Test

In the previous section some expressions to calculate each of the proposed model parameters have been derived, but by using empirical data it is necessary to verify that indeed every break point is presented so that the model strength is guaranteed. In this sense Chow's contrast (see [14] or [15]), applied to a hypothesis test procedure, allows the determination of the behavior homogeneity for the observed group T respect to the two sub samples T_1 y T_2 where $T = T_1 + T_2$. For linear cases, formally:

- Hypothesis
  Null Hypothesis

$$H_o: \quad y = Xb + u, \tag{2}$$

  Alternative Hypothesis

$$H_A: \quad \begin{aligned} y_1 &= X_1 b_1 + u_1, \\ y_2 &= X_2 b_2 + u_2, \end{aligned} \tag{3}$$

- Decision Rule

$$\begin{aligned} &H_o \text{ rejected if } f > f_\alpha^*, \\ &f_\alpha^* : \Pr\left\{F_{(k,T-2k)} > f_\alpha^*\right\} = \alpha \end{aligned} \tag{4}$$

  Where f_α^* represents the critical reliance value α according to Fisher Law, while f equals Chow's contrast (see. Equation 4):

$$f = \frac{\dfrac{SCR_c - (SRC_1 + SRC_2)}{k}}{\dfrac{(SRC_1 + SRC_2)}{T - 2k}}. \tag{5}$$

In the equation 5, SRC_1 y SRC_2 respectively represent, the error sum of squares from the separate regressions to group 1 and 2, – SCR_c represent the error sum of squares from the pooled regression, k variable represents the estimated parameters and T_1 and T_2 are the number of observations in the two groups

4.2 A Structural Econometric Model

In order to estimate the four regimes of traffic flow over a given day, a structural econometric model is used. This kind of model often applied in times series estimation. In the case of one traffic flow regime, the relation between average speed, $u(q)$, and average flow, q, can be formulate as:

$$u(q) = aq + b \tag{6}$$

Where a and b represent parameters to estimate. As shown in the theoretical part, the parameters a and b correspond respectively to the traffic density and to an additive constant.

Consider U a column vector which represents average speed data observed over the day. The exogenous data are represented with de matrix X and which include also the flow observed over the same day. As shown in the theoretical part, each value of average flow q is associated to a value of average speed u. Parameters to estimate are grouped in a vector column denoted B.

The simple linear model given above can be written in a matrix form as:

$$U = XB' + \mathrm{E} \Leftrightarrow \begin{bmatrix} u_1 \\ \vdots \\ u_n \end{bmatrix} = \begin{bmatrix} q_1 & 1 \\ \vdots & \vdots \\ q_n & 1 \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} + \begin{bmatrix} e_1 \\ \vdots \\ e_n \end{bmatrix} \tag{7}$$

The vector column E represents the unobserved estimation errors.

In order to show the matrix form for the structural model, we consider an example with two regimes:

$$\begin{aligned} u(q) &= a_1 q + b_1 \\ u(q) &= a_2 q + b_2 \end{aligned} \tag{8}$$

Parameters a_1 and b_1 describe the relation between flow and speed in the first regime and parameters a_2 and b_2 describe the same relation for the second regime.

To estimate these regimes, we consider that we have a set of observed data composed of n speed-flow couple. The first p couples describe the observed first regime and $2<p<n<2$. In this case the relation (6) became:

$$U = XB' + E \Leftrightarrow \begin{bmatrix} u_1 \\ \vdots \\ u_p \\ u_{p+1} \\ \vdots \\ u_n \end{bmatrix} = \begin{bmatrix} q_1 & 1 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ q_p & 1 & 0 & 0 \\ 0 & 0 & q_{p+1} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & q_n & 1 \end{bmatrix} \begin{bmatrix} a_1 & a_2 \\ b_1 & b_2 \end{bmatrix} + \begin{bmatrix} e_1 \\ \vdots \\ e_p \\ e_{p+1} \\ \vdots \\ e_n \end{bmatrix} \tag{9}$$

The problem of this model is to define to optimal regime sub-sets. The approach used for that is based on a grid over variation of speed and flow as describe in the theoretical part.

