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Títol

TRAFFIC STREAM MACRO AND MICRO ANALYSIS IN AP-7 TURNPIKE

Autor

SORIGUERA i FARRÉS, JORDI

Tutor

SORIGUERA i MARTÍ, FRANCESC

Departament

INFRAESTRUCTURA DEL TRANSPORT I DEL TERRITORI

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Tutor: Francesc Soriguera Martí

ABSTRACT

The main objective of the present dissertation is the traffic stream macroscopic and microscopic analysis in AP-7 turnpike. This analysis which is done from an important data bases with a vehicle per vehicle registration, pretend to demonstrate that only taking generalized Edie definitions of different variables properly calculated, the results are valid. In other words, estimating correctly different traffic variables, errors are minimized and relations between variables are true, decreasing notably the scatter. Therefore, this calculation of the variables is possible due to this 24 hour data bases which, as was recorded on Sunday 7^{th} of September 2008, includes an important congestion and consequently all traffic states are incorporated in the present analysis.

In a macroscopic level, analysing and representing the Fundamental Traffic Relation which relates the stream as the product of the density for the speed (q=k·v) it is obeyed without scatter if variables are taken in such adequate way. It is important to estimate these factors averaging in fixed groups of N vehicles instead of taking time aggregations, as well as introducing the average speed as the space-mean speed (SMS) instead of time-mean speed (TMS). Moreover, the macroscopic relation where the occupation is calculated as the effective average length for the density ($occ. = \bar{l} \cdot k$) is also obbeyed following these rules. These analysis are done not only per section, as well per each lane.

Furthermore, in a microscopic way, is demonstrated when free flow regimes with low rates of vehicles, that negative exponential distribution is the mathematical distribution that better represents space and time headways with random arrivals. In spite of congested traffic, where the car-following phenomenon appears, the distribution that better fits is the normal and the average and the deviation values of it are lower than free regime case. Moreover, in a stationary state with one unique type of vehicles, the speed frequency distribution follows a normal distribution. Anyway, this is not evident, due to defficencies when measure such as including congestion onset data, congestion dissolve or also data from mixed traffic with two classes of vehicles which makes skew distributions or even make appear bimodal ones. In the study is also checked that the relation between time and spatial average speed where $TMS = SMS + (\sigma_{sms}^2/SMS)$ has an accotated error lower than 0,40%.

Moreover, some car-following models are analyzed and adjusted not only per lane level, but also for different types of vehicles combinations. Therefore, it is concluded that time and space headways let by two light vehicles for any speed range follow a pattern, as well as its average values are considerably lower than other possible combinations. On the other hand, values are maximums and exponential regression have more scatter when one heavy vehicle is following another heavy one.

Finally, fundamental diagrams of all studied sections among AP-7 are represented from stationary states. Then, main characteristics as free flow speed, propagation speed, optimum density, capacity and jam density of each section are identified and quantified.

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RESUM

El present treball té com a objectiu principal l'anàlisi tant macroscòpic com microscòpic del flux de trànsit de l'autopista AP-7. Aquest anàlisi que parteix d'una potent base de dades amb registres vehicle a vehicle, pretén demostrar que únicament prenent les definicions generalitzades d'Edie de les diferents variables calculades correctament, els resultats són vàlids. És a dir que, a partir d'una correcte estimació de les diferents variables del trànsit, els errors es minimitzen i les relacions entre variables es compleixen reduïnt-ne notablement la dispersió. Gràcies doncs a aquesta base de dades de 24 hores de registres vehicle a vehicle el càlcul de les diferents variables del tràfic és possible. A més, la informació registrada al diumenge dia 7 de Setembre de 2008 inclou les dades d'una important congestió de forma que tots els estats del trànsit estan contemplats en aquest anàlisi.

Així doncs, a nivell macròscopic d'estudi, l'Equació Fonamental del Trànsit que dictamina que el flux és proporcional a la densitat per la velocitat (q=k·v) es compleix sense cap tipus de dispersió en el cas que les variables es prenguin de forma adequada. És fonamental l'estimació de les diferents variables a partir de ponderar grups fixats d'N vehicles (per exemple 30), enlloc d'agrupar-les en intervals temporals, així com també prendre com a velocitat mitjana la velocitat mitjana espaial (SMS) enlloc de la mitjana temporal (TMS). Així mateix, la relació entre variables macroscòpiques que calcula l'ocupació com el producte de la longitud mitjana efectiva per la densitat ($occ. = \bar{l} \cdot k$) també es compleix seguint aquestes premises. Aquest anàlisi es desenvolupa a dos nivells: tant per tota la secció, com també per a cada carril.

Pel que fa a l'anàlisi de les variables microscòpiques, es demostra que en règims de flux lliure de trànsit, on hi ha poca circulació, les distribucions de freqüències tant dels intervals de pas com dels espaiats que segueixen les arribades aleatòries es poden aproximar a funcions exponencials negatives. En canvi, en casos de congestió on es produeix el fenomen del *car-following,* la distribució que més s'ajusta al fenòmen és la normal, i tant els valors mitjos com les desviacions són menors en aquest cas que en l'estat lliure. D'altra banda, es prova que en un estat estacionari de trànsit i una única classe de vehicles, la distribució de freqüències de les velocitats segueix una normal. Malgrat tot, aquest fet no és evident fruit de deficiències en la mesura com la incorporació de dades d'inici de congestió, de dissolució de congestió o l'existència de dues classes de vehicles que poden provocar distribucions esbiaixades o bimodals. Alhora, es comprova que la relació entre velocitats mitjanes temporals i espaials de la forma: $TMS = SMS + \sigma_{sms}^2/SMS$ té un error acotat i inferior al 0,40%.

A més a més, s'analitzen i s'ajusten models de *car-following* no només a nivell de carril sinó també en funció del tipus de vehicle. Es conclou doncs, que els intervals i els espaiats que es deixen entre dos vehicles lleugers per a qualsevol velocitat de circulació segueixen clarament un patró i que els valors mitjos que prenen són substancialment inferiors a les altres possibles combinacions. L'extrem oposat on aquests valors són màxims i on la regressió té molta més dispersió es troba en la combinació de dos vehicles pesats.

Finalment, s'extreuen també a partir de períodes estacionaris els diagrames fonamentals de les variables macroscòpiques de totes les seccions d'anàlisi i es quantifiquen els valors característics de cada secció: velocitat de flux lliure, velocitat de propagació, densitat òptima, capacitat i densitat màxima.

CONTENTS

I. INTRODUCTION AND OBJECTIVES

The purpose of the present dissertation is to analyse the traffic stream characteristics in AP-7 turnpike through the different fundamental macro and micro variables considered.

Due to deficiencies detected not only in the aggregation of the recorded information but also in the calculation of the different macroscopic and microscopic variables, the present study aim to demonstrate that if variables are estimated in a correctly way, errors are minimized and relations between them are true. For this reason, the present work has also the objective to realise the comparison with not properly defined variables results, so errors accumulated and the scatter can be easily detected.

For this mentioned evaluation, is basic a powerful registration data including all traffic states and without any type of aggregation. For this reason a vehicle per vehicle data is used which each vehicle information is recorded separately. In addition, the data was recorded in AP-7 turnpike on Sunday 7th of September 2008, so it includes an important congestion and consequently all traffic states are incorporated in the present analysis.

Therefore, in a macroscopic level, the present dissertation pretends to demonstrate the methodology for the accomplishment of the different relations between macroscopic traffic variables such as the Fundamental Traffic Relation. This analysis will be done, not only per section but also per lane, so the study of the different lanes behaviour can be developed.

Otherwise, in a microscopic stage, this dissertation aim to analyse the frequency distribution of the space headways, time headways and the individual speeds for different traffic states and view also the circumstances that can alter this resulting distributions. The objectives are to observe the mathematical distributions that best fit for the different traffic regimes and to develop all the possible conditions that modify the frequency distributions (variation of the average, deviation, kurtosis or skewness).

Moreover, an important objective of this analysis level is to study the existing car-following models which relate the space and time headways with the speeds, so it can be determined the good or poor fit of the data. An important point of this analysis is to differentiate the type of vehicles. In other words, the objective of this section is to study the different behaviours of the four possible combinations of light and heavy vehicles and view similarities and differences between them.

Finally, is pretended to estimate the main traffic characteristics (capacity, optimum density, density jam, free-flow speed and propagation speed) of each section of the turnpike stretch analysed, from representing each fundamental diagram.

II. BACKGROUND

This work presents a methodology for measure and evaluate the data so macroscopic traffic variables and relations among them be true. Comparisons between results using inconsistent definitions (Hall 1989, 1996, Banks 1995) and consistent Edie (1965) ones are developed. As in past studies the data scatter represented in following results is largely the result of having extracted the variables in ways inconsistent with Edie's definitions and from having measured these variables over regions of small number of vehicles.

Cassidy and Coifman (2001) viewed that measuring data over some specified number of vehicles instead of over some fixed time aggregation guarantee a consistent estimator of the different averaged macroscopic variables. Cassidy also affirmed that data measurement strategies must follow from the definitions assigned to the variables and not vice versa. For this reason, the data analyzed is composed by the minimum possible aggregation which is vehicle per vehicle variables registration.

The relations between these macroscopic variables were analyzed by Cassidy (1998), demonstrating that freeway locations exhibit reproducible bivariate relations among traffic variables if each measurement is taken while the average values of these data are not changing over time or space. In other words, if traffic conditions are approximately stationary.

On second place, there exists poor bibliography of microscopic analysis due to lack of vehicle-vehicle data bases. Datas used for analysis made in the past are done with not accurate aggregation methods, such as big aggregated times that do not allow to represent the real micro phenomenon, or aggregated methods that do not contemplate the analysis per lane, just per section. Therefore, this kind of aggregations mix different behaviors and different traffic states, so these states are not stationary and the micro conduct is not viewed in such a correct way.

May (1990) developed microscopic flow characteristics, classifying different time headway distributions and evaluating and selecting mathematical distributions for them. Moreover, May investigated the microscopic speed characteristics, estimating also mathematical distributions for the different conditions.

Whereas some pioneers as Pipes (1953) developed some car following theories which were continued by Forbes (1958) and by General Motors researchers (Chandler "et al" 1958, Herman "et al" 1959, Gazis "et al" 1959). While Pipes and Forbes suggested that distance headways and time headways were linearly to space-mean speeds, General Motors studies were much more extensive so the investigators developed five generations of car-following models, involving the response as a function of the sensitivity and the stimuli of drivers.

Nevertheless, there are no studies which develop this micro analysis separating the type of vehicle. Vehicle per vehicle data allows a car following analysis separating the different combinations of light and heavy vehicles.

III. METHODOLOGY

The data provided by Acesa for the present work is composed by 24 hours recorded information with double loop detectors in each section lane. Data registration is done vehicle per vehicle, which means the minimum aggregation possible and allows knowing different variables of each vehicle crossing the AP-7 section. The important difficulty of recording this kind of data base is due to the significant amount of information registered.

The final data from the detectors is composed of 7 measured variables. The first one is the date and the second one the instant of the measure (hh:mm:ss). The third variable registered is the individual speed of the vehicle in kilometers per hour and the four its length in decimeters. The fifth data recorded is the time spent by the vehicle over the detector zone in milliseconds and the gap length between the front edge of the vehicle and the rear one of the predecessor (in meters) is the sixth one. This last measure is also able to get it calculating it from the individual speed and the off time as it follows: $gap_i = V_i \cdot t_{off(i)} + d_1$ (Soriguera 2008). Finally, the last variable measured is the numeration of the position of the vehicle in a 3 minutes aggregation interval. Next table resumes all these variables and its units:

VARIABLE:	Date	Time	Speed	Vehicle length	Occupation time	GAP	Position (on the aggregation interval)
UNITS:	DD/MM/YYYY	HH:MM:SS	km/h	dm	ms	meters	N

TABLE 1 Variables and units registered by the double loop detectors

In the present study the provided data of the vehicle length (L_i) is not considered and is calculated from the other variables to get better precision. So it is taken from the product of the vehicle speed (V_i) and the occupation time (Occ.T.), less the loop length (two meters) as it follows:

$$L_i = V_i \cdot (Occ.T.) - 2{,}0$$

It is useful to visualize a diagram of the trajectory of a vehicle (its front and rear edges trajectories are represented) and the double loop detector to understand the different variables mentioned:

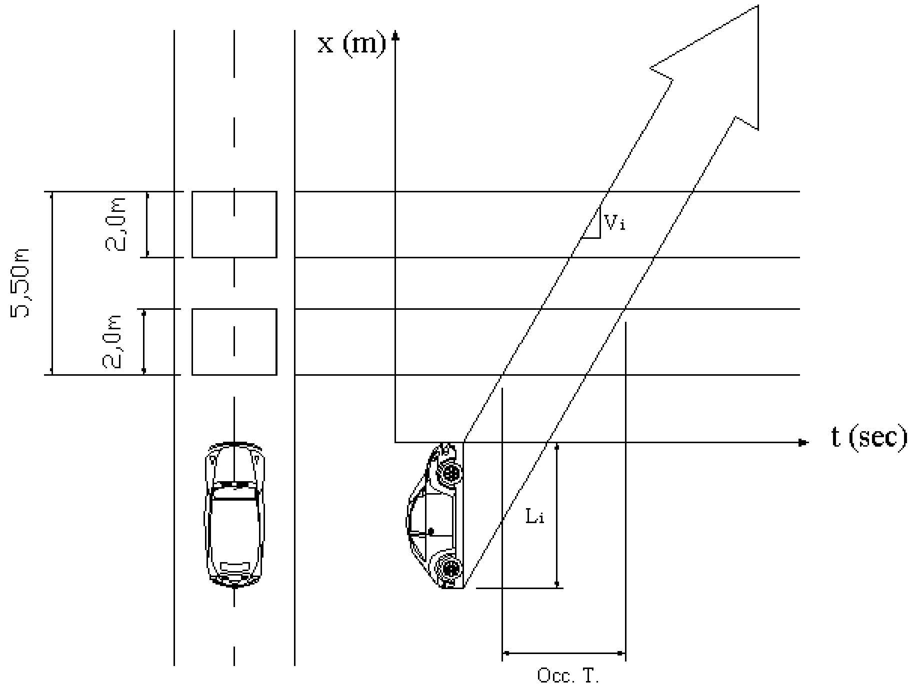

FIGURE 1 Vehicle trajectory over a double loop detector shown with two lines

Furthermore, the calculation of macroscopic variables in macroscopic analysis is done choosing the period time of analysis so that the front and rear lines for all N=30 vehicles trajectories within the region. In brief, instead of fixing a period time of aggregation, the number of vehicles is fixed as N=30 for averaging the variables and having a reasonably consistent estimator even in light traffic conditions.

Apart from that, the selection of stationary periods of time is necessary for reproducible bivariate relations among macroscopic traffic variables. To find when traffic conditions are approximately stationary is necessary the inspection of cumulative curves of vehicle arrival number and vehicle speeds.

Data measured by detectors at different sections is used to construct curves of cumulative vehicle arrival number by time *t, N(x,t)*. A function of the form $q_0 t$ is subtracted from each *N(x,t)*, so the resulting magnitude is much smaller (on the order of 30% or more) and this helps to promote visual identification of changing arrival rates. Then, the identification of reasonably defined linear slopes is done and the starting and ending times are selected.

In addition, the cumulative curves of vehicle speeds are analyzed. Stationary periods are those where all vehicles travel at the same speed, so the slope in a cumulative speed curve is defined by a linear approximation.

Finally, for existing stationary conditions is necessary to evaluate the percentage of heavy traffic and observe that it is constant during over the period. Due to this limitation, the methodology for some cases is to analyze the data of just the third lane of the section. The third lane, which is the quickest one, is where less number of heavy traffic circulates, so it is easier to find stationary conditions without important variations of heavy traffic presence.

Besides macroscopic evaluation, the microscopic analysis is also done although in a different way. In that case, the methodology consists in the analysis of the histograms representing the frequency distributions of the microscopic variables for the different traffic regimes.

A part, in this section, the study of the data is done considering the whole section and also differencing the type of vehicle crossing the section (separating light and heavy traffic). The criterion used to differentiate light and heavy traffic is a length of 5,0 meters. Therefore, the process is more difficult due to the lack of microscopic data and the poor accurate treatments done.

In that section the methodology is: firstly identifying the type of vehicles, secondly classifying the four possible combinations of car followed by car (light vehicle following another light one, light following a heavy vehicle, two heavies or a heavy vehicle following a light one). Finally, the averages of the different variables are calculated fixing the number of vehicles N=30.

IV. THE DATA

The registered data for the present study is composed by 24 hours recorded information vehicle per vehicle over nine sections with double loop detectors in each lane and situated in both traffic directions among AP-7 turnpike located east coast of Spain.

Data was collected during Sunday 7th of September of 2008 by Acesa. As the registration was at the end of a weekend, an important traffic stream moves to Barcelona on the evening time. That's why the selection of that date, so on one hand light traffic conditions appear at first hours of the day and on the other a congested state emerges at last time of the registration. Moreover, as the data coincides on a day off, the traffic is characterized by the absence of commuter drivers and the poor percentage of heavy traffic.

The AP-7 analyzed stretch, with the exact situation of the nine detectors and the entrances and exits of the motorway, is shown on figure 2:

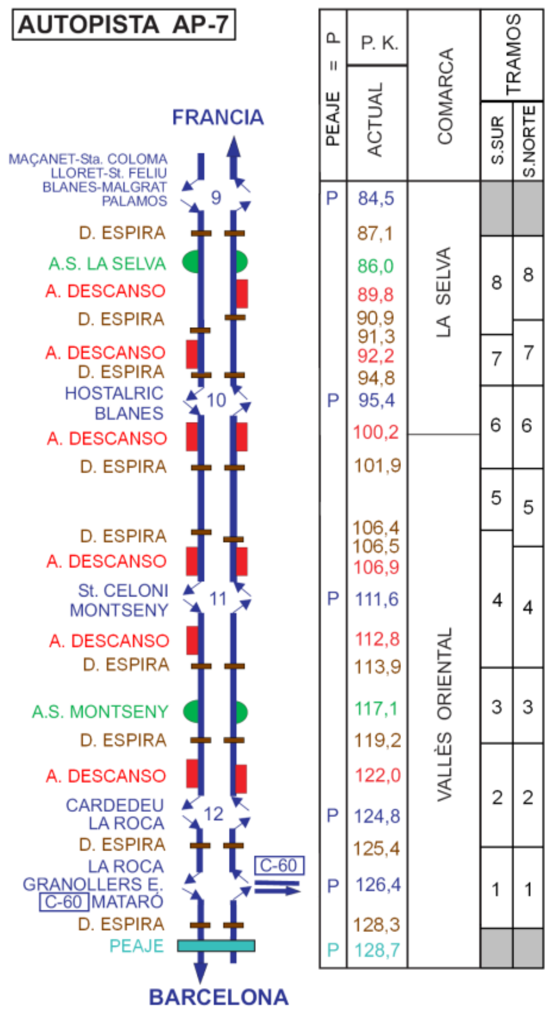

FIGURE 2 Studied stretch of AP-7

Because of the amount of data registered by Acesa, the analysis of the present study is being centered in the study of one of the sections.

The main reason for the election of one of the double loops detectors is the registration of all the traffic states, so there also exists a congestion set. As it has been mentioned, on Sunday time, a big volume of traffic is returning to Barcelona after the weekend. Therefore the registered data travelling to the North is obviated and it's only analyzed the traffic stream moving to the South to Barcelona city. Moreover it is interesting that worked data includes an important congestion state, so the detectors situated closer to Barcelona have bigger stream of vehicles that were incorporated all AP-7 tranche long.

The method for distinguishing traffic states of one section is based in the analysis of vehicle arrivals over time (flow time series) and the distribution of vehicle speeds. This process to get an idea of the traffic stream is done taking a 3 minutes criteria, so those are data per lane averages measured over all lanes in a 3 minutes period time aggregation.

Analyzing N-t curves of P.K. 128.3 section (figure 3) it is easily identified two pikes: the first one about midday, and the second one and more important because of its duration and volume about 19:00. This second important arrival of vehicles is bigger than the first one and it could be considered almost constant from 17:00 to 23:00.

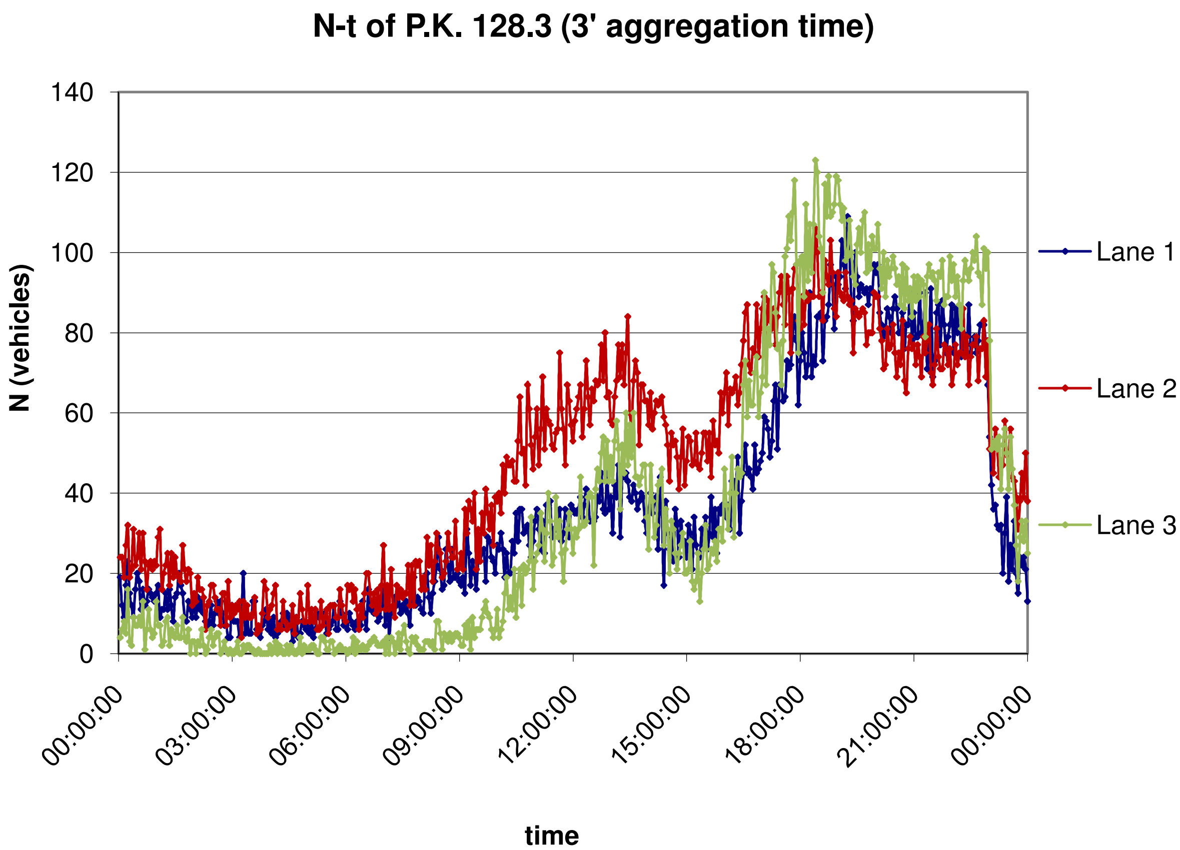

FIGURE 3 N-T curve of P. K. 128.3 South traffic stream from a 3 minutes criteria

Moreover, regarding V-t graphic (figure 4), there are observed congestion conditions in the same period of time, where a decrease of the average speeds that cross the sections appears in the three lanes.