In this model, we describe the variation of speed and flow over each four regimes and between two successive regimes (Figure 8). The first regime represents the free-flow regime. This case starts when the flow is null and the speed is higher. Over this regime, when flow start to increase, speed increase but it is still less sensible to the flow's variations. When speed became sensible to the flow's variations, the transition regime start. The grid to define the end of the free-flow regime is made around of the value of the couple of speed and flow which represents the end of this regime and observed data that describes this first regime are grouped.

The second regime, named transition regime, is characterized by a sensible variation of both speed and flow in other words, speed continue to decrease and flow continue to increase. When the flow starts to decrease but speed continue to decrease the end of the second regime is reach and the third regime start.

The third regime, named congested regime, is characterized the decrease of both speed and flow. This situation persists over the third regime until the speed starts to increase in order to return to free-flow regime or transition regime.

The fourth regime named hysteresis regime and last one is characterized by an increasing variation of speed and a decreasing variation of flow.

5 Application and Model Estimation

5.1 Test Chow Example

The empirical data on stream, speed and concentration obtained from the broadcasting station in the previously described and studied zone (cf. section 2) at MS-5 point (PK

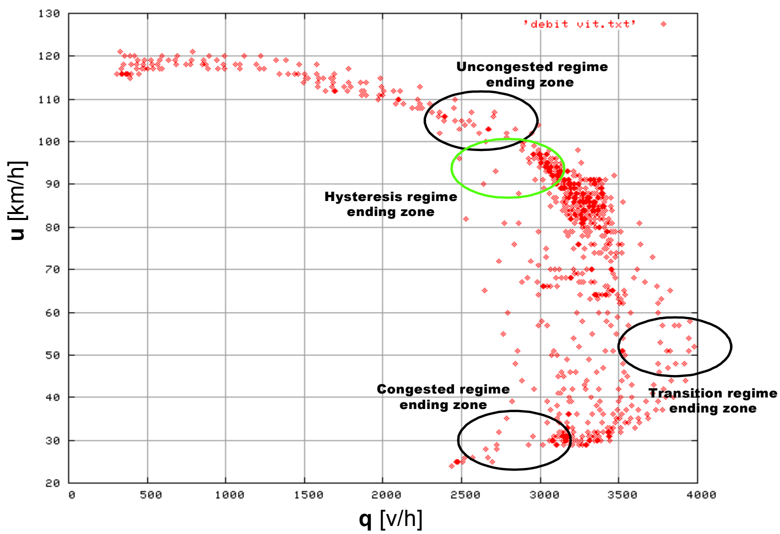

Fig. 8. Provided ending zone regimes

A14+0500 in direction to Paris) were used to apply hypothesis test described above. The variable values correspond to the 6-minutes aggregated data from 6:00- 13h on 21/01/98. The results are summarized in table 3 in which Chow test was apply to flow-concentration relationship in order to identify consecutive phases of the proposed model (see section 2, table 1,2): Free Flow (*F*) vs. transition (*T*), transition (*T*) vs. Saturation (*S*) and saturation (*S*) vs. hysteresis (*H*). These phases were noted down in tables *F+T*, *T+S* and *S+H,* respectively.

There were a total of 60 observations analyzed. In the table 2 and 3, the number of data take into account in each phase tested is indicated by the *n*. It may be observed that while in the three comparisons, null hypothesis is rejected, so that sample does not present homogeneity so tendency rupture points between the two compared phases do exist; Chow's contrast values (*f*) are less marked between steady stream and strained stream, as well as much higher for the other contexts. This stating agrees with the macroscopic variable diagrams described in section 2.