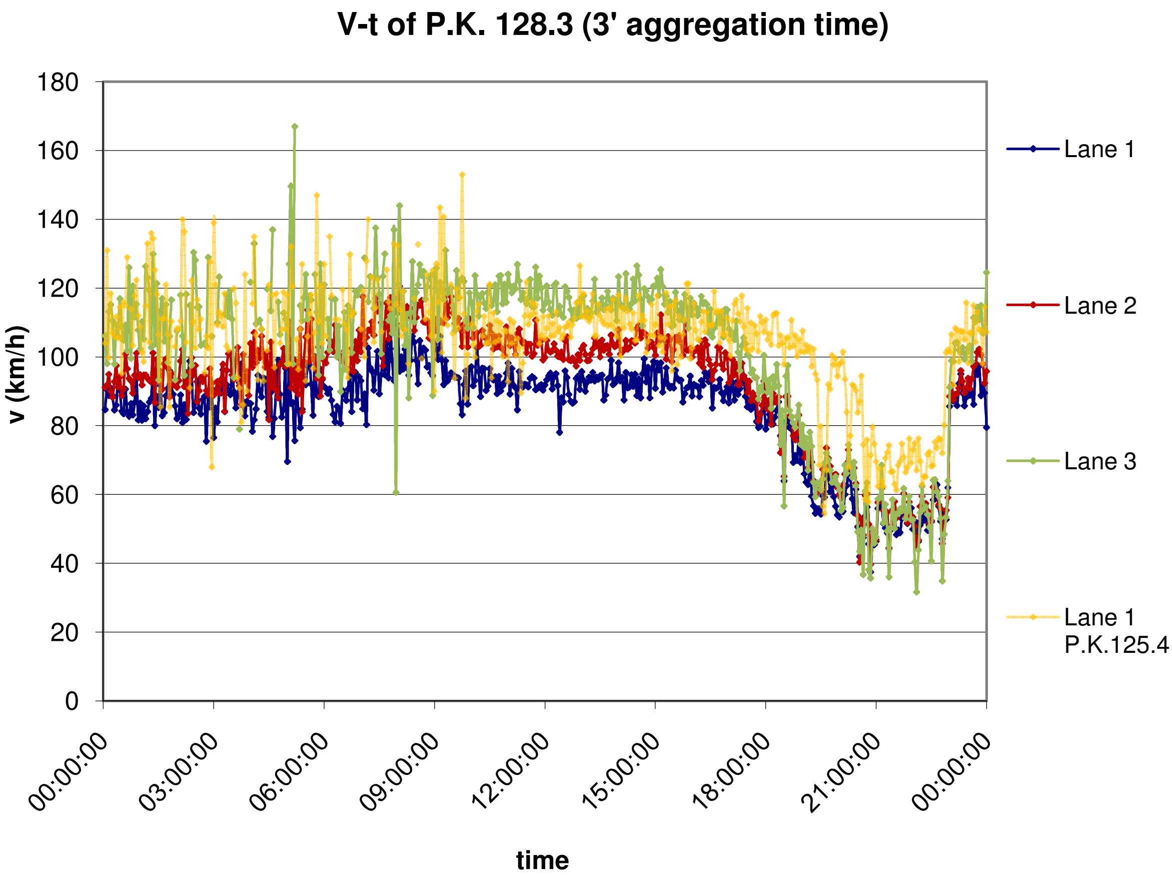

FIGURE 4 Speed-T curve of P. K. 128.3 South traffic stream from a 3 minutes criteria

The speed average represented is the space-mean speed for the 3 min intervals. Comparing the three lanes of P.K. 128.3 with the data from the first lane of the predecessor section 125.4 is able to realize that in this section, vehicles cross through it more slowly than the others. It is observable that average speeds of the first lane (the slowest one) of P.K. 125.4 section is at the same range as the third lane of P.K. 128.3 section (the quickest). The cause of this driver behavior is because the toll plaza is situated only four hundred meters downstream, so the vehicles start to breaking down for stopping.

Moreover, it is also useful to analyze the occupation time over the detector, because it is a measure of the density of the freeway. So in figure 5 there is represented it during all the whole day of the registered data, with the 3 minutes criteria too:

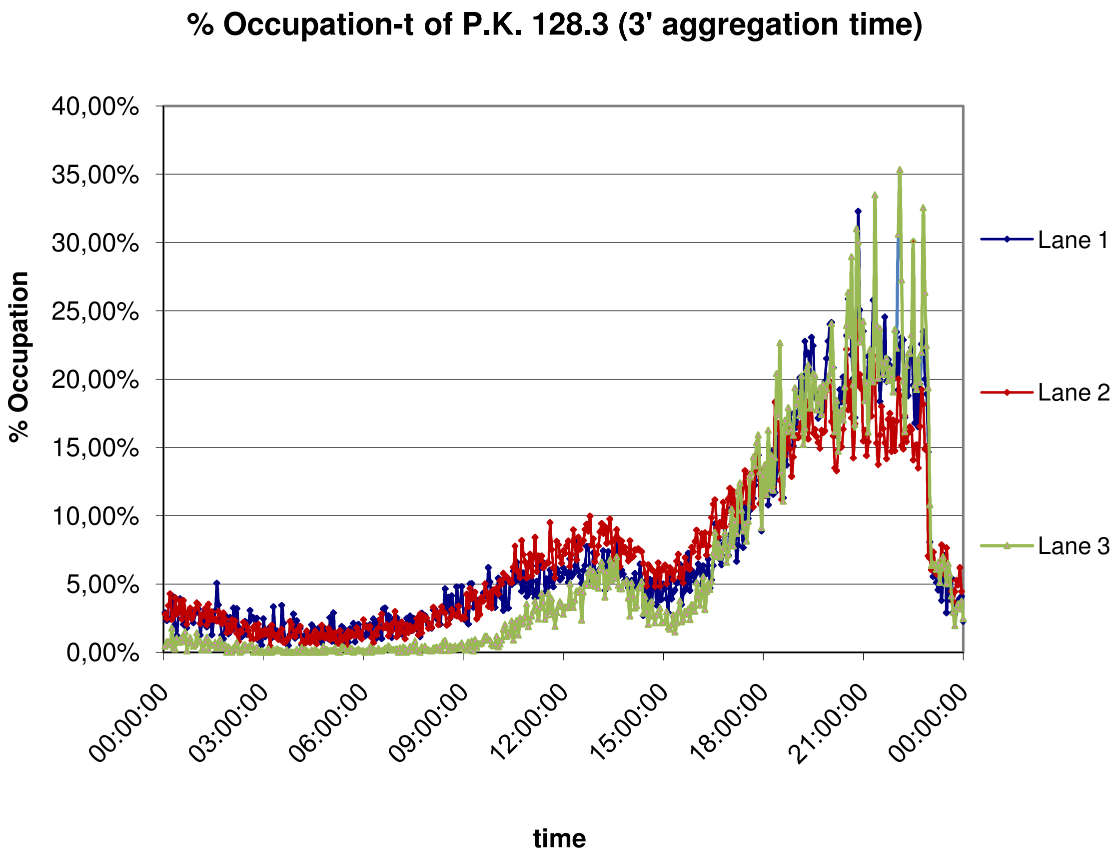

FIGURE 5 Ton-t of P. K. 128.3 South traffic stream from a 3 minutes criteria

The features on the curve show two periods of time with an increase occupation percentage, which mean bigger densities. Those periods are situated again about 12:00 and from 18:00 to 23:00, which confirms two peaks of a decrease of the level of service of the motorway.

The upstream analogous section in the P.K. 125.8 has a close performance, although it has a particularity. It belongs to a short tranche of four lanes, isolated from the rest of the motorway composed by three lanes design so it is not representative. Therefore, from all nine sections 24 hours registered data, the work is centered in P.K. 128.3 section. The southern detector data has all traffic states and an important congestion set during rush hours.

V. RESULTS

1) Macroscopic Variables Estimation

1.1) Flow

Traffic flow is defined as the number of vehicles passing a point in a given period of time, therefore is expressed as an hourly flow rate. It is extremely important to know the flow rates and not only their temporal, spatial and modal variations, but also the composition of the traffic stream. In fact, understanding the flow is an important characteristic on the level of operational analysis such as control warrants, accident analysis. However, flows have to be also considered on the level of the investigation leading to operational improvements such as priority lanes, reversible lanes and flow restrictions (May 1990, p. 54-77).

In our case it is really important to know how traffic flow rates vary over time. The study of this rate will allow knowing the problematic hours where AP-7 will have bad level of service and congestion because of overpassing the motorway capacity and the consequently reduction of speed.

The paired detectors situated all over the freeway allow knowing the instant when the car passes a lane section. So it is easy to calculate the traffic flow of a section in a period of time. Anyway, the computer algorithm to get the flow from the measured data consists to fix a discrete number of vehicles *N*, instead of over some fixed time T. In this way, aggregation time T_{agg} may be chosen so that the front and rear edges (represented as lines) for all *N* trajectories within the region span L as it is shown in next figure:

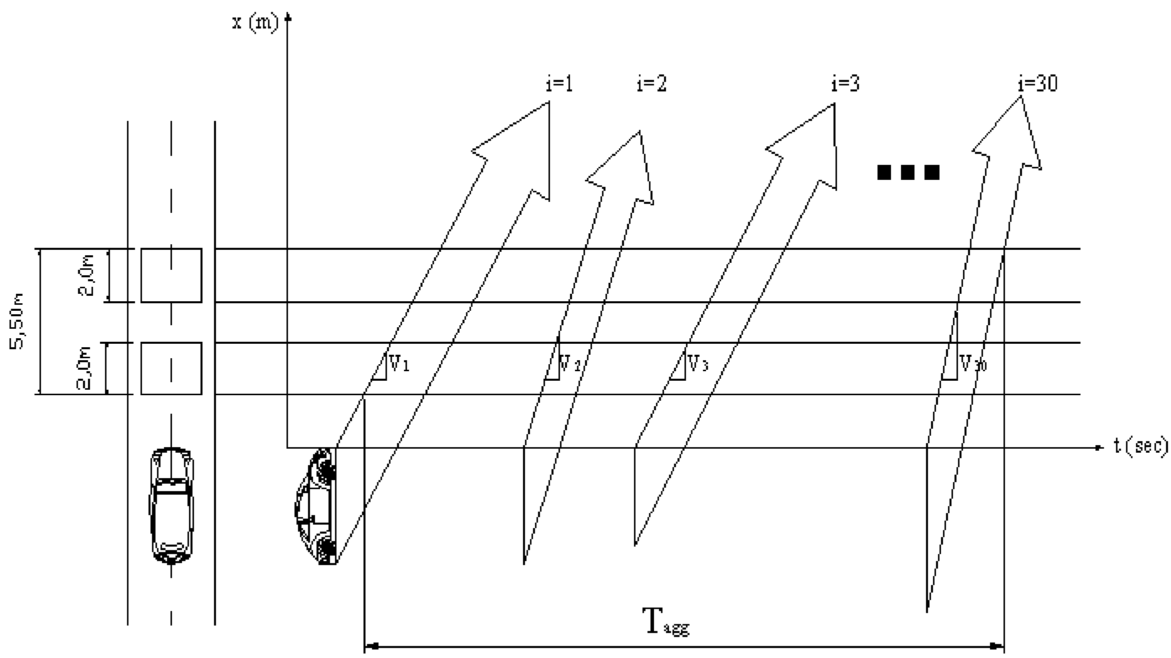

FIGURE 6 Detector region with N=30 trajectories over time

Therefore, the traffic flow is calculated fixing N as a group of 30 vehicles, so data measured allow knowing the total time spent since the first car cross the section until the 30 crosses it too. The ratio of the thirty vehicles studied per this time is the traffic flow passing the section analysed in a period of time:

$$q = {}^{N}/_{\tau} = {}^{30}/_{\tau}$$

If T was fixed, some aggregated periods when the lightest traffic conditions (especially from 3:00 to 5:00) would be calculated from just some vehicles registers, and consequently the error would be so significant.

Stream's Error Determination. In a stationary period the relative error produced depends of the number of the observations or vehicles (N) and of a counting dispersion index (γ_n) as:

$$(relative\ error)^2 \overset{\text{def}}{=} e^2 = {}^{\gamma_n}/_{N}$$

Where the index is $\gamma_n = {}^{Var(n)}/_{E(n)}$ and can be estimated from a sample of the stationary period as:

$$\hat{\gamma} = {}^{S_{\bar{x}}^2}/_{\bar{x}} = \left[\frac{1}{M}\sum_{i=1}^{M}(n_i - \bar{n})^2\right] \Big/ \left[\frac{1}{M}\sum_{i=1}^{M}(n_i)\right]$$

Then so, as bigger is M, the estimator $\hat{\gamma}$ is closer to γ.

Therefore, it is important to view if the N=30 vehicles selection is good enough (so the relative error is sufficient small). For this reason, a 5% relative error is chosen, so the number of necessary observations will be calculated to compare with the 30 vehicles considered. Moreover, the error with 3 minutes criteria will be calculated too, to know the error if not the number of vehicles but the period τ is fixed. These calculations are done from third lane data where there is no presence of heavy traffic and therefore, stationary periods are easier to find.

Choosing some stationary periods as in methodology point explained, from data registered on the third lane of section P.K.128.3, where the different traffic states are considered, the results of the variables are:

HOUR:	$\bar{q}$ veh/hour	$\bar{N}$ vehicles	dev(n) vehicles	γ_n	$e = \sqrt{\gamma_n/N}$ %	N (if e=5%) vehicles
	(τ=3' aggregation)					
0-1:30	218,0	10,90	4,071	1,470031	6,705%	20
16:26-17:00	1.391,4	69,57	64,102	0,921385	3,076%	27
20:00-20:25	1.934,0	96,70	20,810	0,215202	1,492%	9
21:00-21:40	1.830,8	91,54	28,323	0,238009	1,414%	8

TABLE 2 Stream's error determination of selected stationary periods from 3rd lane data of P.K. 128.3 section using 3' time aggregation

It is observable that from 0h to 1:30 (in free flow traffic) the relative error considering a τ=3 minutes criterion is the biggest due to the light traffic conditions: less than 11 vehicles per period is not enough number of vehicles to get a good estimation of the stream. Otherwise when traffic increases until top rates (from 20:00 to 20:25 and from 21:00 to 21:40), the number of vehicles in the 3 minutes intervals grows up, and therefore error decreases.

Furthermore, it is important to realise that the number of vehicles to get an error of 5% is always less than 30. It means that the mentioned selection of 30 vehicles for afterwards calculations is consistent and stream estimations with this criterion will have less than 5% of error.

Stream's Evolution Along The 24hours Data Registration. Then, estimating the flow (blue points) in the studied P.K. 128.3 section including all three lanes with the N=30 vehicles criteria during the whole day data registration it is able to represent the evolution in the next figure:

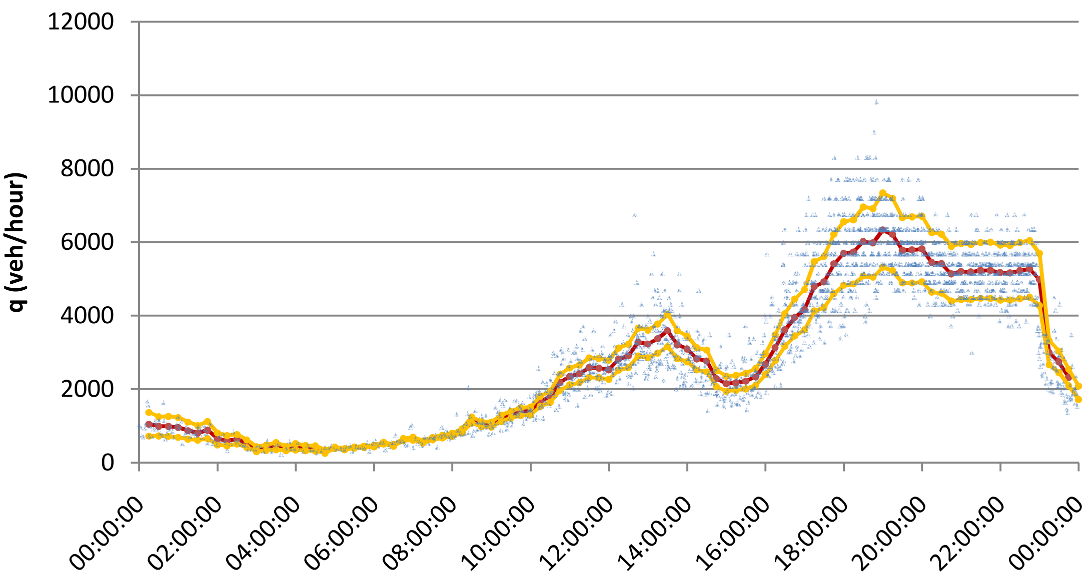

FIGURE 7 The 24 hour evolution of the stream with N=30 vehicles criteria through the three lanes of P.K. 128.3 section

Moreover, averaging in 15 minutes intervals the calculated data points the red line is plotted. The dispersion of this mean is also represented with yellow lines using the dispersion index $\gamma_n = {Var(n)}/{E(n)}$ so about the 68% of the values lie within them.

At first sight, figure 7 is really similar than figure 2. In fact, both represent the number of vehicles that cross the studied section with different criteria. But the main tendency is also similar.

It is also observable a first period of day (night period) from 0:00 to approximately 9 o'clock, when traffic is low. There exist free-flow traffic conditions where the vehicles don't interact between them because the stream is so little (less than 1.000 vehicle/hour in all the period).

Later on the day, flow starts growing until around 13:00 when there is a first peak. This episode of time from midday to 14:00 traffic is much considerable and overcome in some moments the 4.000 vehicle/hour.

Behind the peak, stream starts decreasing, but not less than 1.400 vehicles/hour. This phase is quite short, because after 15 hours flow raise again. There is the second peak, bigger in value and in duration than the first one. It takes all the evening and afternoon time because it corresponds to the return operation to Barcelona city after the weekend. In this segment of time, stream values vary from 4.000 to 8.000 vehicles/hour.

1.2) Space-Mean Speed (SMS) & Time-Mean Speed (TMS)

Speed is a fundamental measurement of the traffic performance of the existing highway system so it is a key variable in the design or redesign of new facilities and a measure of performance given the demand and control along the freeway. The speed is also used as an indication of level of service, in accident analysis and in traffic engineering studies (May, p. 116-133).

Estimation of this macroscopic variable is done using the two loops detectors which register the individual speed of each vehicle crossing the detector, allowing us to calculate the average speed in a fixed period of time.

This macroscopic characteristic of a traffic stream is expressed in kilometres per hour and is the inverse of a vehicle's pace. Basing the approach on direct measurements of the individual vehicles' speeds, to obtain the mean speed as the total distance travelled by all the vehicles in the measurement region, divided by the total time spent in this region, and can be formulated as it follows:

$$\overline{v_s} = \frac{\sum_{i=1}^{N} X_i}{\sum_{i=1}^{N} T_i} = \begin{cases} \dfrac{\sum_{i=1}^{N} v_i \cancel{dt}}{N \cancel{dt}} = {}^{1}/_{N} \sum_{i=1}^{N} v_i \\ \dfrac{N \cancel{dx}}{\sum_{i=1}^{N} {}^{\cancel{dx}}/_{v_i}} = \dfrac{1}{{}^{1}/_{N} \sum_{i=1}^{N} {}^{1}/_{v_i}} \end{cases}$$

First, on one hand the arithmetic mean of speeds of vehicles passing a point is the time-mean speed (TMS) and on the other, the harmonic mean of speeds passing a point during a period of time is defined as the space-mean speed (SMS) which also equals the average speeds over a length of turnpike. In case stationary conditions of the traffic stream exist, both speeds would be the same.

Spatial Speed's Error Determination. If we know individual speeds, the necessary number of observations (N) is proportional to a variation coefficient C_{v_p} and dependent on the relative error (e_{v_s}) of the space mean speed as follows:

$$N = {\left[C_{v_p}^2 \cdot \left(e_{v_s} + 1\right)^2\right]} \Big/ {e_{v_t}^2}$$

Where: $C_{v_p} = {}^{S_p}\Big/_{\overline{p}}$ and which $\overline{p}$ is the pace (inverse of individual speeds).

Otherwise, if we work with the space means speeds in a period τ, we consider each $\overline{V}_j$ as an observation. On that case, the necessary number of intervals τ, will be:

$$M_\tau = {\left[C_{v_{\overline{p}}}^2 \cdot \left(e_{v_s} + 1\right)^2\right]} \Big/ {e_{v_s}^2}$$

Where: $C_{v_{\bar{p}}} = {S_{\bar{p}}}/{\bar{\bar{p}}}$ which $S_{\bar{p}}{}^2 = \frac{1}{M}\sum_{j=1}^{M}(\bar{p}_j - \bar{\bar{p}})^2$

And: $\bar{\bar{p}} = \frac{1}{M}\sum_{j=1}^{M}\bar{p}_j = \frac{1}{M}\sum_{j=1}^{M} 1/\bar{V}_j$

Finally, the error can be isolated from the second degree equation giving the following formula as a solution:

$$0 = \left[C_{v_{\bar{p}}}^2 - M_\tau\right]\cdot e_{v_s}^2 + 2C_{v_{\bar{p}}}^2 \cdot e_{v_s} + C_{v_{\bar{p}}}^2 = \left[1 - {M_\tau}/{C_{v_{\bar{p}}}^2}\right]\cdot e_{v_s}^2 + 2e_{v_s} + 1$$

$$e_{v_s} = \left[-2 \pm \sqrt{4 - 4\cdot\left(1 - M_\tau/C_{v_{\bar{p}}}^2\right)}\right] \Big/ 2\cdot\left(1 - M_\tau/C_{v_{\bar{p}}}^2\right)$$

Temporal Speed's Error Determination. To determine the temporal speeds error, is just the coefficient of the variation coefficient and the number of vehicles. In case we work with the individual speeds the relative error is calculated as follows:

$$e_{v_t}^2 = {C_{v_v}^2}/{N} \text{ where } C_{V_v} = {S_v}/{\bar{v}}$$

Or else, if we know the temporal speeds averages in a time τ, the calculus will be:

$$e_{v_t}^2 = {C_{v_{\bar{v}}}^2}/{M} \text{ and } C_{V_{\bar{v}}} = {S_{\bar{v}}}/{\bar{\bar{v}}} = \sqrt{\frac{1}{M}\sum_{j=1}^{M}(\bar{v}_j - \bar{\bar{v}})^2} \Big/ \left(\frac{1}{M}\sum_{j=1}^{M}\bar{v}_j\right)$$

Results for same different stationary states periods from Table 3 of both speeds errors assuming a τ=3minutes aggregations are resumed in the next table:

HORA:	$\bar{\bar{p}}$ h/km	$S_{\bar{p}}^2$ h/km	$C_{V_{\bar{p}}}$	e_{v_S} %	$\bar{v}_t$ km/h	S_{TMS} km/h	C_{V_v}	e_{v_t} %
	SMS				TMS			
0-1:30	0,00903	4,709E-07	0,0759	1,406%	112,83	8,5437	0,07445	1,359%
16:26-17:00	0,00916	6,097E-08	0,0269	0,726%	109,92	1,1404	0,010201	0,267%
20:00-20:25	0,01597	4,068E-06	0,1263	4,16%	62,61	3,70057	0,05811	1,838%
21:00-21:40	0,01882	8,788E-06	0, 1575	4,57%	57,40	2,65644	0,04446	1,233%

TABLE 3 Space and temporal speed's error determination of selected stationary periods from 3rd lane data of P.K. 128.3 section with 3' time aggregation

It is observable that the committed errors in the average's speed calculations with the mentioned criteria are reasonable because both space-mean speed and time-mean speed with 3 minutes aggregation time criteria have relative errors lowers than 5%.

Space Mean Speed's Evolution Along The 24hours Data Registration. If the space mean speed mentioned is calculated during all the data registration period, following the N=30 vehicles aggregation criteria, we get the following blue points on next figure:

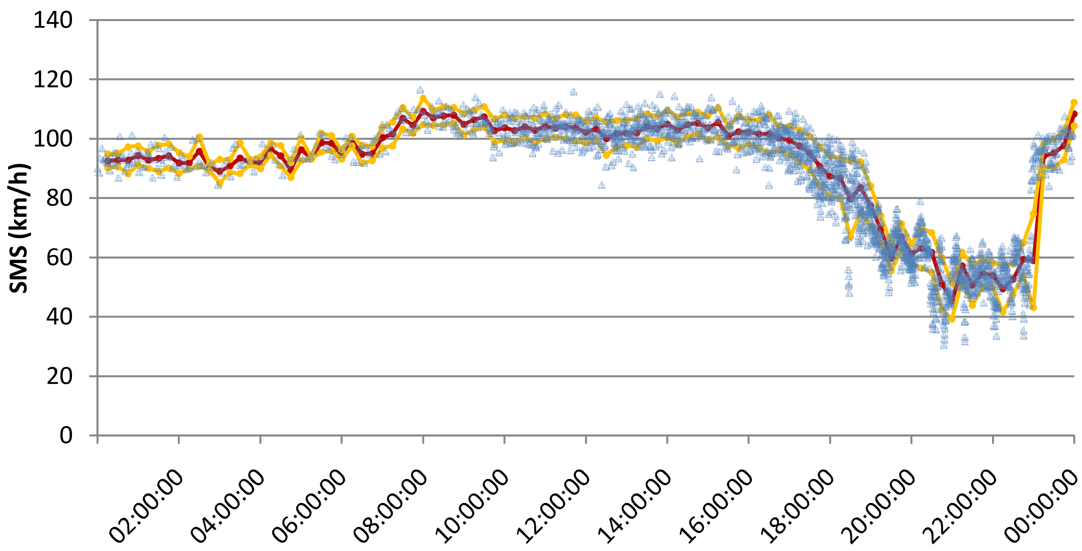

FIGURE 8 The 24 hour evolution of the space-mean speed with N=30 vehicles criteria in all three lanes of section P.K.128.3

Figure 8 is really similar to figure 4, where the space-mean speed is represented with the 3 minutes time aggregation criterion. But in this case the calculated average speeds belong not to a lane but to the whole P.K. 128.3 section.

As it is commented in chapter IV, the vehicle's speed average varies along the day and specially the last period of the day, when congestion conditions appear. Before this situation, speeds basically vary on a 30 km/h range from 85 to 115 km/h.

When free-flow traffic conditions disappear, as seen in figure 5 from 16 hours on, stream gets top rates (rush hour). Then, the space-mean speeds start decreasing because interaction between vehicles rises and levels of service A and B finish. Later on, between 20:30 to 22:45 speeds fall to less than 70 km/h (even less than 40 km/h in some moments) due to the fact that motorway has three lanes cannot handle such a big stream and car-following appears (Rothery 2002).

Finally, about 22:56, the stream decreases and queues began to dissipate so vehicles start circulating at higher speeds. In figure 8 there is a jump at this time, showing that vehicles go faster because of interaction absence.

1.3) Density

This third macroscopic characteristic gives idea of how crowded a certain section of the freeway is. It is typically expressed in number of vehicles occupying a length of roadway (usually per kilometre). It can only be measured in a certain spatial region, and it is not direct measured by the two loops detector therefore can only be estimated (May, p. 192-200).

Density can be calculated from speed and stream measurements using the Fundamental Traffic Theorem:

$$q = k \cdot SMS$$

The Fundamental Traffic Theorem requires the space-mean speed. However, another technique for determining it is based on the measurement of occupancy and using the equation:

$$k = \sum_{i=1}^{N} tti \Big/ T_{agg} = \sum_{i=1}^{N} \left(3{,}5\, m / v_i \right) \Big/ T_{agg}$$

Occupation's Error Determination. To calculate the relative error of the occupation estimation, a dispersion index of t_{on} in a period τ is determined as:

$$\gamma_{t_{on}} = {S_{t_{on}}}^2 / \bar{t}_{on}$$

Then, the relative error is:

$$e = \sqrt{\gamma_{t_{on}} / T_{on}}$$

Errors for different traffic states in stationary periods assuming a τ=3minutes aggregations are resumed in the following table:

HOUR:	$\overline{t_{on}}$ ms	dev(t_{on}) ms	$\gamma_{t_{on}}$	$e = \sqrt{\gamma_{t_{on}} / T_{on}}$ %
0-1:30	1.302,6	710,43	0,545	9,96%
16:26-17:00	14.435,4	1.901,60	0,132	3,52%
20:00-20:25	34.235,6	5.571,12	0,154	4,88%
21:00-21:40	38.789,46	7.810,27	0,201	5,58%

TABLE 4 Occupation's error determination of selected stationary periods from 3rd lane data with 3' time aggregation

Therefore, the relative error of the estimation of the occupation is low, although in free-flow state (from 0h to 1:30) is around 10% due to the light traffic conditions.

Densities Evolution Along The 24hours Data Registration. In figure 9, the densities during the 24 hour data registration are calculated. The method used is the one already mentioned in section III consisting on fixing the number of vehicles (N=30 vehicles), so the evolution is as follows:

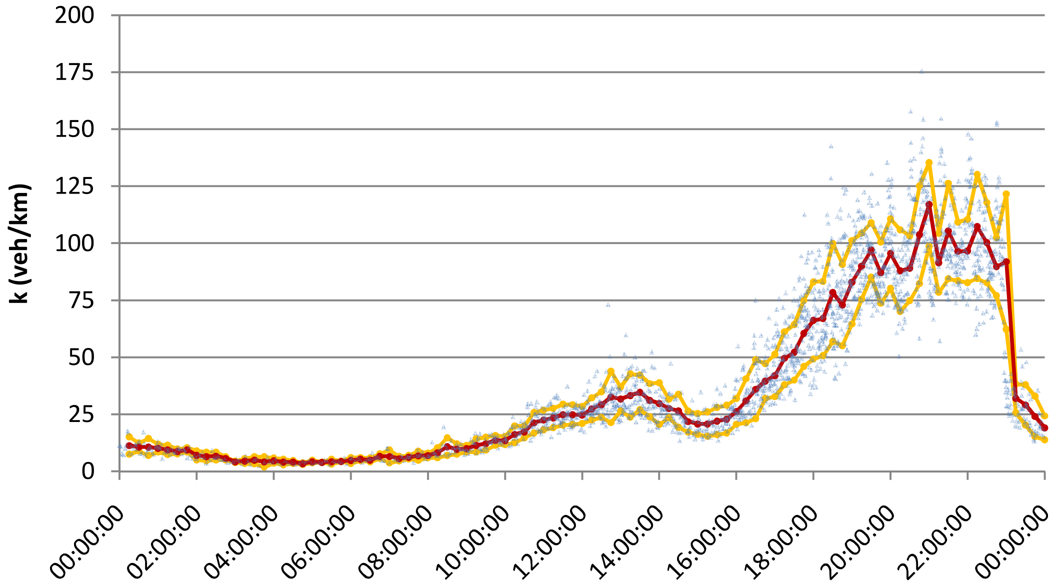

FIGURE 9 The 24 hour evolution of the density with N=30 vehicles criteria in the whole P.K. 128.3 section

As density depends on the occupation time of loops detectors, figure 5 of chapter IV has the same shape as figure 9.

As seen in figures 7 and 8, the first stage of day from midnight until approximately 9 o'clock, the level of service (High Capacity Manual 2000) of motorway is A or B, corresponding to low streams, low densities and high vehicles speed showing densities lower than 20 vehicles/kilometre.

After 9 o'clock, density starts to increase until values of 40 vehicles/kilometre reaching, at some particular peaks around 50 vehicles/kilometre. This first peak is analogous to the one seen in figure 7 to high streams and in figure 8 to the speed reduction.

Anyway, as stream and speed average evolutions in figure 7 and 8, the main phase of congestion is presented from 19:30 to 22:00. In this period time highest densities are reached (more than 125 vehicles/kilometre in many instants) but also worst level of services, E and specially F appear in this section and vehicles queue grow upstream flow.

1.4) Relation Among Stream, Average Speed and Density

It has been discussed the validity of the relation among average vehicle speed ($\bar{v}$), stream (q) and density (k), and although there are many ways of taking averages such as to define these variables, Edie (1965) has proposed a family of definitions so that $\bar{v} = q/k$ holds as true by definition. Therefore, in the following points, measured data will be treated consistently with Edie definitions.

If each vehicle trajectory is defined with two lines (representing the vehicle's front and rear), and these could be taken from the measured arrival and departure times to the detector zones, as shown in the figure:

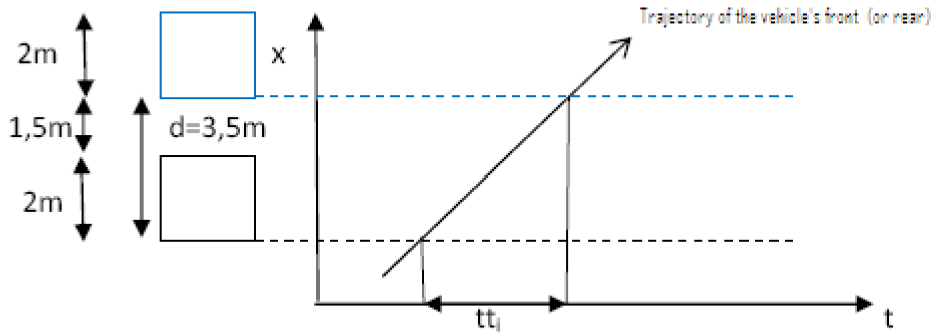

FIGURE 10 Space-time diagram with the two loop detectors.

In turn, the period time of analysis (T) may be chosen so that the front and rear lines for all *N* trajectories within the region span L, where L is still considered to be the distance separating the upstream edges of the two detector zones. With this choice of T, one may measure τ_j with the upstream detector because these are the τ_j's that would be measured by a detector placed anywhere within L, provided that each jth vehicle maintains a constant p_j over L and the detectors are calibrated to have zones of equal size.

For illustrating the relations among $\bar{v}$, q and k the vehicle trajectories were partitioned into consecutive, nonoverlapping rectangular regions. By selecting T so that all *N* trajectories in a region spanned L, T varied across the regions.

Although the variables could have been measured for any *N*, the illustration presented here involved reasonably consistent estimators from regions with $N \approx 30$. However, Ts are generally selected in a way that each region held *N=30* vehicles.

Per Lane Analysis. Next figures present the plots of $^{q}/_{\bar{v}} = \hat{k}$ per each lane, where the estimator $\hat{k}$ is the average of the density between the detectors sampled at closely spaced times following the mentioned data analysis with N=30.

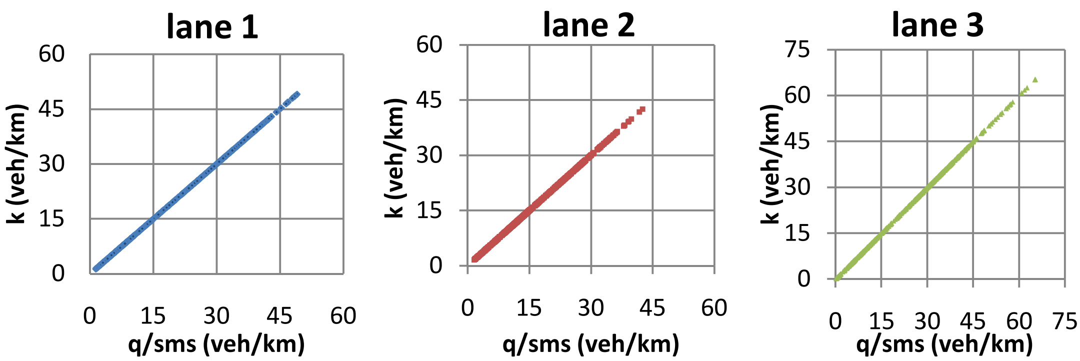

FIGURE 11 Fundamental traffic relation (k=q/sms) from left to right lane 1, 2 and 3 with N=30 vehicles aggregation

The range of conditions $^{q}/_{\bar{v}} \approx \hat{k}$, the scatter in these data is smaller in dense traffic because slower vehicle speeds gave rise to a nearly continuous sampling procedure.

Alternatively, with regard to extracting occupancy at the speed trap, a detector measure the time each jth vehicle spends over the detector zone τ_j and the measured occupancy is taken as: $\rho = \frac{\sum_{j=1}^{n} \tau_j}{T} = \frac{\frac{1}{n}\sum_{j=1}^{n} \tau_j}{\frac{1}{n} \cdot T} = q \cdot \sum_{j=1}^{n} \tau_j$

And assuming that each jth vehicle maintains a constant speed (and its pace $p_j = v_j^{-1}$) over L (which is 3,50 meters so it is relatively small), the summed length of the detector zone and the vehicle (l_j) is the ratio of τ_j to p_j, as such,

$$\rho = q \cdot \sum_{j=1}^{n} (l \cdot p_j) = q \cdot \frac{1}{\bar{v}} \left[\bar{v} \cdot \frac{1}{n} \cdot \sum_{j=1}^{n} (l_j \cdot p_j) \right] = k \left[\frac{\frac{1}{n} \sum_{j=1}^{n} (l_j \cdot p_j)}{\sum_{j=1}^{n} p_j} \right] = k \cdot \bar{l}$$

Where the term $\bar{l}$ is the average vehicle length relating ρ to k and is called effective average vehicle length weighted by the peaces. The effective vehicle length is the addition of the vehicle length and the length of the detector (2,0 meters).

For the analogous relation, next figures are plots of k versus ρ, which slope is the effective average length $\bar{l}$. Data scatter here occurs in part because $\bar{l}$ varied across the regions and traffic stream change during the observation periods, especially in the first lane where there is mixed light and heavy traffic.

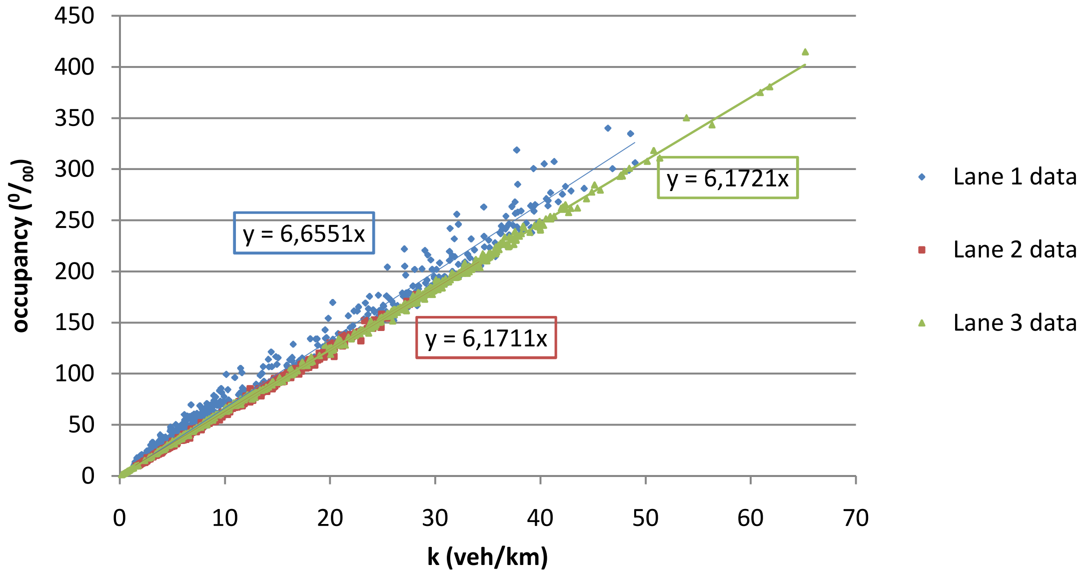

FIGURE 12 Occupancy versus density (k=q/v) per lane diagram with N=30 vehicles aggregation during 24h data

Moreover, the scatter of each data has its lineal regression to estimate the slope of each lane stream. Logically and as it has been mentioned the presence of heavy traffic especially in the first lane, the effective average vehicle length of it is on the first lane bigger than the analogous ones (6,655 meters versus 6,171 m and 6,172 m of second and third respectively). Remember that these values include the detector length due to are effective lengths.

Nevertheless, considering that the truck length average is around 16 meters, the 6,655 meters value of the first lane is pretty low. This result is mainly caused because data recorded was registered on Sunday, when heavy traffic defined as vehicles larger than 5 meters, is less than on a working day.

Per Section Analysis. Considering the whole section of the motorway studied, we are able to obtain the followings figures (13 and 14) which relate the estimator of density $\hat{k}$ and the rate $^{q}/_{\bar{v}}$. In a way that we can check out the fulfilment of the relation between these three macroscopic characteristics which is also called Fundamental Relation of Traffic Flow Theory.

Analysing it with the 30 vehicles group method mentioned in the beginning of the present chapter, we can obtain the following scatter plot.

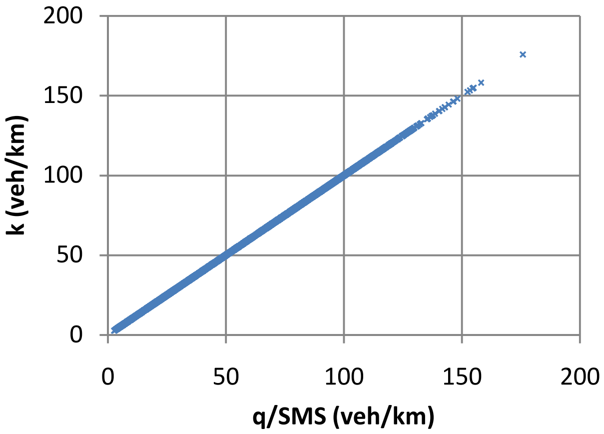

FIGURE 13 - q/SMS versus k with N=30 in section P.K.128.3 during 24h data registration

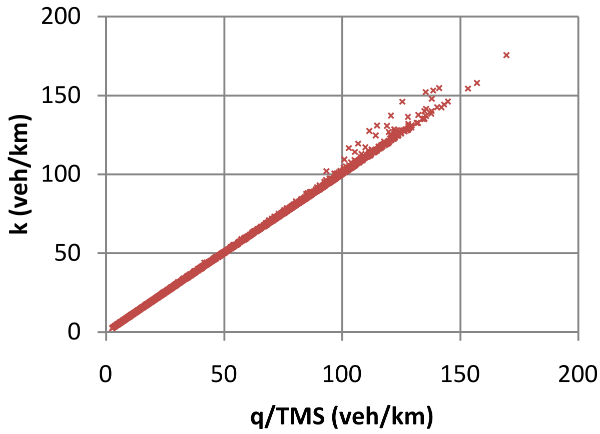

FIGURE 14 - q/TMS versus k with N=30 in section P.K.128.3 during 24h data registration

Figure 13 shows that the relation q=k·v is almost lineal. Data in this plot span a broad range of traffic conditions.

There are illustrated the effects of using both types of speed (space-mean speed and time-mean speed in figures 13 and 14) explained in chapter 1.2. As it is known the Fundamental Traffic Equation relates the ratio of the stream and the density with the harmonic average of the vehicles instantaneous speeds (SMS). Although, the arithmetic average because of its calculus facility it is more frequently used and wrongly introduced in the Fundamental relation.

Thus, it is able to realise that in one hand the relation q=k· SMS is an identity while in the other, the relation q=k· TMS has more scatter for high densities conditions (Cassidy and Coifman 2001).

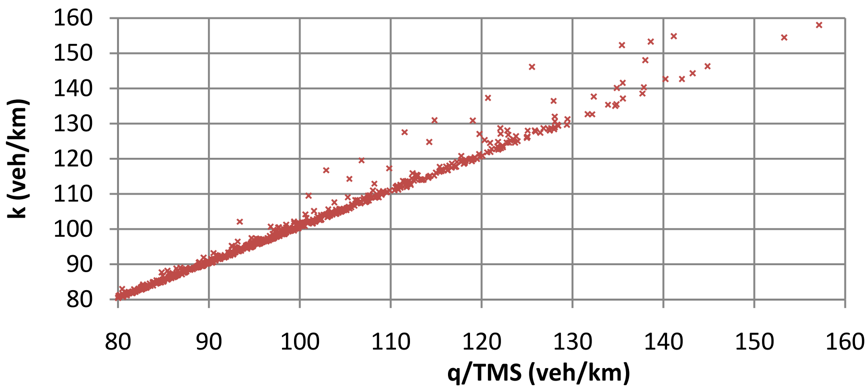

FIGURE 15 Scatter data zoom of q/TMS versus k plot with N=30 in section P.K.128.3 during 24h data registration

This pattern of scatter occurs because the positive bias is proportional to the variance in vehicles speeds, which is often large in dense traffic. Anyway, it is not such important due to the fact that data is registered on Sunday. Thus, there is less heavy transit and therefore the variance is reduced leading to $SMS \approx TMS$.

Next figure exhibits this relation like if measurements are taken over fixed 3 minutes intervals. This aggregation time, fixing not the number of vehicles but the time, is the most common data aggregation used in transport field.

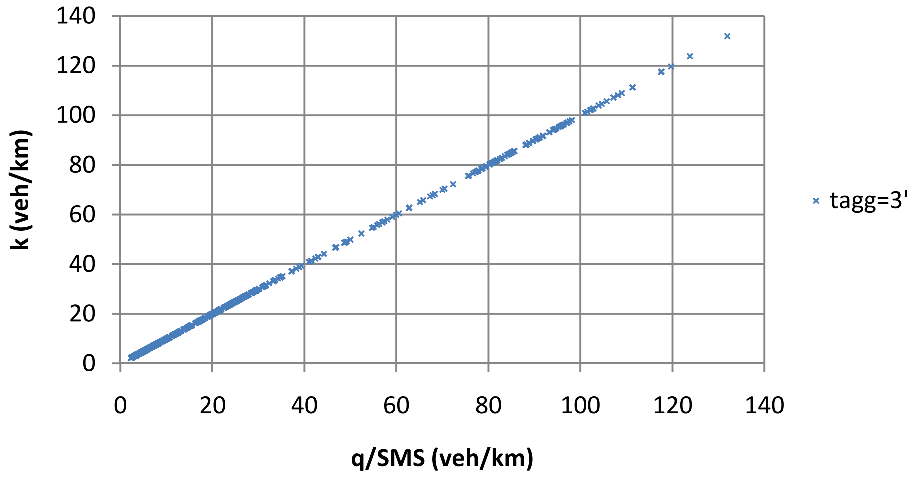

FIGURE 16 q/SMS versus k with 3 minutes aggregation time in section P.K.128.3 during 24h data registration

Data in figure 16 shows also an identity relation between the density (k) and the ratio between the stream (q) and the space-mean-speed (SMS). In the mentioned figure does not appear more scatter than the one seen on figure 13 where is fixed the number of vehicles (N=30) because taking an aggregation time of 3 minutes interval is such a big interval that it groups more than 30 vehicles in almost all periods of the registration day. For this reason, data is analysed again with a 30 seconds time aggregation, showing the following relation:

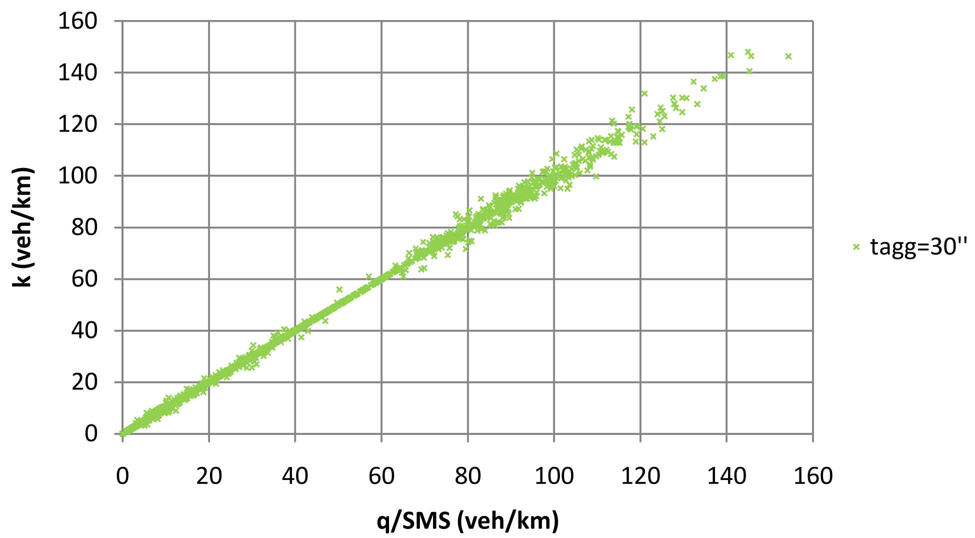

FIGURE 17 q/SMS versus k with 30 seconds aggregation time in section P.K.128.3 during 24h data registration

Figure 17 exhibit much more scatter than do data in figures 16 and 13. This scatter increase is attributed to taking of measurements over fixed 30 seconds intervals, which affected data in two ways: on one hand some data points came from regions holding some trajectory with an $x_j<L$, and variables could not be measured in the Eddie way already described because of t_j and x_j were not obtained. On the other hand, in dense traffic, data was drawn from regions of small N because the streams were low. Thus, l is expected to vary across these regions.

Then again, the relation of the density k and the occupancy ρ in the whole section is also represented in the following figure (extracting the observations over groups of N=30 vehicles):

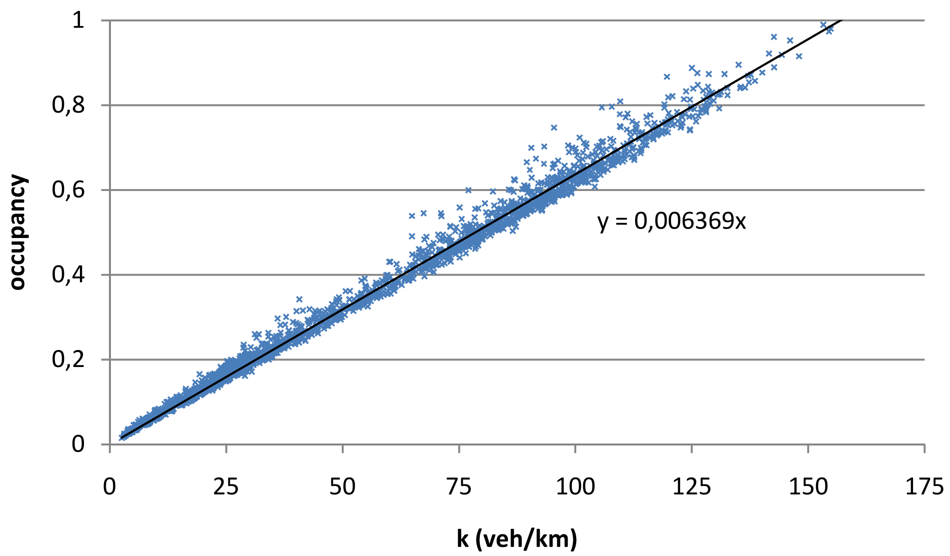

FIGURE 18 Density versus occupancy in P.K. 128.3 section with n=30 vehicles aggregation

Data scatter in figure 18 occurs because traffic stream changes during the observation period. There exists light and heavy transit mixed, so the slope l varies. Further, the scatter is slightly more pronounced in dense traffic conditions than in free stream conditions as a result of the measurement errors that occur whenever a vehicle does not travel at a constant pace (p_j) over the detector.