Table 3. Results of Chow test example

Restricted	Not restrict.	n	$f > f_\alpha^*$	Restricted	Not restrict.	N	$f > f_\alpha^*$
F+T	**F**	21	440.34>19.5	**S+H**	**S**	15	12735>19.5
	T	5			**F**	40	
T+S	**T**	5	5630>19.5				
	S	15					

5.2 Structural Model Example

The data used in estimation represent flow and speed variations over the five days of the week (from Monday to Friday). These data are represented in figure 8. However, no reasonable estimation can be produced specially for the hysteresis regime. Two solutions can be used. The first one consists in considering only data that describe a typical day. The second solution consists in using average speed and flow value. For each time of the day, we calculate an average speed and flow over the five days. In this paper, we apply the second one. Results of this manipulation are illustrated in the figure 9 and table 4.

In table 4, the values in brackets represent the standard variation. All parameters are significant at 5% except for the value of *a* in the first regime. The adjusted R-square is equal to 0.98. The sign of each parameter is in the correct sense. Representation of the fitted models is represented in the Figure 9.

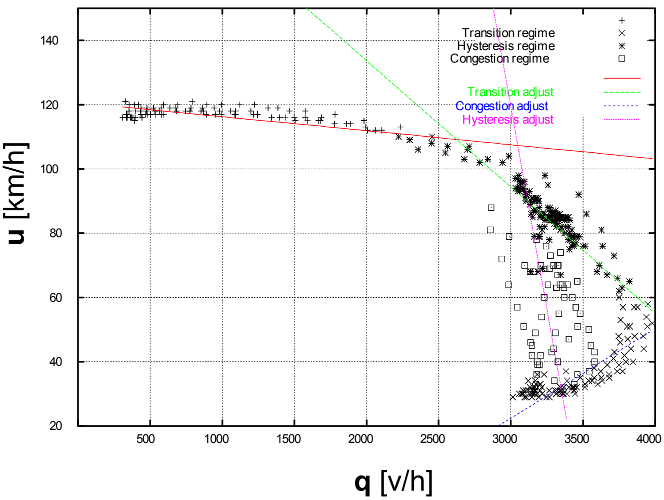

Fig. 9. Linear estimation by the structural econometric model proposed

The table 5 shows the value of the speed-flow couple. They are calculated by intersection between each two successive regimes. As long as speed is less than 19,15 *km/h*, the free-flow regime persist and the increase of the flow does not influence the speed. When flow is close 2624 *veh/h*, the second regime begins and speed starts to decrease. The congested regime starts when flow reach 4072,61 *veh/km* and speed decreases quickly and in the same time flow also decreases. The hysteresis regime is reached when flow is equal to 3346,30 *veh/km* and speed equal to 32,03 *veh/km*. In this case and in order to return to transition regime or free-flow regime, flow continues to decrease but speed starts to increase. The last column in the table 5 represents the density in each breaking point between two successive regimes. These values are calculated using the fundamental low. For example, the transition regime begins when the density is around 24 veh/km.

6 Final Comments

Three important contributions have been pointed out, firstly, an alternative to characterize traffic hysteresis phenomenon in an effective way through macroscopic data.

That characterization is based on the empirical analysis of the macroscopic traffic variables where a bottleneck urban road section and continuum is presented. Secondly, two econometric techniques have been proposed in order to identify the break points of each traffic regime, which at the time demonstrates the proposed model real efficacy. Finally, with the purpose of solving frontier points finding problematic, an algorithm for locating them through tendency rupture points has been developed; moreover, model adjustments can be done. This tool is necessary to analyze dense road networks containing a number of traffic broadcasting stations. As an example, in the case of Paris urban highway net, there are about 500 permanent stations registering traffic variables every 6 minutes. Despite this advance, improvements on process rapidity in real time usage should be worked on. Project which may be left out in future works.