The slope of a best-fit line drawn through data in figure 18 define an effective average vehicle length of $\bar{l} = 6{,}376\, m$. Considering that the effective length is the addition of the vehicle (a typical light vehicle length is 4,1 meters) and the detector length (2,0 meters) the result has a logical value although it is a little bit higher because of the presence of some trucks.

Data in figure 18 presents values of occupancy really high, close to 1, which is the top value possible. That mean that during the entire interval measured the detector is occupied. Although in data analysis there are some values even higher than 1 because it may happen a measure error, while probably counting more vehicles or motorcycles. Likewise, these dense conditions happen when having an aggregation time small, because all 30 vehicles cross the two loop detectors really close.

Extension To Multi-lane Analysis. Furthermore, it is possible to get those three macroscopic variables per section, from the aggregation formulas of the different lanes of the studied motorway.

In case of multi-lane traffic, the total stream per section is the addition of each lane stream as:

$$q_{section} = \sum_{l=1}^{l=3} q_l$$

The density in a particular instant *t* in some motorway length is also the addition of each the three lanes of the studied section:

$$k_{total} = \sum_{l=1}^{l=3} k_l$$

Finally, the third macroscopic variable is calculated by averaging sub streams' mean speeds. The space-mean speed is averaged using their densities as weight factors:

$$SMS = {\sum_{l=1}^{l=3}(k_l \cdot SMS_l)}\Big/{k_{total}} = {\sum_{l=1}^{l=3}(k_l \cdot SMS_l)}\Big/{\sum_{l=1}^{l=3}(k_l)}$$

Equally, the time-mean speeds' weights are the stream of each lane analyzed:

$$TMS = {\sum_{l=1}^{l=3}(q_l \cdot TMS_l)}\Big/{q_{total}} = {\sum_{l=1}^{l=3}(q_l \cdot SMS_l)}\Big/{\sum_{l=1}^{l=3}(q_l)}$$

Applying these formulas in data calculated with the 3 minutes criteria, is verified the fulfillment of the aggregation, so that the results from data per lane coincide with the analysis from the full data per section.

2) Microscopic Analysis

2.1) Time Headway (h)

The time headway is defined as the elapsed time between the arrivals of pairs of vehicles. So it is the difference of the arrival time of two consecutive vehicles at the observation point where the double loop detector is situated. It can be shown as:

$(h)_{1-2}=t_2-t_1$ for the first and the second vehicle
and $(h)_{j-(j+1)}=t_j-t_{j+1}$ for a pair of successive vehicles

This stream characteristic is important because affects the safety of the vehicles and also the stream and capacity of a highway and therefore the level of service of it. So that is why it is so interesting to know the time headway distribution, to understand the different possible situations that can be occurred and the consequent driver behaviour. It must be a minimum time headway because of safety, which means a drivers reaction time and it depends of information, expectation, ability and experience. That distribution determines the requirement and the opportunity for passing, merging and crossing.

The time headway is the addition of two time intervals: the occupancy time to pass the observation point and the time gap between the rear of the lead vehicle and the front of the following vehicle. So, it is used to be the elapsed time between the leading edges of two consecutive vehicles, although it could be taken the time between the passages of identical points of these vehicles.

The shape of the time headway distribution varies considerably as the traffic stream rate increase. This is observed in figure 19 and is due to the increasing interactions between vehicles in the traffic stream:

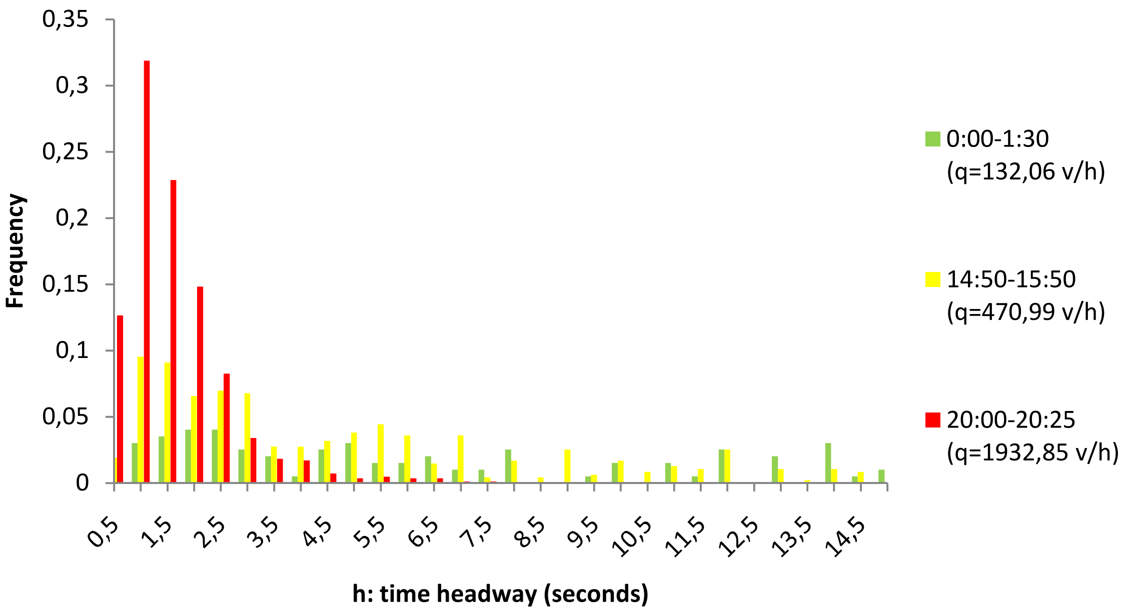

FIGURE 19 Time headway frequency distribution for different traffic states' stationary periods from 3rd lane data of P.K. 128.3 section

In figure 19 three time headway frequencies distributions are represented. These three distributions belong to three different traffic states registered in the third lane of the section studied P.K. 128.3.

For example, first selected period corresponds to the first hour and a half data registration (from 0 hour to 1:30), under very low stream conditions (q=132,09 vehicles/hour) there is very little interaction between the vehicles and the time headways appear to be somewhat random. In fact, the frequency distribution is extensive from 15 seconds on. Time headways until more than 100 seconds appear, so any point in time is likely to have a vehicle arriving as is any other point in time. Moreover, the arrival of one vehicle at the studied section in time does not affect the arrival time of any other vehicle. Because of this random situation the average time headway of this period is large (27,400 seconds) and the standard deviation too (32,591 seconds).

The negative exponential distribution is the mathematical distribution that represents the distribution of random intervals such as time headways from random independent arrivals (Poisson process):

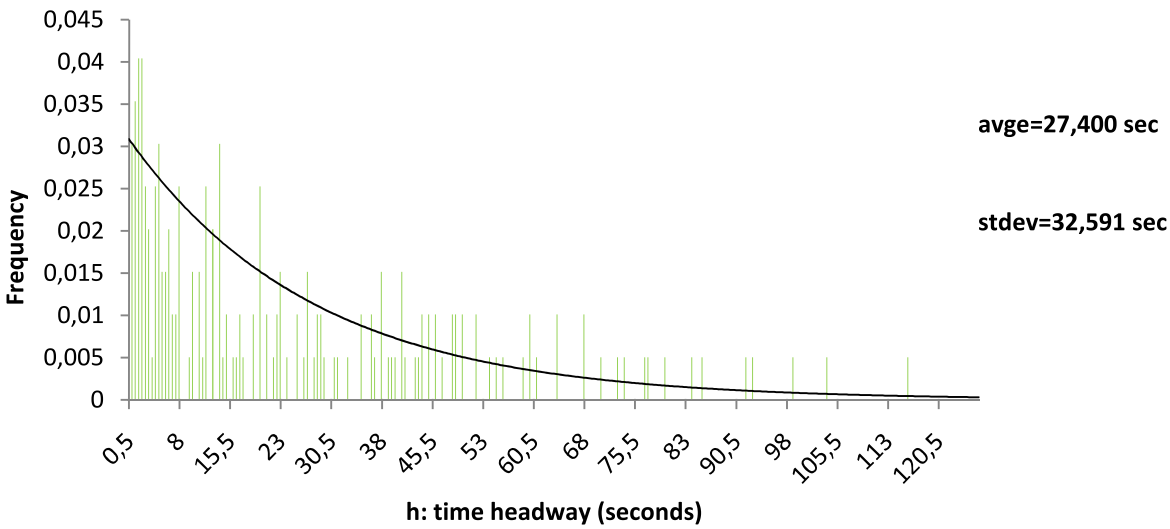

FIGURE 20 Time headway frequency distribution from 0:00 to 1:30 data from 3rd lane in P.K.128.3 section

A chi-square value is calculated for each comparison of two distributions using the equation:

$$\chi^2_{\mathrm{CALC}} = \sum_{i=1}^{l} \frac{(f_o - f_t)^2}{f_t}$$

Where:

-f_o is the observed number or frequency of observations in time headway interval i

-$f_t$is the theoretical number or frequency of expected observation in time headway interval i

-i is any time headway interval

-l is the number of time headway intervals

The chi-square value of distributions represented in figure 20 is 1,0794. This value, close to zero, indicates a good fit between both distributions and the hypothesis is likely to be accepted.

Otherwise, if the selected stage is a stationary period where traffic congestion appears, the interactions between vehicles increase, and headways are of vehicles, that are following one another. Thus, as the traffic stream level approaches capacity, almost all vehicles are interacting and are in a car-following process. In this process all time headways are approximately constant. The only difference from real life would be that while the driver would attempt to maintain a constant headway, driver error would cause some variation regarding this constant headway.

In figure 21, the time headway distribution from the registered data from 20:00 to 20:30 in lane 3 in P.K. 128.3 section (where stream is 1932,85 vehicles/hour) is represented:

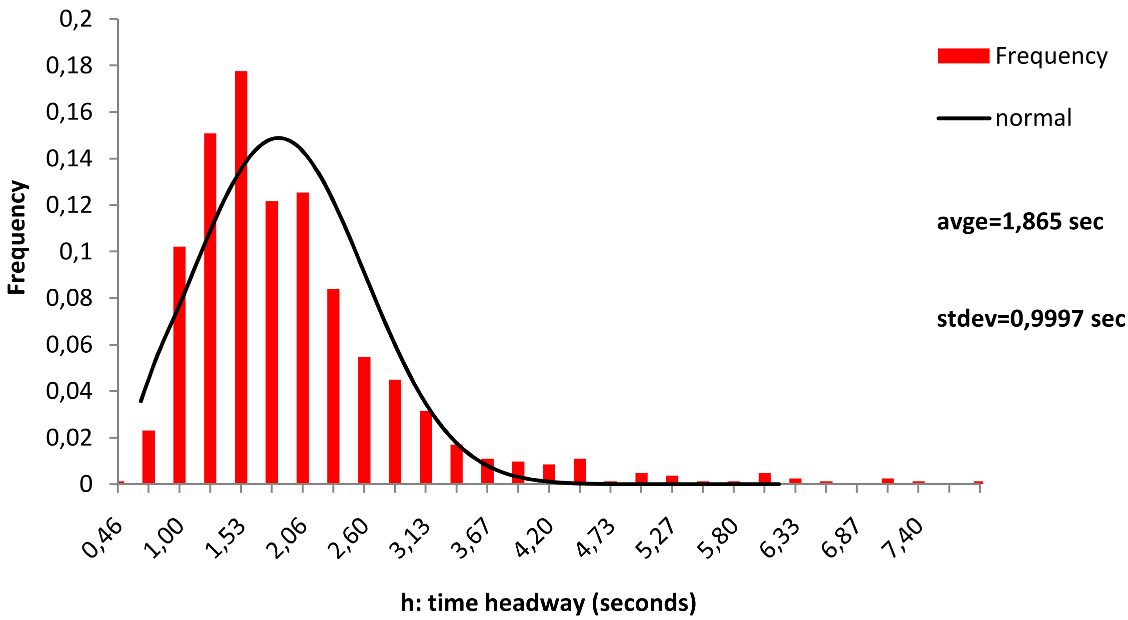

FIGURE 21 Time headway frequency distribution from 20h to 20:30 data from 3rd lane in P.K. 128.3 section

As it is discernible in figure 21, the normal distribution is a mathematical distribution that can be used when drivers attempt to drive at constant time headway. When traffic congestion appears, the average headway decreases around 1,865 seconds of average because vehicles move closer each other (car-following situation). Also the standard deviation is lower (0,997 seconds) due to as vehicles move together their headways are so similar and just driver errors cause the time headways to vary about the intended constant time headway.

The chi-square value comparing the theoretical normal frequency and the field data one is 3,0276. This value corresponds to a quite good fit of both frequencies although the normal distribution is shifted to the right of the measured distribution.

The intermediate headway state lies between the two boundary conditions exemplified by the random and constant headway states. Time headways from data registered in the third lane from 14:50 to 15:50 corresponds to this state. The average stream during this period of time is 470,99 vehicles and its time headway average is 7,65 seconds. This headway average is higher than 1,865 of congestion period state and lower than 27,400 from free-flow state. The reason is because stream is big enough so many vehicles circulate with headways from 0,5 to 3,5 seconds so they interact between them although there are an important proportion of drivers that drive as under low stream level. Also the deviation of the individual speeds of the intermediate state (8,73 seconds) is situated between both due to this state characteristics.

2.2) Distance Headway (S)

The distance headway is the longitudinal space in the traffic stream from a selected point on the lead vehicle to the same point on the following one. There is usually selected the front edges of the vehicles, because are more often detected in automatic detection systems like the two loops detectors of our study.

This distance of vehicle n+1 at time t is the addition of the length of the previous vehicle (n) and the gap length between the two consecutive vehicles as it follows:

$$s_{n+1}(t)=L_n+g_{n+1}(t)$$

That microscopic property can be considered as a traffic density characteristic and it affects the safety. A minimum space must be available in front of every vehicle circulating so its driver is allowed to react without colliding with the vehicle ahead or any fixed object in an unexpected situation.

Moreover it also affects the capacity and level of service of vehicles in the traffic stream. The capacity of the roadway increases by spacing vehicles closer together, although it exists a critical spacing which up to it, the capacity decreases due to the reduction of speed because of the prevention of the users to have enough distance from the previous vehicle to react.

Analogous as figure 19, the space headway frequency distribution of three selected stationary periods are represented as follows in figure 22:

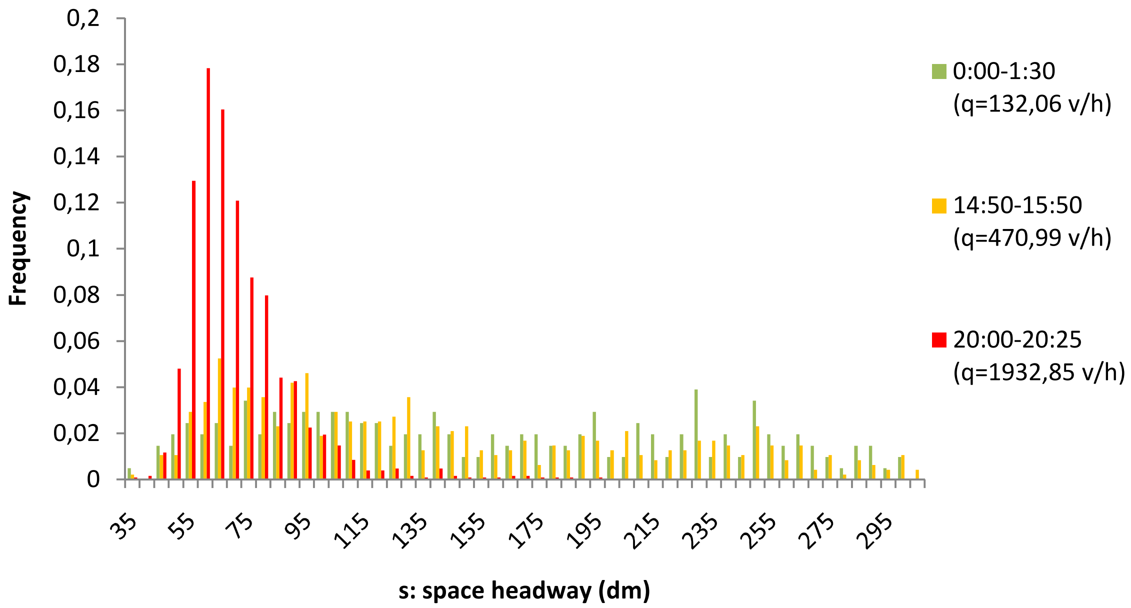

FIGURE 22 Space headway frequency distribution for different states' stationary periods from 3rd lane of P.K. 128.3 section data

It is noticeable, as in figure 19 with time headway, that the three selected stationary periods corresponds to three different traffic states from the 24 hour data registered. Therefore, the first and the second state correspond to free flow traffic states and the third one to congestion state.

The following table resume averages and standard deviations of space headways from the stationary periods mentioned belonging to the third lane of P.K. 128.3 section data:

Space headway (S) (in dm)	Average	Deviation
0:00-1:30	156,490	72,529
14:50-15:50	139,161	69,862
20:00-20:25	68,549	18,270

TABLE 5 Average space headways of selected stationary periods from 3rd lane data of P.K. 128.3 section

First state, from the first hour and a half data registration, has the highest space headway average of 156,49 decimetres (or 15,649 meters) and the highest deviation (72,529 decimetres). The reason of its values is because this day period of time, when stream is so low (132,06 vehicles/hour) the space headway between two vehicles is so big and also random. Due to this circumstances, the deviation is so important (46,3% of the average) so there exists variability of the distance between consecutive vehicles. Arrival of one vehicle doesn't affect of the arrival of the following one.

On second place, the stationary state registered from 14:50 to 15:50 data corresponds to a period of time when the stream has increased, but congestion has not appeared yet. Then, both variables decrease less than first state. The average is reduced more than 7 decimetres and the deviation less than 3 decimetres. The reason of that diminution is because as more vehicles circulate through the motorway, the space headway between each other is lower. Moreover, the deviation is lower due to this state is not as random as the first one.

In both cases, speed frequency distributions tends to be constant, and although the lower space headways are more frequent, distances until 300 meters appear.

Finally, the frequency distribution of the space headways from the congested state of the data registered between 20:00 and 20:25 is plot in figure 20. In this case, almost all vehicle space headways are lower than 120 meters. For this reason the average value is much lower than other two cases (more than a half). When traffic congestion appears, vehicles circulate together and distances between them are low.

Moreover, when car-following conditions appear the deviation is reduced considerably. The value of first two cases (around 70 decimetres) is reduced to 18,27 decimetres because drivers are not able to choose freely their movements as they travel together.

2.3) Vehicular Speed

The vehicular speed is the speed of individual vehicles passing a point during a specified period of time. It is a fundamental measurement of the traffic performance on the highway system. The speed is a representative measurement of the design, demand and control on the highway system and also of level of service.

It is desirable to find appropriate mathematical distributions to represent speed distributions because each mathematical distribution has unique attributes, and if a measured distributions can be said to have similar attributes and hence greater knowledge of the measured distribution can be inferred. It is also desirable to find appropriate distributions for purposes of computer simulation for which individual vehicles speeds are needed as input. Using mathematical distributions it is easier and more flexible.

Then so, in a traffic stationary state and with a constant percentage of heavy transit, the speeds distribution follows a normal distribution. The presence of different type of vehicles (heavy transit varying along time), selecting non-stationary periods or problems in measure alters the normal distribution. For this reason, next cases are exemplified with stationary periods from first lane data, where the presence of heavy traffic is higher.

If we incorporate in data measured different traffic states makes skew the frequencies' distribution. This distribution is different before, while and after the breakdown (Maerivoet and De Moor 2005).

Congestion Onset. For instance, if we select such a considerable period of time where there is free flow state and also a small congestion period which begins. We have a congestion onset where data doesn't follow a normal. The deviation grows up and the skew goes down. In figure 23 is represented this situation:

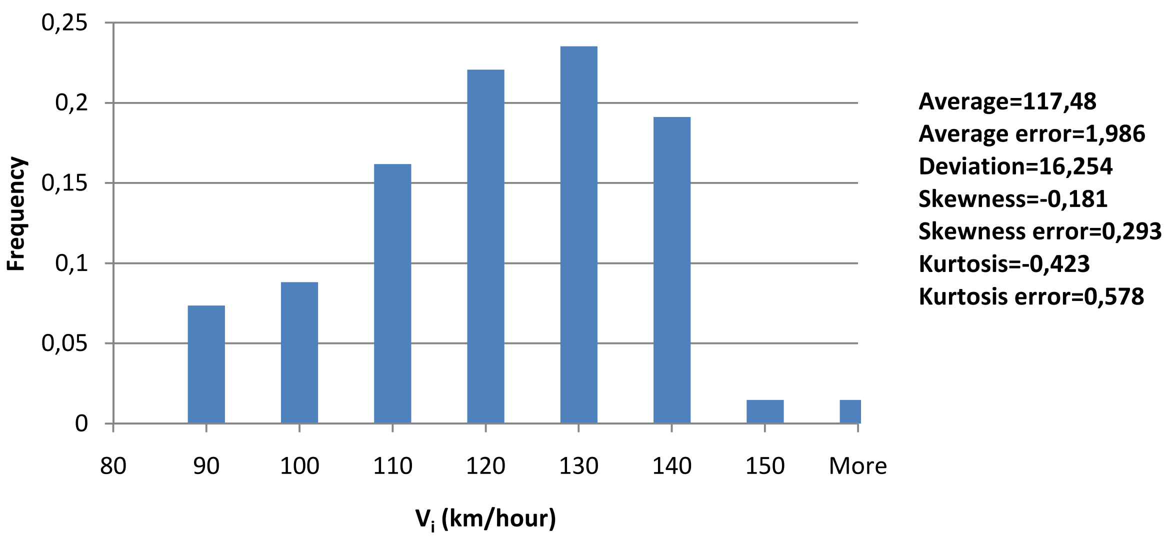

FIGURE 23 Speed's frequency distribution from 06:26 to 07:44 data of the 3rd lane of P.K. 128.3 section

It is observable in figure 23 how the vehicles which circulates through the third lane (the fastest one) from 06:26 to 07:44. Around half past six the free flow is present, so the vehicles can circulate at free speed without interaction between them (almost of them from 110 km/h to 140 km/h of speed). But as the stream increases along time (congestion on-set) after seven o'clock the speeds start decreasing. So then, it is observable that frequency distribution doesn't follow a normal distribution because of its considerable skewness (a -0,181 value). This asymmetry is negative which means that the distribution has a long left tail corresponding to slower speeds than the 117,48 kilometres per hour average.

A congestion on set is presented because of frequencies of lowest speeds (less than 100 km/h) are higher than highest ones (more than 140 km/h).

Congestion Dissolve. On the other hand, if the stationary period selected is situated with a main stage of congestion and also the beginning of its dissolution when cars can accelerate and start travelling faster, then we have a congestion dissolve situation when the normal distribution is also modified but in a different way.

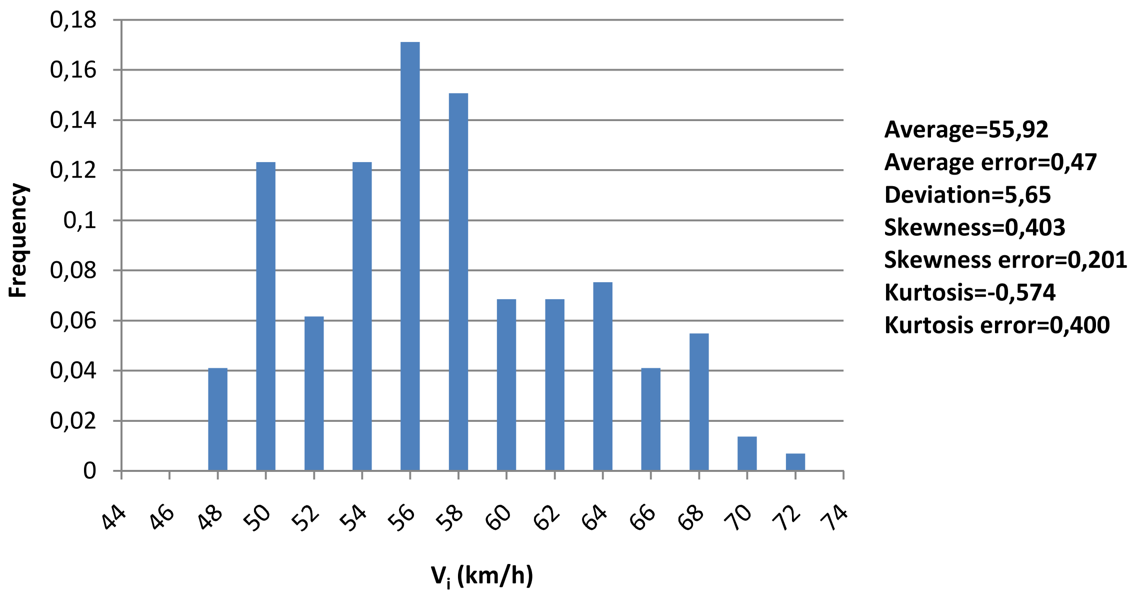

FIGURE 24 Speed's frequency distribution from 19:59 to 20:05 data of the 3rd lane of P.K. 128.3 section

The speed's frequency distribution of data registered in lane 3 between 19:59 and 20:05 is represented in figure 24. The 55,92 km/h average corresponds a slowly speed due to the congestion. Moreover distribution skewness appears again but with the sign changed. Now, this asymmetry is positive because the right tail corresponding to higher speeds is longer than left one of congestion's speeds. Likewise, there is some negative kurtosis which means that speeds cluster less around central point and have shorter tails than a normal distribution.

Stationary State. Selecting a properly stationary state, the frequency distribution fits to a normal distribution as is visible in figure 25:

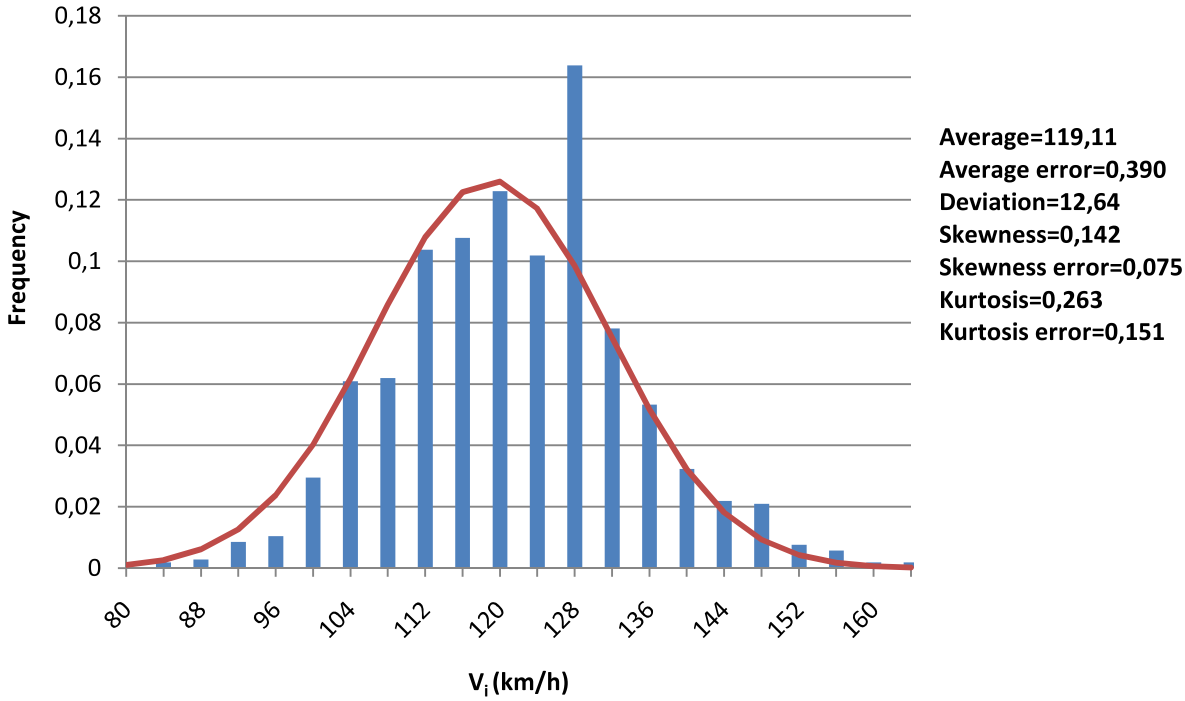

FIGURE 25 Speed's frequency distribution from 10:45 to 12:30 data of the 3rd lane of P.K. 128.3 section

The selected period belongs from the motorway third lane from 10:45 to 12:30 which is characterized of a stationary period with a free flow conditions. And that's why the speed average of 119,11 km/h is considerable. Moreover, it is discernible the adjust of a normal distribution (figure's red line) because of its skewness and kurtosis lower values. These values are closer to zero than congestion onset and congestion dissolve situations which means that tails are more symmetric and also that the distribution tails are just a little bit longer than normal ones.

It is also evident in figure 25, the good fit to a normal distribution except in the speed interval from 128 to 132 km/hour. The reason because of this peak in the mentioned interval is the speed limit of 120 km/hour. The interval were most drivers circulate is between these speeds, a little bit higher than the speed limitation of the motorway AP-7.

Additionally, it is interesting to analyse if the selected stationary period of time belongs to a free flow or to a congestion episode. Both situations are represented in figure 26 where are represented the speeds registered from 00:00 to 1:30 and from 21:00 to 21:08.

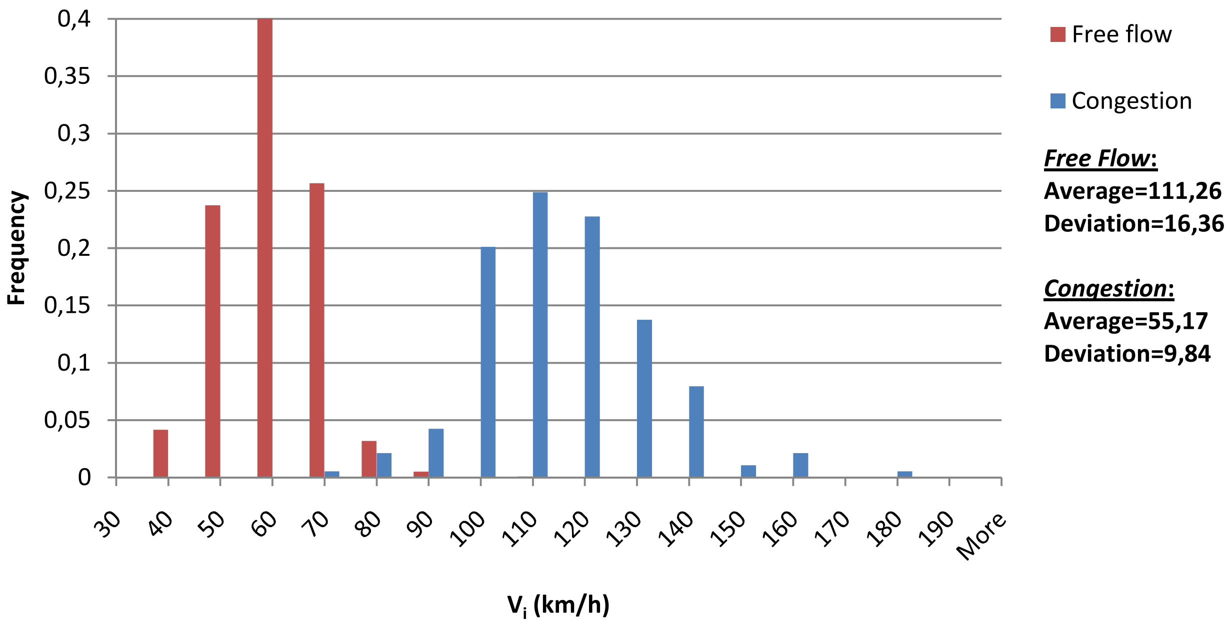

FIGURE 26 Speed's distribution from 00:00 to 1:30 (free-flow state) and from 21:00 to 21:39 (congestion state) datas of the 3rd lane of P.K. 128.3 section

Congestion speed frequency distribution (in red colour in figure 26) is situated on the left hand of the free flow one (in blue colour). That situation is logical due to in first circumstance vehicles circulate slower than in second one. Also is verified with the averages registered: 55,17 km/hour in car-following situation versus 111,26 km/hour in light traffic condition. When free flow traffic the vehicles are unimpeded by other vehicles, the drivers are able to drive on maximum speeds allowed (considering geometric design of the via, engine capability or other vehicle characteristics).

As can be seen in figure 26, another phenomenon happens that differentiates both regimes. The deviation of jam situation is much lower than unconstrained phase (9,84 km/h versus 16,36 km/h which is almost 40% less). In free flow, drivers strive to attain their own comfortable travelling speed (for example if a vehicle find a slower one moving ahead, it can easily change lanes in order to overtake the slower vehicle), so the variability of the speeds is considerable and the speeds range is important (from 70 km/h to 180 km/h).

In contrast, in congested phase, vehicles are not able to freely travel at their desired speed so it is reasonable to assume that drivers are more mentally aware and alert, as they have to adapt their driving style to the smaller space and time headways. Drivers have to brake in order to avoid a collision with the leader directly in front and that's why vehicles circulate to lower and similar speeds. Then so, the deviation diminishes because almost cars go at the same speed and the peak of the congestion state histogram is higher than free flow one. Likewise the velocities range is narrower, from 30 km/h to 80 km/h.

Authors like Van Lint (2004) say that the phenomenon is in the other way: the speeds deviation in free flow regimes are lower than in congested phases. The reason of this contradiction with the present study is due to the stationary states definition. In the congested regimes selected in those cases, there are incorporated inside different congested states.

If we consider congestion state all those traffic states where there exists any interaction between vehicles (more than 50 vehicles/km is chosen), the free flow stationary states are well defined but nor in the congested one. This one is composed by many of them. To demonstrate that, the congested state (CS-0) from 21:00 to 21:39 is selected and discomposed to smaller stationary states. That stationary state is composed by 1.200 measured vehicles that circulated through the third lane motorway between this period of the day. So then, a second group also stationary (CS-400) is extracted from CS-0. CS-400 is composed by data measured from 21:00:12 to 21:13:24 which 400 vehicles are registered crossing through the 128.3 kilometre section. Afterwards, from CS-400 there are extracted the first 200 vehicles that passed the studied section from 21:00:12 to 21:06:53 which conforms the CS-200 congested state. Finally another stationary state of 100 vehicles (CS-100) is analyzed from the measures from 21:03:43 to 21:06:53.

Speed frequencies of CS-400, CS-200 and CS-100 are represented in figure 27:

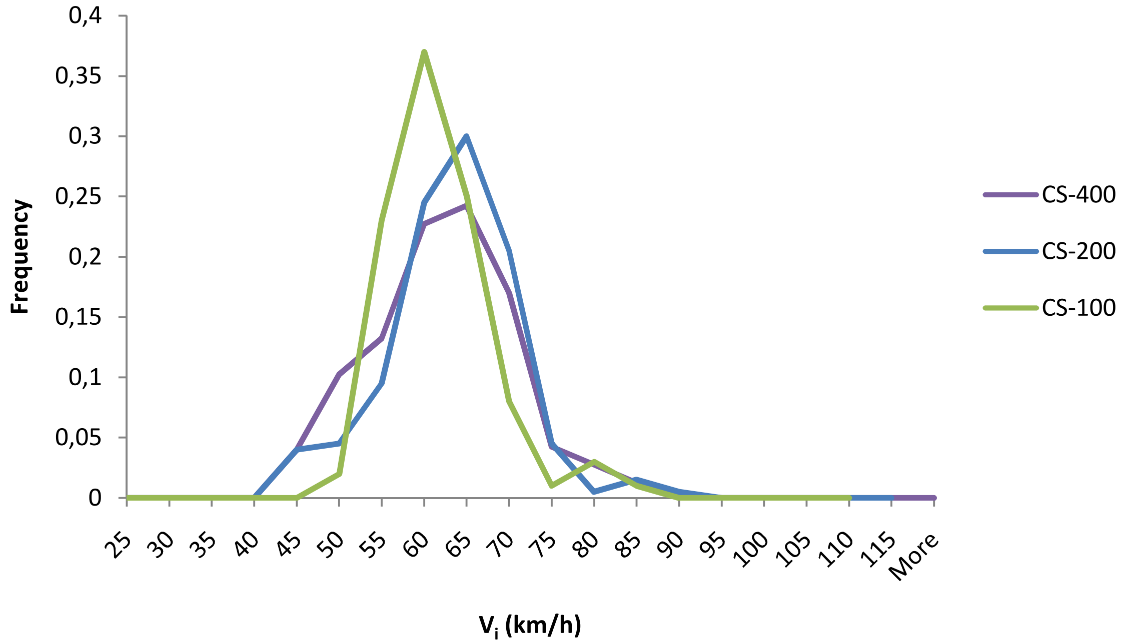

FIGURE 27 Speed frequency distribution of the different congested stationary states from 3rd lane of P.K. 128.3 section data

It is observable in figure 27, how as much we restrict the definition of the congested state the speed frequency distribution gets narrow. That happens due to the variability decreases as the selected group gets smaller.

Another useful way to verify this fact is viewing the standard deviations of the different states with the origin congested state CS-0.

Speed (in km/h)	CS-0	CS-400	CS-200	CS-100	Free-flow
Average	55,15	60,18	61,18	64,52	111,26
Standard deviation	9,851	8,394	7,511	5,973	16,361

TABLE 6 Average speed and standard deviation values of different congested states and free-flow states from 3rd lane of P.K. 128.3 section data

Viewing the table, it is evident the reduction of the standard deviation as the definition of the congested stationary state is being limited. So then, the variability of the speeds in a reduced congested stationary state is much lower than a free flow stationary state. As it is explained in the beginning of this section, on free flow state the speed range is wider and its deviation is also much considerable (16,361 versus 5,973 in CS-100). That's because of drivers can adopt their desired speed without interferences.

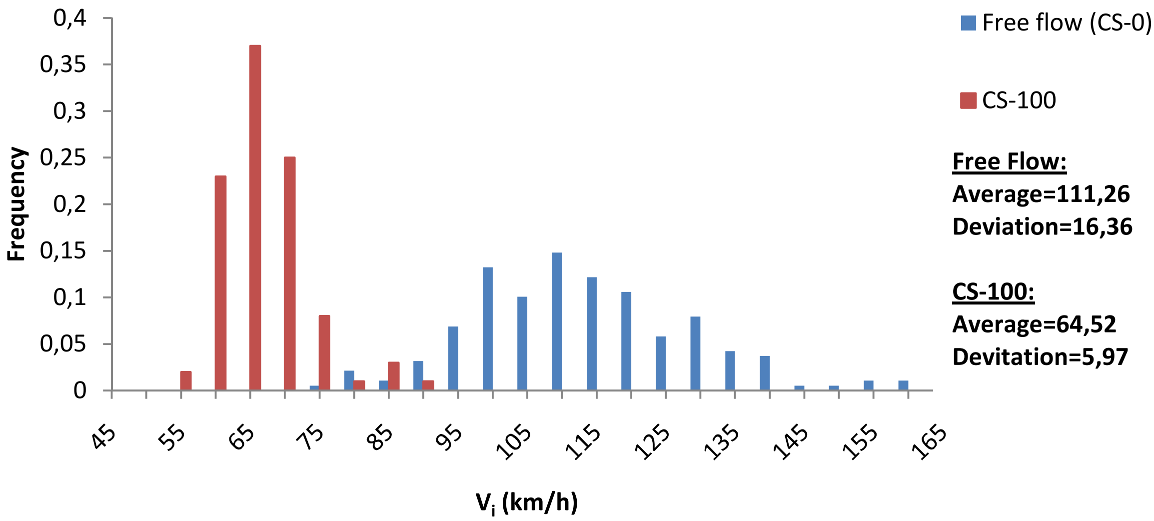

FIGURE 28 Speed frequency distribution of free-flow data and congestion state from 3rd lane of P.K. 128.3 section data

As it is seen in figure 28, the two speed frequency distributions of the CS-100 corresponding to a really short stationary period from 21:00:12 to 21:06:53 and the Free Flow one from 00:00 to 1:30, are represented. The second one (blue columns) with wider range and longer tails which means more deviation (2,74 bigger than CS-100 deviation).

Bimodal Distributions. Another common phenomenon that can affect the frequency distribution and distort the normal distribution can be the presence of two classes of vehicles (heavy and light transit at the same time).

When these situations happen, the resulting distribution can be bimodal distribution or to a lesser extent cause some skewness to it. The extreme case of existing a bimodal distribution is due to there are two normal distributions. There are one big distribution for light traffic (because almost vehicles crossing the studied section on data registered on Sunday are light) and a second one, smaller, for heavy one (with a lower mean because of slower speeds circulation which causes the skewness of the global distribution).

These traffic circumstances are more common when there are free-flow stationary traffic conditions because light and heavy vehicles circulate with very different speed. While free-flow state, light traffic circulates at their desired speeds which use to be really high (even more than the 120 km/hour legal restriction) while heavy one has their own limitations of mechanical or because weight so circulate slower. On congested traffic states, where occupations are higher than free-flow ones, the speeds of both classes use to be more uniform, and the bimodal distribution doesn't occur. For example when the congestion is considerable enough and high densities are reached, the car-following appears and all vehicles circulate at similar speeds, with really low deviation. Then, there is no distinction between classes of vehicles.

Moreover, the stationary state where this analysis happens without difficulty is for the first lane (lowest one) or for the whole section. The motive is because on these cases both classes of vehicles mix easily.

Therefore, on figure 29 there are represented the different speed's frequency distributions depending of the class of the vehicle from a stationary state's data:

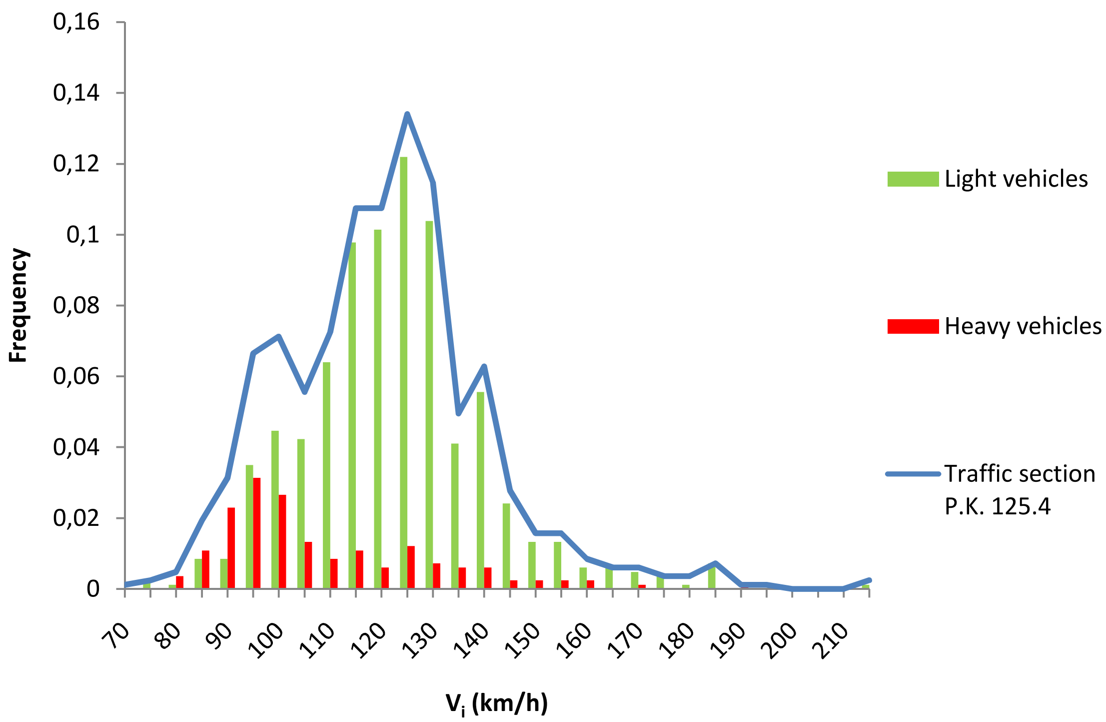

FIGURE 29 Speed's frequency distribution for traffic classes from data registered since 3:00 to 6:00 stationary state on P.K. 125.4 section

The blue line represents the speed's frequency distribution for the whole section P.K. 125.4 from data registered from 3:00 to 6:00. This period of time is stationary because of constant vehicle arrival, constant speeds and stable proportion of heavy traffic. Moreover, free-flow conditions are presented due to the poor traffic circulating at this Sunday time.

It is discernible in figure 29 how the heavy vehicles speed distribution (in red colour) is asymmetric with a long right tail (significant positive skewness) and is situated on the left hand of the whole traffic of section P.K. 125.4. The peak of this small distribution produces a small peak on the global one.

On the other hand the speed frequency distribution of the light vehicles (in green colour) is bigger due to the high percentage of this class of vehicle and its peak is more centred and on the right hand of the heavy one.

On the following table there are represented the averages and the deviations of the three distributions:

Speed (in km/h)	Light traffic	Heavy traffic	Whole section traffic
Average	120,59	107,17	118,43
Deviation	18,32	21,76	19,83

TABLE 7 Average speed and standard deviation values for traffic classes from 3:00 to 6:00 stationary state on P.K. 125.4 section data

It is observable how the average speed of heavy traffic is pretty lower than light one, although it has more deviation (due to the mentioned skewness). Additionally, it causes a small diminution of the average of the whole frequency distribution.

SMS-TMS Relation. It is important to distinguish between the space-mean-speed and the time-mean-speed. As seen in chapter 1.2 these variables are different averages of individual vehicle speeds. TMS is the arithmetic mean of the speeds of vehicles passing a point on a highway during an interval of time. Alternatively, the SMS is the harmonic mean of the speeds of vehicles passing a point on highway during an interval of time. The space-mean speed is a traffic density speed estimate and reflects the spatial dimension of speed and thus is utilized in the standard speed-flow-density relationships. With respect to both speeds, Wardrop (1952) derived the equation relating them as shown in the next equation:

$$TMS = SMS + {}^{\sigma_{sms}^2}/_{SMS}$$

With the statistical sample variance defined as follows:

$$\sigma_{sms}^2 = \frac{1}{N-1}\sum_{i=1}^{N}(v_i - \bar{v}_s)^2$$

Note, that that SMS is equal to TMS only when the variance of the SMS is equal to zero (all vehicles have the same travelling speed). If it doesn't happen and the variance of the SMS is greater than zero, SMS is always less than TMS. The practical difference between SMS and TMS is often negligible for light traffic conditions; however, under congested traffic conditions both mean speeds are substantially different (around 10%).

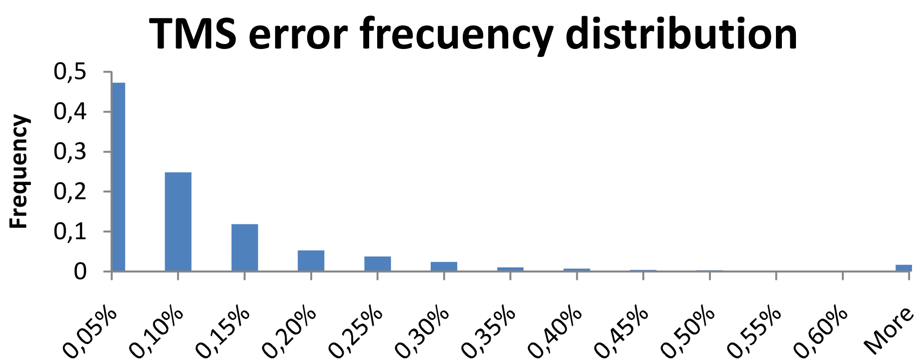

FIGURE 30 Frequency distribution of the relative error between TMS estimated and TMS calculated from all the three lanes of P.K. 128.3 section data

Equation is applied to estimate the TMS from SMS. However, in most cases the TMS is available and it is desirable to estimate SMS from the TMS (for example a loop detector does not measure/estimate space-mean speeds).

For this reason, it is also useful the following relation where the SMS is estimated from TMS (Rakha and Zhang 2005):

$$SMS = TMS - {\sigma_{tms}^2}/{TMS}$$

Then so, as data series has recorded all the instantaneous vehicles' speeds, both averages have been calculated (in N=30 groups as is mentioned in chapter 1.4). Analysing these results from all section data with the estimation of both speeds (using last equations), the error's histograms of the speeds will be the following:

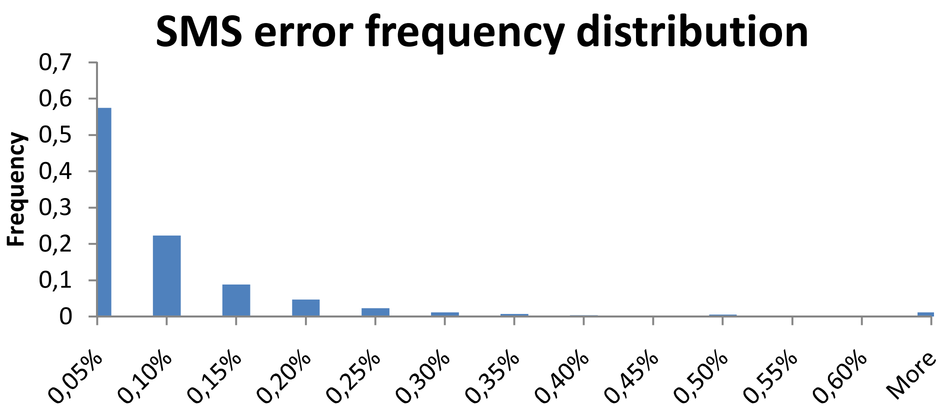

FIGURE 31 Frequency distribution of the relative error between SMS estimated and SMS calculated from data

It is demonstrated that the relationship between time-mean and space-mean speed that was derived by Wardrop and presented in several textbooks like May (1990, p. 129-133) produces an error in the range of 1 percent in time-mean speed estimates.