Table 4. Estimation results for structural econometrics model

Regime	Model parameters	
	A	b
Uncongested	-0.00437	120.62
	(0.0022)	(2.8808)
Transition	-0.03926	212.19
	(0.0078)	(25.819)
Congested	0.02792	-61.41
	(0.0072)	(25.205)
Hysteresis	-0.25302	878.70
	(0.0395)	(128.43)

Table 5. Breaking point regimes for structural econometric model

PHASES	Flow [veh/h]	Speed [km/h]	Density [veh/km]
Uncongested – transition	2624.55	109.15	24.04
Transition – congested	4072.61	52.31	77.85
Congested – hysteresis	3346.30	32.03	104.47

Implications about integrating this phenomenon in the planning of infrastructure are important. Any applications concern instant travel time predictions as well for socio-economical evaluation. For instance, for the studied section MS-5 point (section 2.1), the proposed approach allows travel time prediction with a relative average error margin of -3%. On the contrary, a traditional approach, based in a delayed function (i.e. [16]), BPR travel time function adjusted to minimize quadratic errors among empirical values and function forecasting values by the function, show a relative average error margin of 40%.

Another field of potential application of the model is referred to planning dynamic models (i.e. [17]), in which users decisions (time, schedule, departure times) are strongly affected by travel times in a certain instant of time. The integration of hysteresis phenomenon implications to that type of processes will be matter of new studies.

Acknowledgements

This research was funded by the Mexican National Research Council (CONACYT) and the University Autonomous of Mexico State (UAEM) through the projects 41078 and 1597/2002 respectively. Same way, we would like to thank The Regional Direction of Parisian Infrastructure (DREIF) for gladly providing us data and the required information about the case study.

References

1. Hall, F. Traffic stream characteristics. In TRB-NRC (Ed) Traffic Flow Theory : A State of Art Report. Monograph. TRB-NRC, Washington DC. (1997)
2. Treiterer and Myers J. A.: The hysteresis phenomenon in traffic flow. Proceedings of the 6th International Symposium of Transportation and Traffic Theory, Sydney. 13-38. Bucley, D. J. (editor). (1974)
3. Zhang, H. M. : A Mathematical theory of traffic hysteresis. TR B 33, 1-23. (1999)
4. Chowdhury, D., Santen, L. and Schadschneider A.:Statistical physics of vehicular traffic and some related systems. Physics Report Vol. 329, 199-329 (2000)
5. Sánchez, O and de Palma A. "Relación fundamental, congestión en un cuello de botella y histeresis: análisis y evidencias en la autopista parisina A-14" In Lindau, Ortùzar et Strambi (eds) Ingeniería de tráfico y transportes: avances para una era de cambio. 145-158. ANPET. Gramado. (2000)
6. Wardrop, J. G. : Some Theoretical Aspects of Road Traffic Research. Proceedings of the Institution of Civil Engineers 2(1), 352-362. (1952)
7. Gerlough, D. L. and Huber M. J.: Traffic Flow Theory: a Monograph. Special Report, TRB, Washington (1975)
8. Newell, G. F.: Applications of Queuing Theory. Chapman and Hall, London (1982)
9. Hall, F., V. F. Hurdle and Banks J.H.: Synthesis of recent work in the nature of speed-flow and flow-occupance (or density) relationship on freeways. Transportation Research Record 1365, 12-18. (1992)
10. Daganzo, C.: Fundamental of Transportation and Traffic Operations. Pergamon, New York. (1994)
11. Leutzbach, W. :Introduction to the Theory of Traffic Flow. Springer-Verlag, Berlin. (1998)
12. Sánchez, O. Planification d'infrastructures de transport routier : théorie et applications selon une approche de simulation discrétisée. Septentrion, Lille (2000)
13. Small, K.: Urban Transportation economics. Harwood Routledge, Taylor and Francis. (2001)
14. Chow: Test of equality between sets of coefficients in two linear regressions. Econometrica, Vol. 28, 591-605 (1960)
15. Guajarati, D.: Essencial of econometrics- Mc Graw Hill, New York (1999)
16. Spiess, F.: Conical Volume-Delay Fonctions. Transportation Science. 153-158. (1990)
17. de Palma, A., F. Marchal and Nesterov. Y. : METROPOLIS : A Modular System for Dynamic Traffic Simulation. Transportation Research Record 1607. 178-184. (1997)