It is observable in figures 30 and 31 where frequency distributions from all three lanes data of section P.K. 128.3 are represented, the relative error in the estimation of both variables produces an error lower than 0,40%.

3) Analysis Of Variables: Diagrams

3.1) Micro Level Analysis

The microscopic variables analyzed in the traffic stream related with the car-following models are covered in this chapter. Therefore, the distance and the time headway between vehicles are analyzed versus the speed in diagrams.

Analysis Per Lane. First of all, it will be analysed these micro variables per each lane of the three ones of the studied section.

The spacing is calculated as the inverse of the density, from a properly analysis in groups of 30 vehicles and the speed is considered as the harmonic average (SMS). The shaded band which represents the results of field studies is represented in figure 32:

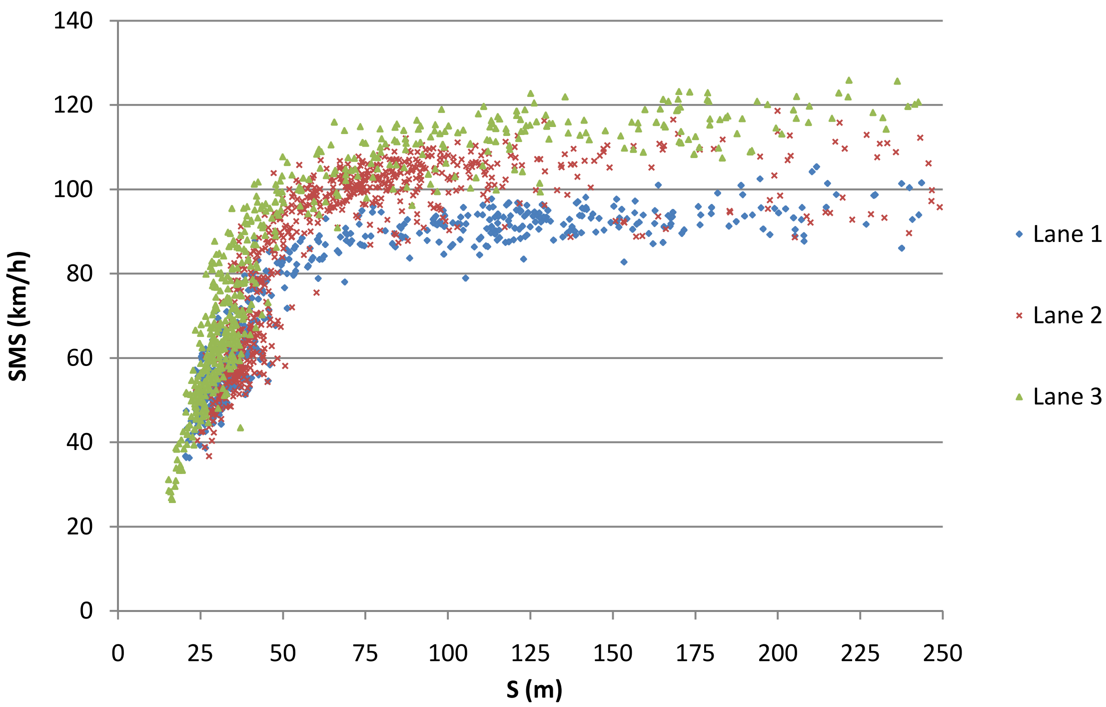

FIGURE 32 Average space headway versus space-mean speed

Where it is interesting to realise when the average space headway increases, the density (space inverse) decreases, and the space-mean speed increases too. Speed continues rising with bigger space headways until it reaches a maximum (the free flow speed). From then on, space-mean speeds remain constant for bigger average space headway, which means that driver experiences no influence from its direct frontal leader.

Anyway, the study of this micro variable is done when there exists interaction between vehicles. Therefore, it is analyzed what happens at low space headways.

A zoom of figure 32 about these cases is represented in next figure 33:

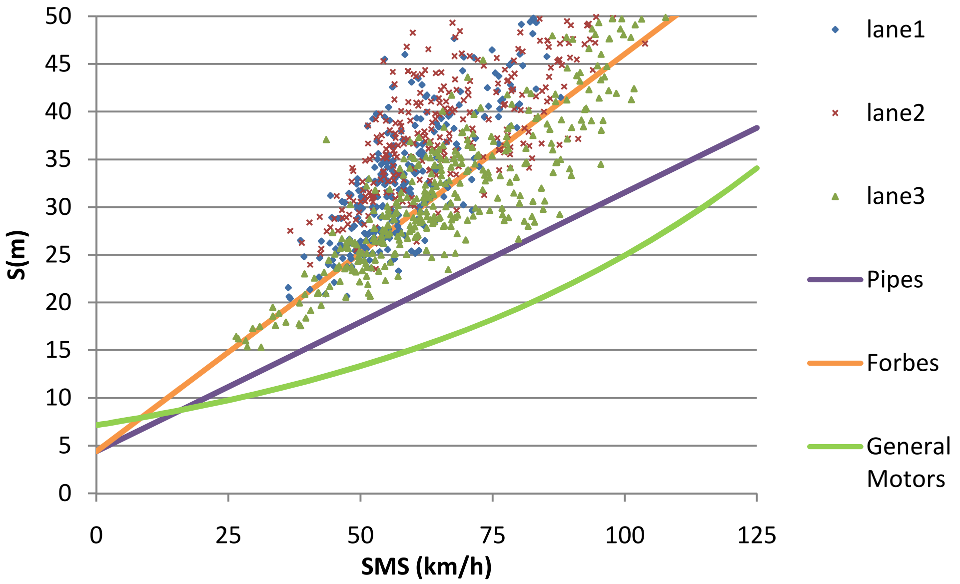

FIGURE 33 Space headway (S) versus space-mean-speed (V) per lane

Note that as the space-mean-speeds increase the distances headways also grow up. So Pipes car-following theory which associate a minimum safe distance headway proportional to the vehicles velocity is reasonable useful.

Pipes characterized the motion of vehicles in the traffic stream suggesting the following rule: "For following another vehicle at a safe distance is to allow yourself at least the length of a car between your vehicle and the vehicle ahead for every ten miles per hour (16,093 km/h) of speed at which you are travelling". The resulting equation for distance headway as a function of speed is:

$$d_{MIN} = [x_n(t) - x_{n+1}(t)]_{MIN} = L_n \cdot \left[\frac{\dot{x}_{n+1}(t)}{16{,}093}\right] + L_n$$

And is represented in the figure 33 with a purple line. The value of L_n chosen is 4,376 meters and corresponds to the average from data registered. Finally, is confirmed that all data points verify this safety condition.

The minimum headways according to Pipes' theory are slightly less than corresponding measurements up to 90 km/h speed range but are considerably less at higher speeds. Data points closer to the Pipes limit correspond to the third lane registration, which means that the vehicles which travel in less safety conditions (let lowest space headway) are those ones which drives through the fastest lane of the motorway.

Furthermore, Forbes (1958) which lineal model is also represented in figure 33 approached car-following behaviour by considering the reaction time required for the following vehicle to notice the need to decelerate and break down. Forbes approximated that the minimum distance headway was proportional to this reaction time (Forbes estimated to 1,50 seconds) and to the speed, so the minimum distance headways can be approximated as:

$$d_{MIN} = \Delta t \cdot [\dot{x}_{n+1}(t)] + L_n = 1{,}5 \cdot [\dot{x}_{n+1}(t)] + 4{,}376$$

Also, another car-following model is considered. Developed by researchers associated with the General Motors group the theories were much more extensive and are of particular importance because of the accompanying comprehensive field experiments and the discovery of the mathematical bridge between microscopic and macroscopic theories of traffic stream. The research team developed five generations of car-following models, which took the form: response=function(sensitivity, stimuli), where the response was represented by the acceleration of the following vehicle and the stimuli as the relative velocity of both vehicles.

The third model considered that the response was proportional to the speeds difference and function of a constant sensitivity parameter, α_0, which dimension is velocity. Finally, it also measured that this response acceleration decreased as the distance headway between the vehicles rose. The final equation of the third model was:

$$\ddot{x}_{n+1}(t+\Delta t) = \frac{\alpha_0}{[x_n(t) - x_{n+1}(t)]} \cdot [\dot{x}_n(t) - \dot{x}_{n+1}(t)]$$

Integrating this expression with respect to t, it was obtained:

$$\dot{x}_{n+1}(t+\Delta t) = \alpha_0 \cdot \left[\ln\left(x_n(t) - x_{n+1}(t)\right)\right] + C_1$$

If a new constant C_2 is defined as:

$$C_1 \stackrel{\text{def}}{=} \alpha_0 \cdot [\ln(C_2)]$$

The third General Motors microscopic model is equivalent to Greenberg macroscopic one which relates the speed (space-mean speed μ) as a function of density (k):

$$\mu = \mu_0 \cdot \ln\left({}^{k}/_{k_j}\right)$$

So α_0 and μ_0 are the optimum speeds corresponding when motorway reaches capacity stream and C_2 and k_j are the maximum densities.

Then, it is possible to get the space headway from speeds:

$$s = \left(x_n(t) - x_{n+1}(t)\right) = \exp\left(\frac{(\dot{x}_{n+1}(t+\Delta t) - C_1)}{\alpha_0}\right) = \frac{\exp\left({}^{\dot{x}_{n+1}(t+\Delta t)}/_{\alpha_0}\right)}{\exp\left({}^{C_1}/_{\alpha_0}\right)}$$

And if we note:

$$a \stackrel{\text{def}}{=} \left[\exp\left({}^{C_1}/_{\alpha_0}\right)\right]^{-1} \text{ and } b \stackrel{\text{def}}{=} {}^{1}/_{\alpha_0}$$

We get an exponential expression to get the space headway from the space mean speed as:

$$s = a \cdot \exp\left(b \cdot \dot{x}_{n+1}(t + \Delta t)\right)$$

In figure 33, there is represented the General Motors function taking typical values for the variables C_2 and α_0 (140 vehicles/km and 80 km/hour). Although is possible, considering the cloud of points of three lanes, to adjust the General Motors exponential model for each one of the three motorway lanes, so both unknown variables are determined.

Data points considered to fit this model perform space headways lower than 50 meters, to consider just closed headways when vehicles interact each other.

In the following figure three cases are adjusted to these General Motors exponential function:

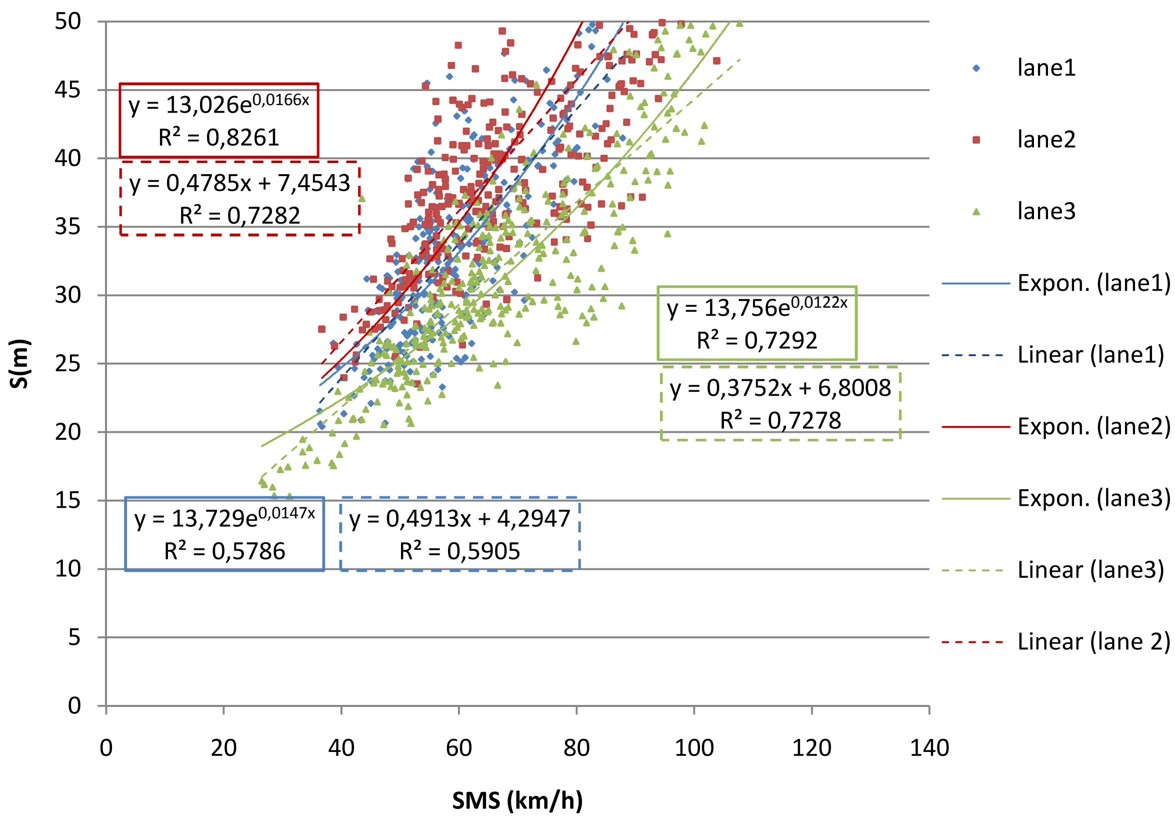

FIGURE 34 General Motors adjust for the space headway versus space-mean-speed per lane of P.K. 128.3 data

The following table resume all the cases and the values of the variables are extracted from the functions adjusted:

MODELS:		General Motors (3rd Generation) $s = a \cdot \exp(b \cdot \dot{x}_{n+1}(t + \Delta t))$				
Variables:		a	b	Optimum Speed α_0 (km/h)	C1	Maximum Density C2 (veh/km/lane)
s<50m	lane 1	13,729	0,0147	68,0272	291,717	72,838
	lane 2	13,026	0,0166	60,2410	261,495	76,770
	lane 3	13,756	0,0122	81,9672	351,334	72,696

TABLE 8 Parameter's values from adjusted G.M. exponential function per each lane of P.K. 128.3 section

The results from the exponential regression are that the optimum speed for the first lane is less than 70 km/hour which is strangely higher than the second lane value. On that lane, the optimum speed is estimated just around 60 km/h, which is too much low value. The highest value for the optimum speeds is estimated around 82 km/hour and belongs to lane 3, where vehicles use to circulate faster than others.

Alternatively, while the maximum density of the first and the third lane are really similar (little bit higher than 72 vehicles per kilometre) for the second one is superior (less than 77 vehicles per kilometre).

On the other hand, the time headway (elapsed time between the arrivals of pairs of vehicles) rather than distance headway is more often encountered because of the greater simplicity of measuring. A shaded band is superimposed on figure 34 which represents the results of field studies per each lane which occupancies are higher than 0,20 (the reason is to not consider free flow situation). It is also represented the line corresponding to Pipes' theory.

If the time headway can be a combination of the distance headway and the individual speed measurement: $h_{n+1} = {d_{n+1}}/{\dot{x}_n}$ the minimum safe time headway proposed by Pipes can be determined as:

$$h_{MIN} = \left[{L_n}/{(16{,}093\ \mathrm{km/h})}\right] + \left[{L_n}/{\dot{x}_n}\right] = 0{,}9789 + \left[{4{,}376}/{\dot{x}_n}\right]$$

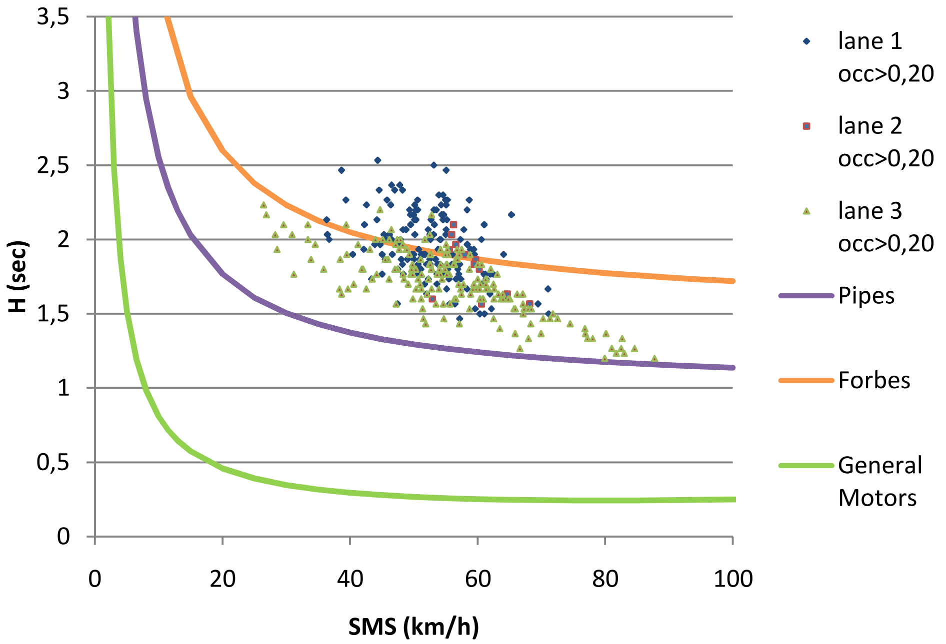

FIGURE 35 Time headway (H) versus space-mean-speed (SMS) per lane of P.K. 128.3 section

Observing figure 35 is noted that as speed increase the minimum safe time headway decreases and theoretically reaches an absolute minimum time headway of 0,98 seconds at a speed of infinity (which corresponds to a reaction time). Since stream rate is the reciprocal of the time headway, the possible stream rate increases with increased speeds. This is true at lower speeds where almost all vehicles are in a car-following mode and are maintaining headways near the minimum headway. However, above some mid range speed all vehicles are not travelling at the same speed, not all vehicles are travelling at minimum headways. Therefore, while theoretically the possible stream rate continues to increase with higher speeds, the traffic capacity is reached in the real world at midrange speeds on the order of 55 to 65 kilometres per hour.

Although the cloud of points is composed of heterogeneous drivers who choose to follow vehicles at different headways for the same speed, there exist some drivers, who tend to have aggressive personalities and select small headways (close to the line that Pipes considers the limit for a safety driving). Those cases, as in figure 34, happen in the third lane, where the cars use to move faster.

Alternatively, Forbes (1958) approached car-following conduct by considering the reaction time necessary for the following vehicle to perceive the need to decelerate and break down. So the time gap between the rear of the lead vehicle and the front of the following one should always be greater than this reaction time. Therefore, the minimum time headway is equal to the reaction time (assuming 1,5 seconds) and the time required for the lead vehicle to traverse a distance equivalent to its length (the average data length is taken), as the following equation:

$$h_{MIN} = \Delta t + \left[{}^{L_n}/_{\dot{x}_n} \right] = 1{,}5 + \left[{}^{4{,}376}/_{\dot{x}_n} \right]$$

Then so, the linked minimum distance headways can be determined as:

$$d_{MIN} = \Delta t \cdot [\dot{x}_{n+1}(t)] + L_n = 1{,}5 \cdot [\dot{x}_{n+1}(t)] + 4{,}376$$

The results of Forbes' car-following theory, represented in figures 33 and 35, is very similar to Pipes' results with minimum safe distance headway increasing linearly with speed while the minimum safe time headway continuously decreases with speed.

In the mid speed range, some of the field study results do not follow the minimum time and distance headways considered by Forbes. So it is able to affirm that some drivers do not drive in such a safety situation.

In figure 34, data of the three lanes is also adjusted to a linear function as Forbes one so the reaction time and the vehicle length free variables can be estimated. Both are resumed in the following table:

	MODEL:	Forbes $h_{MIN} = \Delta t + \left[L_n / \dot{x}_n \right]$	
	Variables:	Δt (sec)	L_n (meters)
s<50m	lane 1	0,4913	4,295
	lane 2	0,4785	7,454
	lane 3	0,3752	6,801

TABLE 9 Parameter's values of adjusted Forbes regression per each lane of P.K. 128.3 section

It is noticeable that the reaction times of all the three lanes of the motorway are lower than the values estimated for Pipes and Forbes. The values from the linear regression estimate a reaction time lower than a half second which is considerable lower than the 1,5 seconds from the General Motors test track and the 1,2 seconds obtained in the field experiments in the Lincoln tunnel (Forbes et al. 1958). Moreover it is patent that on third lane, vehicles circulate in less safety conditions due to lowest reaction time.

Moreover the vehicle length is also estimated with the regression. The value best adjusted is for lane 1, where the 4,295 meters are close to the average vehicle length of data (4,376 meters). But, for lanes 2 and 3 these values are considerably higher (7,454 and 6,801) than the average value, so the Forbes regression is not much adequated on these cases.

Analysis Vehicle Per Vehicle. Additionally, it is interesting to analyse the behaviour in this micro level if we study the traffic stream labelling the light and the heavy vehicles. So it is able to examine the space and time headways in the four possible combinations between the two types of vehicles. The consideration taken is that light vehicles are less than 5 meters length and heavy ones more than 5 meters.

This way so, there is represented the space and the time headway versus the space-mean-speed labelling the possible combinations. The four situations are: light vehicle after another light one (l-l), light vehicle following a heavy one (h-l), heavy beside light (l-h) and finally two heavies situation (h-h).

Data registered of the following figures belongs to the first lane, which is better because of its more circulation of trucks and therefore more cases in each situation.

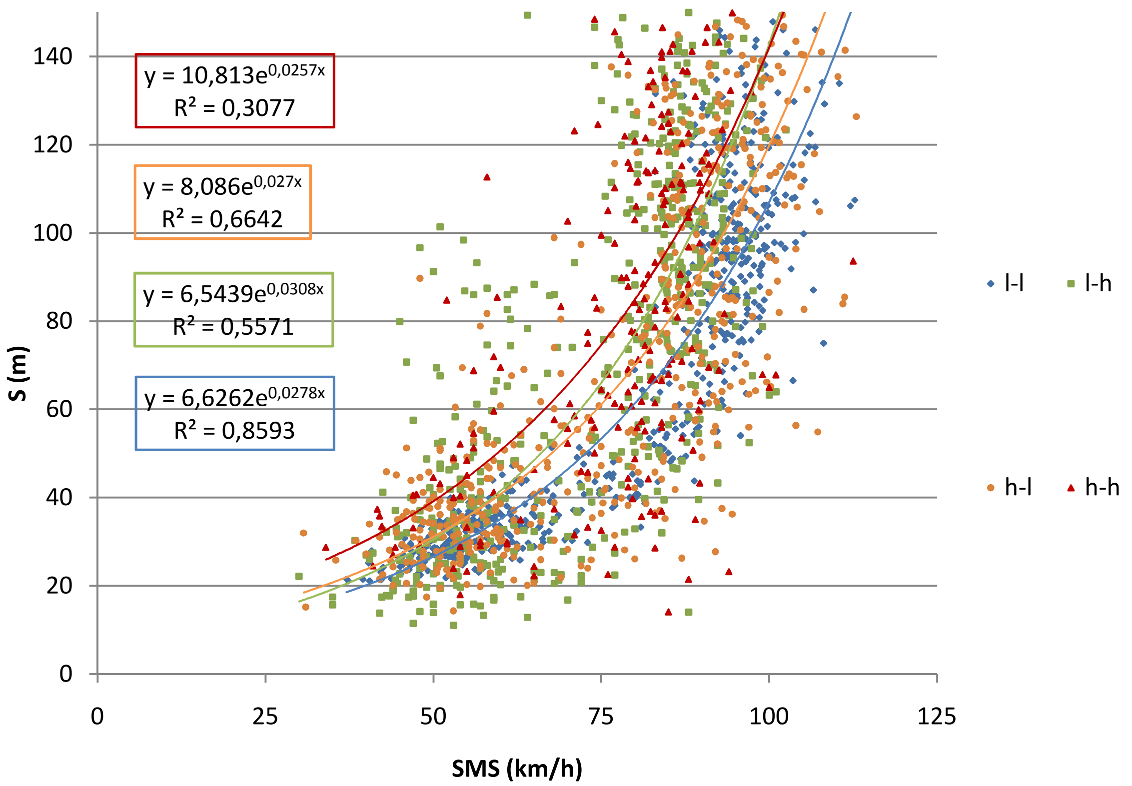

FIGURE 36 Space headway versus space-mean-speed in lane 1 of P.K. 128.3 section data for N=30 vehicles analysis

In figure 36, there are represented four clouds of points representing the different circumstances. Moreover there is a trend line for each one fitted in an exponential regression. This analysis is centred in close space intervals (to compare to car-following models), that's why the figure is a zoom of data registration with less than 150 meters of space headways.

First of all, it is observable that the behaviour when two light cars circulate together is quite a lot predictable because its R-square coefficient is the greatest one (R^2_{l-l}=0,8593) and close to 1,0 (is manifested that data band is quite narrow). In contrast to when two heavy vehicles circulates together are uncorrelated (R^2_{h-h}==0,3077), which means that they drive independently each other. The other two combinations that involve both type of vehicles (h-l and l-h) fit the exponential quite well although have lower values than light-light combination. Furthermore, average space-headways for l-l combination are the lowest ones per any space-mean speed and for h-h the highest ones.

Moreover, it is discernible that at low speeds l-l, h-l and l-h adjusted functions have similar values. In other words, when vehicles circulate at low speeds (less than 50 km/h) due to congestion, drivers let similar space headways. For example when circulating at 40 km/h, the average space-headway on l-l, h-l or l-h cases is from 20 to 24 meters, while when h-h combination the exponential approach it to 30,23 meters. Therefore, when two heavy vehicles circulate together in a congested state, they let bigger space headways due to their independent behaviour. Next table resumes figure 36, showing space-headway values for different speeds per each vehicles type combination:

AVERAGE SPACE-HEADWAY (m)		General Motors (3rd Generation) $s = a \cdot \exp\left(b \cdot \dot{x}_{n+1}(t + \Delta t)\right)$	
Space-Mean Speed (km/h)		40 km/h	100 km/h
Combination	Light-light	20,147	106,808
	Light-heavy	22,433	142,385
	Heavy-light	23,811	120,318
	Heavy-heavy	30,227	141,281

TABLE 10 Average space-headway values from adjusted G.M. exponential function per vehicles types combination on Section P.K. 128.3

Otherwise, for higher speed range, differences between space-headways for different cases increase. It's noticeable in table 10, when vehicles circulate at 100 km/h, let higher space-headways. As happens for lowest speeds, two light cars let the minimum space-headway of all four combinations. Highest average space-headways (around 142 meters) are when l-h and when h-h mixtures. It means that the successor vehicle use to condition the space-headway let. Then, for example all light vehicles (circulating in a speed v), use to circulate at a similar distance to its predecessor indistinctly which type it is. And also at high speeds, drivers of heavy vehicles let big space-headways independently of the vehicle followed.

In addition, it's observable in figure 36 that adjusted G.M. exponential functions of l-l and h-l have similarities. Both regressions have same shape, just these are separated a small distance. This difference is due to when light vehicle follow a heavy one let more space than if it was another light.

Furthermore, in figure 37 are represented the time headway averages versus its space-mean-speeds.

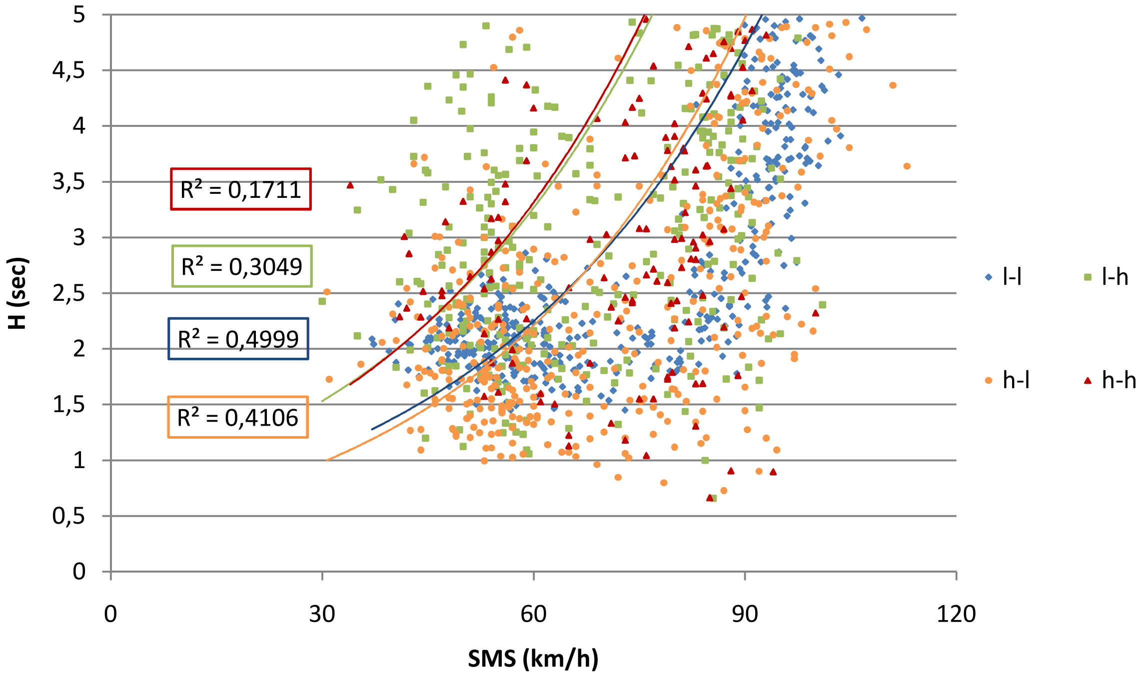

FIGURE 37 Time headway versus space-mean-speed in lane 1 of P.K.128.3 section data for N=30 vehicles analysis

In figure 37, it is noticeable that the trend lines of the combinations light-light and heavy-light have similar properties. Both have less scatter (its R^2 coefficient is higher) than heavy-heavy and light-heavy and also both let less time headways for the same space-mean-speeds. It means that when the following vehicle is light, whatever is the lead one, the time headway between them are smaller than if the following vehicle is heavy. It happens because light traffic travel faster than heavy so for the same space headway, the time to move that distance is lower.

In figure 37, as in figure 36, it is observable that two heavy vehicles do not follow the General Motor pattern as much as the other cases, because of its low R^2 value. It is possible because, heavy trucks as move slower do not interact as much as light vehicles so they circulate independently of other vehicles (they let higher time and space headways).

Table 10 resumes values from figures 36 and 37. The R^2 coefficient illustrates the good or the poor fitness of the exponential regression and a, b, $\hat{a}$ and $\hat{b}$ represent coefficients of adjusting an exponential as follow: $S = a \cdot \exp\left(b \cdot \dot{x}_{n+1}(t + \Delta t)\right)$ and $H = \hat{a} \cdot \exp\left(\hat{b} \cdot \dot{x}_{n+1}(t + \Delta t)\right)$.

.

		GENERAL MOTORS EXPONENTIAL REGRESSION					
Figure:		S-SMS $S = a \cdot \exp\left(b \cdot \dot{x}_{n+1}(t+\Delta t)\right)$			H-SMS $H = \hat{a} \cdot \exp\left(\hat{b} \cdot \dot{x}_{n+1}(t+\Delta t)\right)$		
Variables:		R^2	a	b	R^2	$\hat{a}$	$\hat{b}$
Combination	Light-light	0,8593	6,6262	0,0278	0,4999	0,5114	0,0247
	Light-heavy	0,5571	6,5439	0,0308	0,3049	0,7164	0,0253
	Heavy-light	0,6642	8,086	0,027	0,4363	0,4363	0,027
	Heavy-heavy	0,3077	10,813	0,0257	0,1711	0,6913	0,0261

TABLE 11 Parameter's values from adjusted G.M. exponential function per each lane of P.K. 128.3 section

The good fit of exponential functions of both microscopic variables for l-l combination, more than any other possible combination, is reliable in table 11. Moreover the poor R^2 value of h-h situation is also observable for both regressions. A part, the shape of time headway exponential functions has some particularities. All functions have similar values of $\hat{b}$ from 0,0247 to 0,027, but $\hat{a}$ is different depending of the combination. Values of $\hat{a}$ for l-l and h-l are similar, such as it is mentioned before, time headways of this combinations are closer and lower than other two combinations (l-h and h-h) which are also related having similar $\hat{a}$ value.

3.2) Macro Level Analysis

Whereas the previous sections treated the macroscopic traffic stream characteristics on an individual basis, this section considers some of the relations between them. There are considered the totality of data series measured in all the freeway long, selecting the stationary periods from each 24 hours detectors data.

The equilibrium relation between stream and density is called the fundamental diagram. Due to this equilibrium property, the traffic states can be thought of as moving over the fundamental diagrams curves.

The fundamental diagram of the main section studied (P.K. 128.3) in the present work is represented in the next figure:

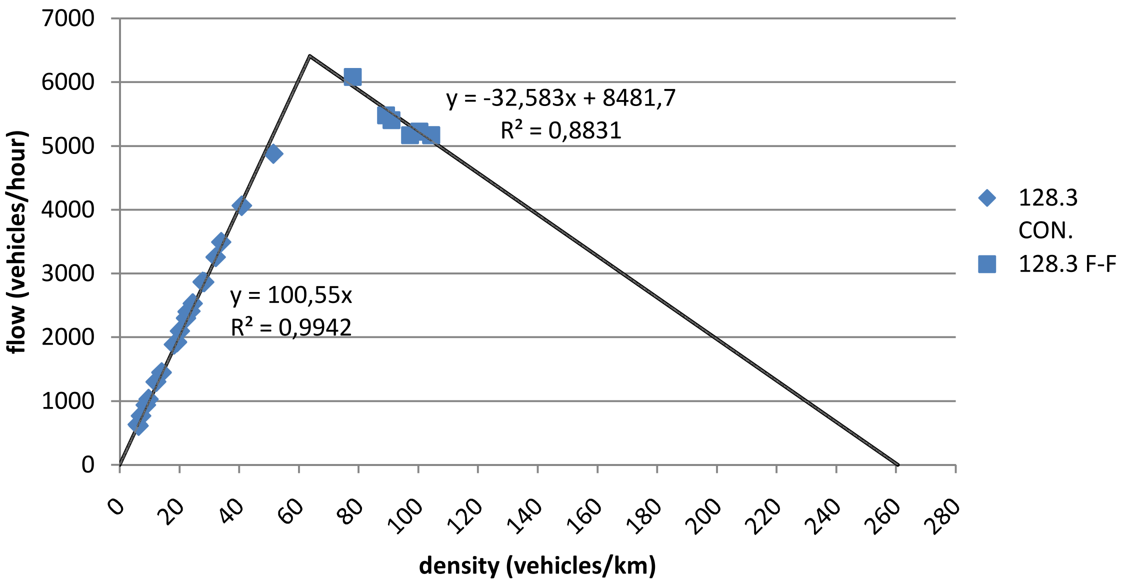

FIGURE 38 Fundamental diagram of P.K. 128.3 section stationary data with N=30 aggregation

Its analysis has been done from Eddies definitions and aggregation already commented fixing groups of 30 vehicles for calculate the different traffic variables.

By constructing re-scaled curves of cumulative vehicle arrival number versus time and cumulative occupancy versus time, sustained periods of nearly stationary traffic conditions separated by non-stationary transitions are observed (Cassidy 1998). These periods are characterized to have average speeds nearly constant. By extracting and plotting the average values of data corresponding to each nearly stationary period, a well defined bivariate relation was observed at each of several freeway measurement locations.

Observing figure 38 it is discernible the good fit of the stationary data points in the two branches of traffic states. Adjusting both states to linear regressions, the coefficient R^2 which is a dispersion measure, is close to 1 due to the good fit of the stationary data points.

The free flow branch, which crosses the origin point where both variables are equal to zero (when there is no stream of vehicles crossing a section, the density is also null), has a slope of 100,55 km/h corresponding to the presumed freely flowing speed. If slope is constant also implies that changing (q, k) states move forward with the vehicles in freely flowing traffic.

In this traffic state, the stream steadily rises with increasing density until the optimum density when the maximum stream appears. A 6.407 vehicles/hour value is obtained calculating where both linear regressions cross. For the P.K. 128.3 section the optimum density associated is 64 vehicles/km.

From then on, stream starts decreasing with higher densities with a lower slope. This negative value of -32,583 km/h is the speed of an interface between stationary traffic states so is ${}^{\Delta q}/_{\Delta k}$. That the relations right branch is linear means that interfaces between queued states presumably propagate at a single speed. This is the second branch corresponding to the congested state where vehicles interact between them, and the top densities are reached (the jam density is the highest one, when vehicles stop so the stream is null). The jam density value can be obtained where the second straight line crosses the density axis so stream is null because vehicles are stopped. On the present P.K. 128.3 section this value is 261 vehicles/km.

Next sections studied of the freeway are situated up-stream in the P.K. 125.4, 119.5, 113.9, 106.4, 101.9 and 94.8. So the correspondent fundamental diagrams of them are represented in figure 37 (see in appendix A fundamental diagrams of each section):

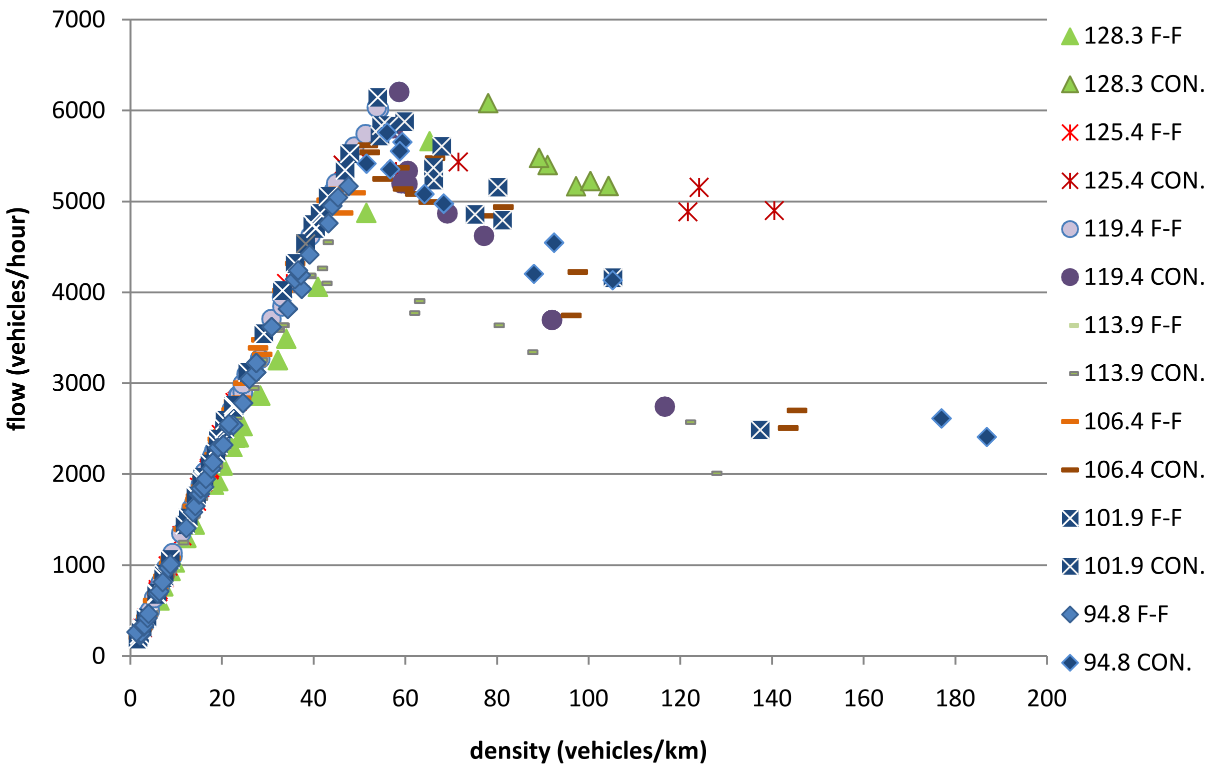

FIGURE 39 Fundamental diagrams of stationary periods and N=30 aggregation analysis from up-stream P.K. 128.3 sections data

Firstly, it can be observed the good fit of all sections fundamental diagrams studied to the triangular form. It can also be detected, for moderately low densities (below the critical density), that the stream increases linearly with the density. This is the free flow branch of the diagrams. And it is really similar in all the motorway sections analysed. Just in P.K. 128.3 section it can be detected a lower free flow speed due to the proximity of the toll. This circumstance also affects the critical density of P.K. 128.3 section, which is bigger than all the other sections analyzed. For higher densities, near the critical one, the fundamental diagram can have slightly of scatter, due to faster vehicles being obstructed by slower vehicles, thereby lowering the free flow speed.

Moreover, in figure 39 it's discernible another differences between fundamental diagrams. P.K. 125.4 section which is composed by four lanes, have different properties such a lower slope on the congested branch. As this section has these particular geometrical characteristics it will be analyzed later. A part, P.K. 113.9 section have a significant lower capacity than other sections. Therefore, it means the presence of a bottleneck closer to this section. The causes of this capacity reduction are because of a bottleneck up-stream P.K. 113.9 section that limits the down-stream flow. It's probable than the entrance number 11 from St. Celoni and Montseny in P.K. 111.6 provoke an increase of the stream until the congestion. Moreover, this AP-7 stretch is characterized for having important ramps. From P.K. 112.0 to P.K. 115.5 the design of the turnpike is composed by ramps up to 3,2%.

As in P.K. 128.3, the triangular model is adjusted for the stationary data points of each section so the main characteristics of each section can be obtained. Those are resumed in the following table:

P.K. Section:		***128.3***	***125.4***	***119.2***	***113.9***	***106.4***	***101.9***	***94.8***
Free flow speed	**S_F** (km/h)	100,55	117,3	115,49	114,07	112,77	118,22	113,23
Propagation speed	**U** (km/h)	32,54	21,94	28,96	23,21	33,06	38,98	23,75
Optimum density	**K_{CAP}** (veh/km)	64	66	53	38	50	51	49
Capacity	**Q_{CAP}** (veh/h)	6.407	5.485	6.104	4.362	5.689	6.029	5.578
Density jam	**K_J** (veh/km)	261	418	264	226	223	206	284

TABLE 12 Main characteristics values from triangular model of sections P.K. 128.3, 125.4, 119.2, 113.9, 106,4, 101.9 and 94.8

The free flow speed (S_F) corresponding to the slope of these traffic state data points of the different sections are quite similar. Except in P.K. 128.3 section where the free flow speed value is close to 100 km/h and lower than predecessors sections, all values are greater than 110 km/hour and lower than 120 km/hour, which means that in this interval there are the average speeds when there are no interactions and drivers can circulate at the desired speeds. The reason because of this low free-flow value in P.K. 128.3 is the proximity of the toll downstream the section. Moreover, it's probable that if there no exists any speed limitation these values will be greater than the limitation value of 120 km/h.

Propagation speeds (U) on the congested branches have more variation between sections, although do not overcome 40 km/h. Propagation speeds vary from 20 to 40 km/h. This value indicates when congestion set, the decrease of the flow when density grows until the maximum values.

The third variable from the linear model is the optimum density (K_{CAP}). It is the number of vehicles per kilometre when stream reach the maximum and it varies from 38 to 66 vehicles/km, although almost data sections have values around 50 vehicles/km. As it has been mentioned before, the lowest optimum density value of P.K. 113.9 section appears because of the bottleneck presence. The highest optimum density value of 66 vehicles/km corresponds to P.K. 125.4 section due to, as it has been mentioned, is composed by four lanes.

Associated with the mentioned density, the capacity (Q_{CAP}) of the motorway is reached. Top streams of all sections are around 6.000 vehicles/hour. Considering that each section have 3 lanes, a rate of 2.000 vehicles/hour/lane can be reached or overcome. On one hand, the commented bottleneck is reflected with an important decrease of capacity in P.K. 113.9 section until 4.362 vehicles/hour, while on another hand the four lanes P.K. 125.4 section has a capacity of just 5.485 vehicles/hour. The reason of such a lower capacity will be developed later on.

Finally, the density jam (K_J) is available. The maximum density when vehicles stop because of congestion and the stream is zero. This density reached varies from 200 to 300 vehicles/km in all sections except in P.K. 125.4 one which is greater (418 vehicles/km) because of more number of lanes.

The section 125.4 is different than the others because there are not 3 lanes but 4, so the fundamental diagram should be more different than the others. In the next figure there is represented it:

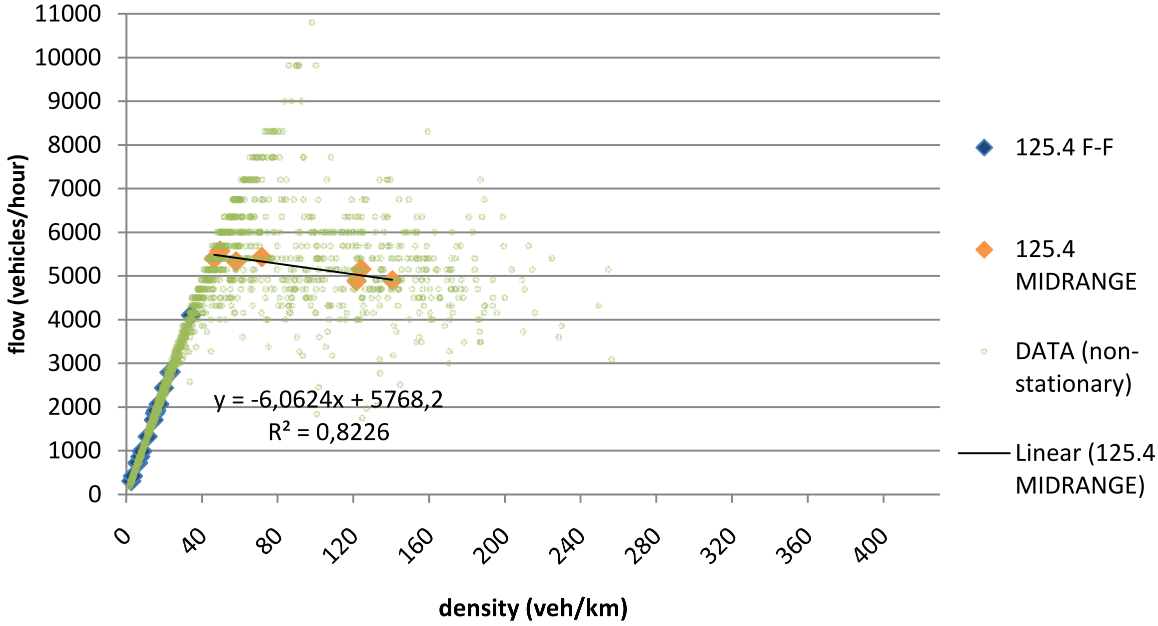

FIGURE 40 Fundamental diagram of section P.K. 125.4 and non-stationary data with N=30 vehicles aggregation period analysis

Observing figures 39 and 40, the free flow branch of P.K. 125.4 is really similar than all the other sections. But the congested branch has bigger differences respect the other studied sections.

First of all, considering the triangular model the capacity stream of P.K. 125.4 reached is lower than 5.500 vehicles. This value is one of the lowest respect all the other sections when it should be the greatest one due to the mentioned section is composed by four lanes.

On second place, the regression slope of the seven stationary points of the mid range densities is just -6,0624 km/hour. The absolute value of this slope is really small compared to the other propagation speeds (U) which are around 30 km/hour.

To understand the probable reason for that behaviour, in figure 40 are also painted in green all data points of the section P.K. 125.4 with N=30 vehicles aggregation and without considering stationary conditions. So it is observable all the cases occurred in the section during the 24 hour data registration.

Then so, it is recognizable an important cloud of points bigger than the triangular model of the fundamental diagram. They are identifiable data points with streams bigger than 8.000 vehicles/hour. These values are not reached in other sections because of the mentioned different number of lanes.

Therefore, the problems of the lineal fit of the stationary points can be attributed to the poor percentage of cases with high streams range that this section can achieve. The reason of that absence can be the presence of a bottleneck up-stream.

In the next figure the problematic and the prior section (125.4 and 119.2) P.K. are also represented:

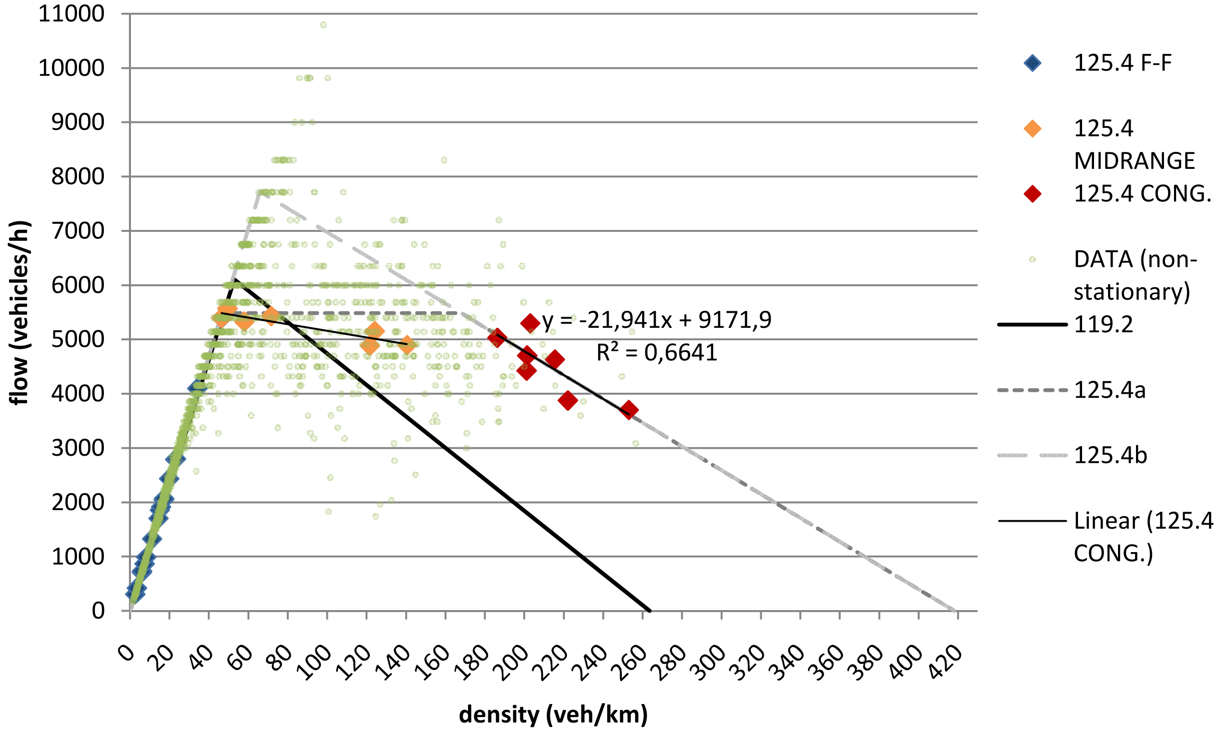

FIGURE 41 Sections 125.4 and 119.2 fundamental diagram and non-stationary data with N=30 vehicles aggregation period analysis

Observing figure 41, it is evident that the triangular model for section P.K. 119.2 (black line) is smaller than the following section downstream. So the limited characteristics of the first section affect the next one.

The model for section P.K. 125.4 is also painted in figure 41 (125.4b) if there were not any limitations up-stream. The capacity reached will be bigger than the other sections one and around 7.727 vehicles/hour. The 21,941 km/h propagation speed is found analyzing the N=30 vehicles aggregated periods with more than 180 vehicles/km. Afterwards, with these data some stationary points have been found (red squares), although with small duration (T_{agg} is just some minutes). Finding when free flow line and congested line cross, the capacity is reached with an optimum density of 66 vehicles/km which value is also bigger than other sections because of one more lane (so can effort more number of vehicles for the same length).

But, as the restriction exists and the stream that arrive to the 4 lanes section is lower (less than 6.000 vehicles/hour), the fundamental diagram of it changes to a truncated triangle as 125.4a. That is why the regression of the stationeries state points has a lower slope as the lane part of density midranges of the model 125.4a.

VI. CONCLUSIONS AND FURTHER RESEARCH

The main conclusion of the present dissertation is that a correct definition and calculation of all traffic variables is fundamental for their consistency and for the fulfilment of the relations among them. The data measurement strategies must follow from the definitions assigned to the variables and not vice versa. For this reason, a data base composed by an information vehicle per vehicle where the registration is recorded without aggregation, guarantee the freedom for the correct analysis calculations.

Therefore, defining the traffic variables in consistent ways with Edie's descriptions preserved relations among on one hand average stream, density and space-mean speed ($q=k \cdot SMS$) and on the other among occupancy, density and the effective length ($occ=k \cdot g$).

Errors and scatters of the Fundamental Traffic Relation that commonly appear in some bibliography are due to the substitution of the space-mean speed for the time-mean speed which is easier to calculate. Although the main cause of scatter of mentioned relations is the time aggregation selected for averaging values variables. As the time selected of aggregation is smaller, the scatter and the error of the relation increase. As Edie defined, the relation among the variables is true if data over some specified number of vehicles is measured instead of over some fixed aggregated time.

Additionally, analysing the vehicle per vehicle data in a microscopic way, allows concluding that the different frequency distributions follow a pattern. As in macroscopic evaluation, a correct analysis of the data is essential for correct results. Then so, stationary states are necessary to be found without any kind of interferences.

Therefore, the shape of the time headway distribution varies considerably as the traffic flow rate increase. Under very low stream conditions where there is very little interaction between vehicles and the arrivals appear to be somewhat random, the frequency distribution can be represented with a negative exponential distribution. Otherwise, if the selected stage is a stationary period where traffic congestion appears, the normal distribution is the mathematical distribution that best fits.

Analysing distance headway distributions, the conclusion is that when low stream conditions, the average space headway and the standard deviation of its frequency distribution are substantial bigger than when higher streams close to congested states. These happens due to when light conditions, the space headway between consecutive vehicles is so big and also random, while on congested states in rush hour all vehicles circulate closer each other or in other words, space headways decrease.

Concerning about vehicular speed frequency distribution, the importance of the measure is determinant for correctly results. Then so, in a traffic stationary state where a constant percentage of heavy transit circulates, accurately measured, the speeds frequency distribution follows a normal distribution. Incorporating any data measured in different traffic states skew frequencies' distribution. For instance, if the selected period is a free flow state but also a small congestion period began, the deviation grows up and the skew goes down. The normal distribution is also skewed, although in this case going up, and the deviation also increases if the selected stationary period belongs to a congestion dissolve. In other words, when the studied period is from data of congested state but also the beginning of some free-flow movements. Another phenomenon that modifies the normal distribution of a stationary state frequency distribution is speed limitation of the motorway. This circumstance causes a peak around interval of little bit higher speeds and the limitation one. Additionally, the normal distribution characteristics depend of if the selected stationary period of time belongs to a free flow or to a congestion episode. Congestion speed frequency distributions have significant lower average and deviations than free flow ones. Logically, when congested phase, vehicles are not able to freely travel at their desired speed while when unconstrained phases, drivers strive to attain their own comfortable travelling speeds. Moreover, as much the definition of the congested state is restricted the speed frequency normal distribution gets narrow, due to the variability decreases as the selected group gets smaller. Furthermore, another common fact that can distort the normal frequency distribution is the presence of two classes of vehicles: heavy and light transit travelling at the same time. When it happens, the resulting distribution can be bimodal due to there are two normal distributions or to a lesser extent cause some skewness to the global distribution. Finally, because of the comparison between the space-mean-speed and the time-mean-speed done in the dissertation data analysis, it can be affirmed that relation between both speeds done by Wardrop in 1952 has just a relative error lower than 0,40%.

Additionally, the microscopic variables analysis of the present dissertation, related with the car-following models let to conclude some variables relations. Analysing data in micro level per each lane of AP-7 turnpike, the space headway is proportional to the space-mean speed, and the minimum safety space headways that Pipes proposed are complied for all lanes. A part, Forbes car-following model is not complied for some data points. Almost registers that let less distance than the minimum safety one fixed by Forbes correspond to the third lane. This fastest lane is where vehicles travel in less safety conditions due to move faster letting lowest space headways than other lanes. Finally, the exponential car-following model proposed by General Motors researchers is, as Pipes model, yield by all three lanes analyzed points from data base.

Furthermore, micro analysis is also possible separating the different type of vehicles. In other words, labelling light and heavy vehicles and studying the space headways between the four possible combinations. Then so, two light cars circulating together have quite a lot predictable behaviour, so they travel closer than any other combination of vehicles. On the other extreme, two heavy vehicles moving together are uncorrelated so they drive independently each other and do it on biggest spaces. Finally, at low speeds light-heavy and heavy-light let similar space headways between them, as where two light cars moving. Otherwise, for higher speed ranges, just heavy vehicles followed by light combination still is similar than two lights. On these speed values the light-heavy combination increase their space headway until similar big values as two heavies moving.

As the space headway micro analysis, the time headway analysis also shows the behaviour between different types of vehicles circulating among AP-7 turnpike. As in space headway analysis two light cars circulating has the most predictable behaviour, while two heavy vehicles which circulate together do it without any kind of pattern.

First case of two light cars moving together have similar properties as a heavy car is followed by a light one, so both let less time headways for the same space-mean speed. As light traffic travel faster than heavy, for the same space headway, the time headway is lower because the same distance is done in less time.

Finally, if a correctly selection and analysis of the stationary periods from each 24 hours detectors data is done, an equilibrium relation between flow and density macroscopic variables appears. It is discernible the good fit of the stationary data points in the two branches of traffic states.

The free-flow branches of all stretch section analyzed, cross the origin point where both variables are equal to zero and have a slope from 110 km/h to 120 km/h. These values correspond to the average speeds when there are no interactions between vehicles and drivers can circulate at the desired speeds. Just the free flow speed of P.K. 128.3 section has a lower value around 100 km/h due to the downstream proximity of the toll so vehicles start breaking.

Apart, second branch slope of the fundamental diagram, indicates the propagation speeds so when congestion set, this value is the decrease of the flow when density grows until maximum values. Propagation speeds of section of the studied turnpike vary from 20 to 40 km/h.

Moreover, the density and the stream when capacity reached can be found from section analysis. The number of vehicles per kilometre when stream reach the maximum varies from 38 to 66 vehicles/km, although almost data sections have values around 50 vehicles/km. Just, on one hand the lowest optimum density value of P.K. 113.9 section appears because of a bottleneck presence on this section, and on the other, the highest one corresponds to P.K. 125.4 section which is composed by four lanes. Therefore, for capacities values happen the same. Top streams of all sections are around 6.000 vehicles/hour, although in P.K. 113.9 an important decrease to 4.362 vehicles/hour appears because of mentioned bottleneck.

Finally, the density jam of each section of AP-7 turnpike varies from 206 to 284 vehicles/km. The maximum density when vehicles stop because of congestion has these values except in case of P.K. 125.4 section where 418 vehicles/km are reached. This four lanes section is the only one of the AP-7 turnpike studied stretch with one more lane than others. Therefore, although the fundamental diagram of P.K. 125.4 section should be bigger than other sections one, it doesn’t happen due to P.K. 119.2 upstream section. The limited characteristics of it, affect the next section so the bigger triangular model cannot be achieved. For this reason, in the intermediate density values the triangle has a lane part corresponding to the capacity (just 5.485 vehicles/hour when values around 8.000 vehicles/hour could be reached due to its design), where stream is constant due to limited flow proceeding from predecessor section. Therefore the fundamental diagram of P.K. 125.4 section is a truncated triangle.

The analyses lead to the following recommendations for further research and more issues that should be treated:

- Increasing more data days. The analysis of AP-7 turnpike could be enlarged to the 24 hour vehicle per vehicle registration data from a business day. The inclusion of this day would allow comparing with a different type of drivers (the commuters ones) and also would include bigger percentage of heavy traffic, very interesting for microscopic analysis for different types of vehicles.

- Enlarging more seasons data. Data from a summer day registration would allow recording the biggest congestions possible in the AP-7 stretch due to the bigger stream happening during holidays period. Moreover it would be useful its comparison between other months data to see the evolution.

- Developing the bottlenecks phenomenon appeared in the analysis. Analyzing deeply the AP-7 turnpike stretch geometric characteristics that cause these impeded circumstances.

- Analysing microscopic characteristics of other sections. The microscopic analysis of the different variables differentiating light and heavy traffic and its possible car-following combinations should be realized to the other AP-7 sections, so the comparison with the results of the present dissertation could be made.

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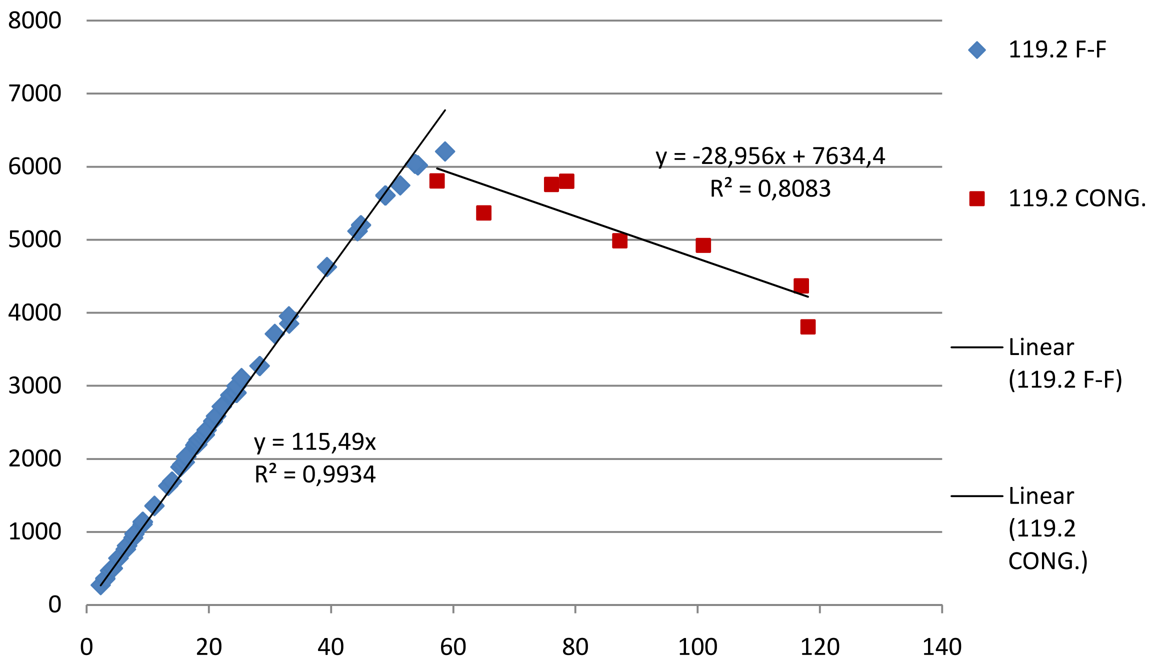
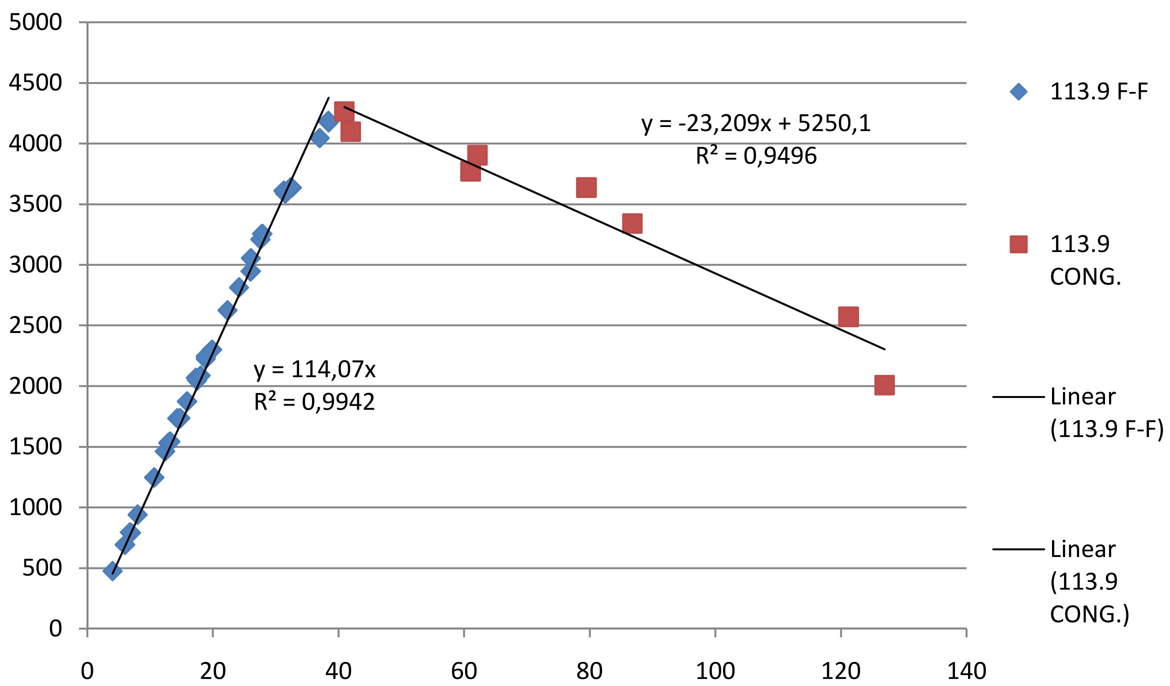
APENDIX: FUNDAMENTAL DIAGRAMS OF AP-7 STRETCH SECTIONS

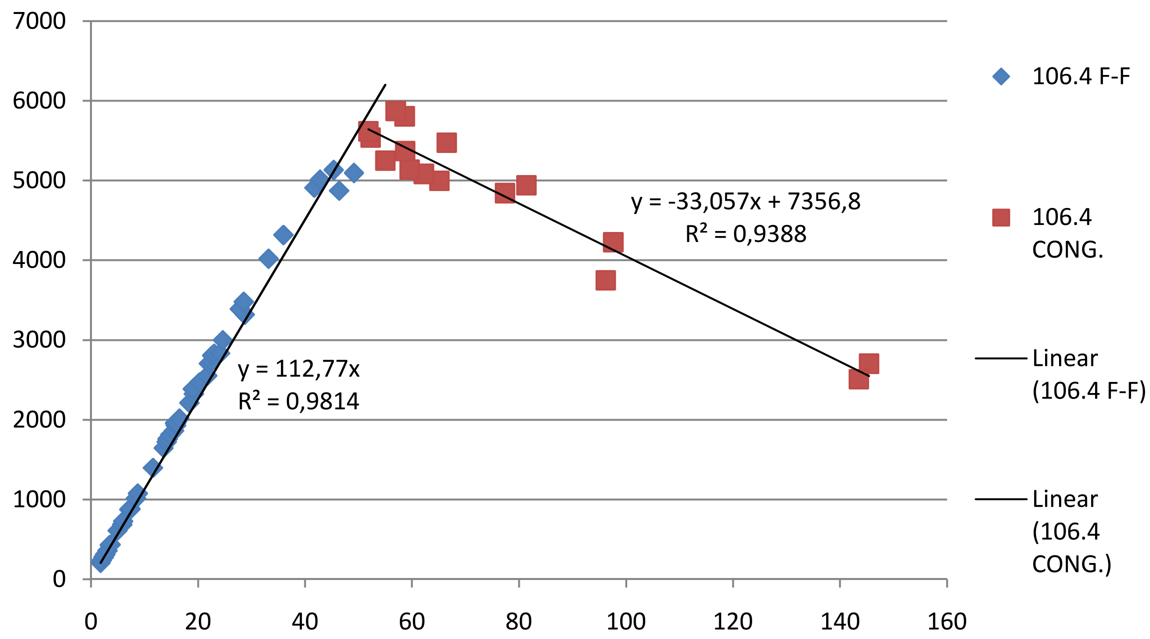
P.K. 119.2



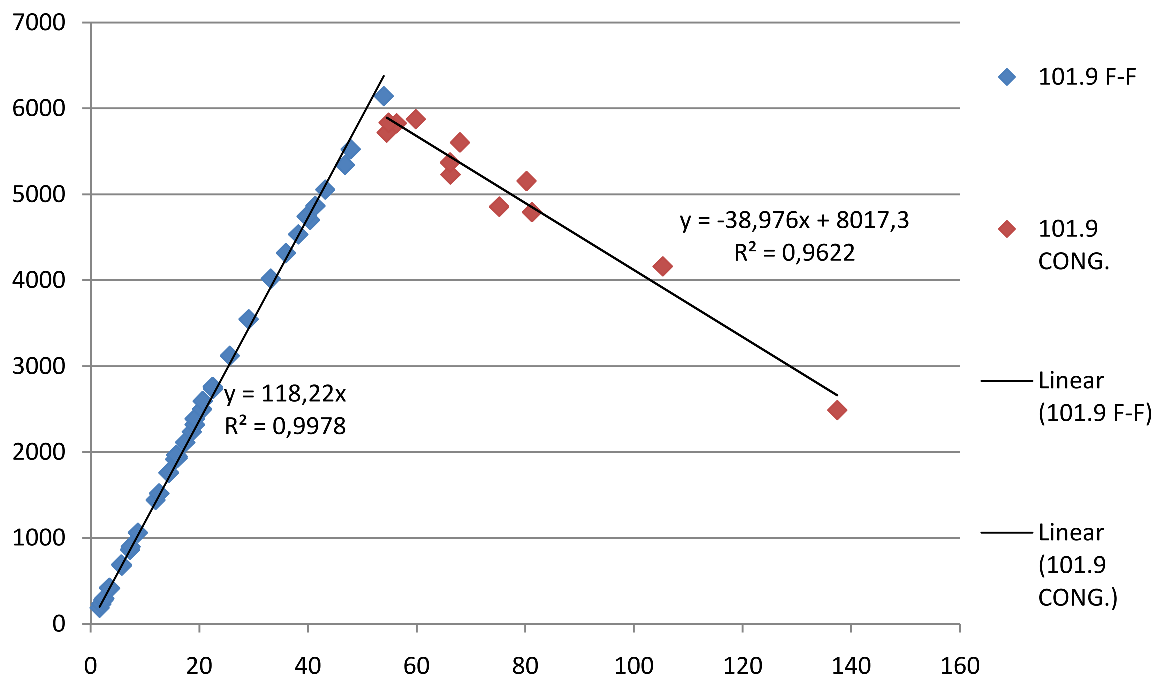
P.K. 113.9



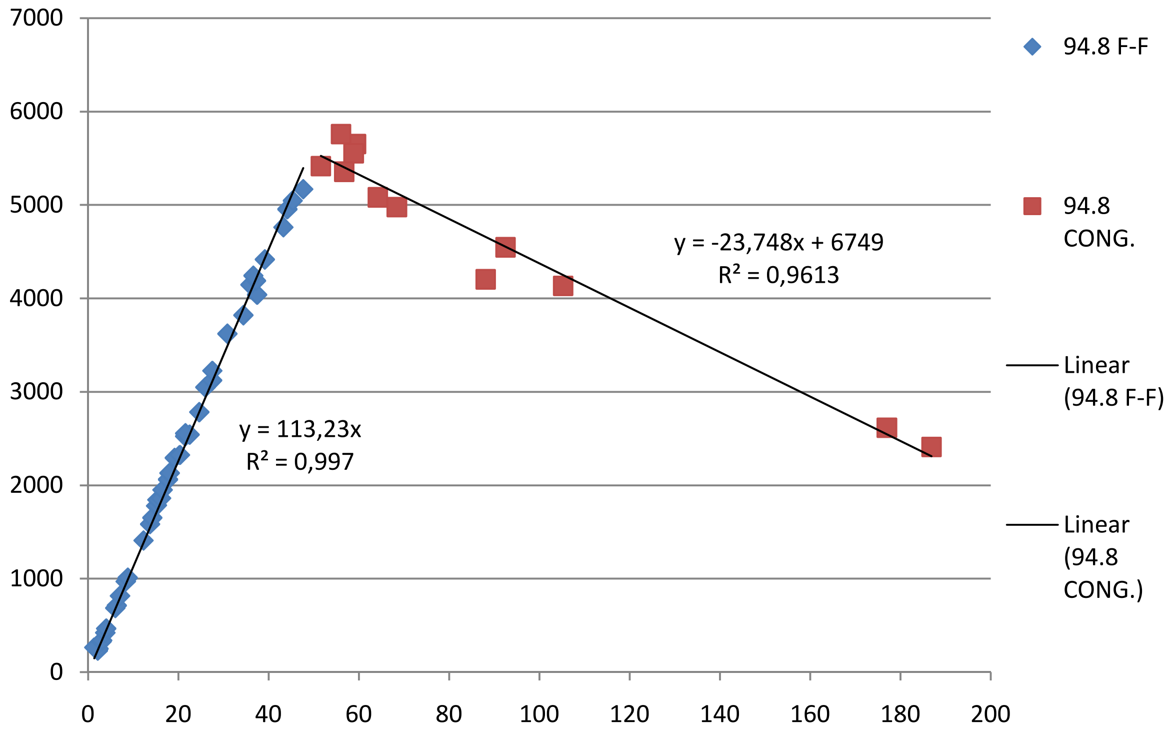
P.K. 106.4



P.K. 101.9



P.K. 94.8


7000
6000
5000
4000
3000
2000
1000
0
0
20
40
60
80
100
120
140
160
180
200
94.8 F-F
94.8 CONG.
Linear (94.8 F-F)
Linear (94.8 CONG.)
y = -23,748x + 6749
R² = 0,9613
y = 113,23x
R² = 0,997