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An empirical analysis of vehicle time headways on rural two-lane two-way roads

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Abstract

Study of vehicle time headway distributions is fundamental in many traffic engineering applications, such as capacity and level of service analysis in several contexts (road segments, priority junctions, roundabouts, merging maneuvers, etc.). In recent years, other fields of interest have also been represented by vehicle generation in traffic micro-simulation models and driving simulation applications. This paper presents results from an experimental analysis on vehicle time headway distributions on two-lane two-way roads. Our attention focused on rural roads in Northern Italy, with data from inductive loops and radar sensors. Statistical analysis of these data allowed us to test a set of headway distribution models, highlighting their goodness-of-fit with reference to empirical distributions. The final aim of the analysis was create a picture of relations between traffic conditions and headway distributions for a typical kind of road.

Keywords: time headway distributions, two-lane two-way roads

1. Introduction

Time headway is the time interval between two vehicles passing a cross-section of a road, measured from front bumper to front bumper. Knowledge of headway distributions plays a significant role in several fields in the context of traffic flow analysis and simulation. In particular, we refer to operative analysis of highways, freeways, signalized and unsignalized intersections, and roundabouts. Several studies appear in literature on this topic (Branston, 1976; Griffiths & Hunt, 1991; Luttinen, 1996; Hoogendoorn & Botma, 1997; Hoogendoorn & Bovy, 1998). In recent years, researchers' attention has also focused on the application of vehicle headway

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distributions in micro-simulation software (Zhang & Owen, 2004), ITS applications (He, Guan, & Ma, 2009; Li, 2009) and driving simulator experiments with regard to vehicles generation (Rossi et al., 2011).

For several years, studies of driver behavior have been carried out at the Transportation Laboratory of the University of Padova by means of both direct observations (traffic surveys and analysis with video recording systems and other vehicle detection equipment) and driving simulator experiments. Methods of analysis and interpretation have been developed, and now allow us to specify, estimate and validate models, both probabilistic and based on fuzzy systems theory, for predicting driver behavior (particularly gap-acceptance behavior) in relation to several traffic and geometric contexts.

Starting from these considerations, a new research project was set up to establish an information system of traffic flow phenomena. The idea was to collect and manage information (traffic data) on traffic operations concerning interrupted and uninterrupted traffic flow conditions for specifying, calibrating and validating mathematical models of observed phenomena.

In this sense, the first research step focused on identifying typical headway probability density functions (pdf's), with reference to two-way two-lane road segments. Lack of information about time headway distribution in Italian contexts (in particular two-way two-lane roads) was one of the reasons for the study.

The data used in statistical analysis of headway came from the traffic monitoring system of the Province of Venice (northern Italy), since such data are data commonly used to characterize the operative conditions of a segment (starting from traffic observations on cross-sections) and could be systematically used to analyse traffic flow characteristics and simulate them.

The paper is organized as follows. Section 2 presents the survey method and traffic data characteristics and analysis; detailed results are reported concerning one of the four analysed road segment cross-sections. The main results are described in Section 3. Concluding remarks and future directions of the research are presented in Section 4.

2. Method

This study was carried out in order to estimate the pdf's of vehicle time headways observed in some cross-sections of rural roads. The traffic data for this study are the sequences of time headways obtained at four Automatic Traffic Recorder (ATR) sites located on rural roads in the Province of Venice. The road network consists of two-lane roads. Each ATR monitors directional traffic volumes on a single lane.

In the following sections, we describe the case-study in detail in order to illustrate the characteristics of the road segments analysed , the data collected, and the methods used to derive information from them (data analysis and results).

The analysis involved three steps:

- direct observation, collection and coding of data at each cross-section, with reference to a certain time interval;
- identification for each section of time sub-intervals having similar flow rates;
- estimation of probability density functions.

2.1. Survey method

The field data used in our analysis came from a continuous survey carried out by the Traffic Monitoring System of the Province of Venice. In particular, we refer to ATR loop detector-based recording time headways in both traffic directions, together with estimates of the length and speed of vehicles.

2.2. Characteristics of traffic data

Traffic flow observations at a certain point (cross-section) of a road segment are useful in describing the traffic flow characteristics of the entire segment only if we accept the hypothesis that the segment is homogeneous (in geometric and functional terms) and, on the segment and for a certain time interval, steady traffic conditions exist (constant traffic volume, regardless of the section position along the road segment, and time-independent traffic density). In our case, functional and geometric characteristics were homogeneous along the segment considered (for at least one kilometer upstream and downstream of the section). We also assume that, with reference to a time sub-interval of 15 minutes, steady traffic conditions prevailed.

Fig. 1 shows the location of the cross-sections examined.

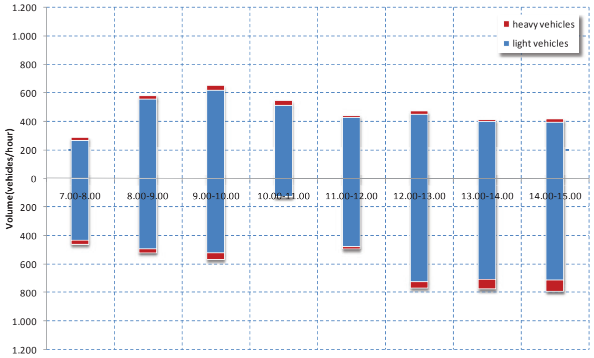
Tab. 1 shows the time period and duration of the on-field surveys and the main characteristics of traffic data collected for each cross-section examined. The sections belong to similar road segments having carriage width ranging from 6.80 to 7.40 meters.

Fig. 1 - Location of four cross-sections analysed.

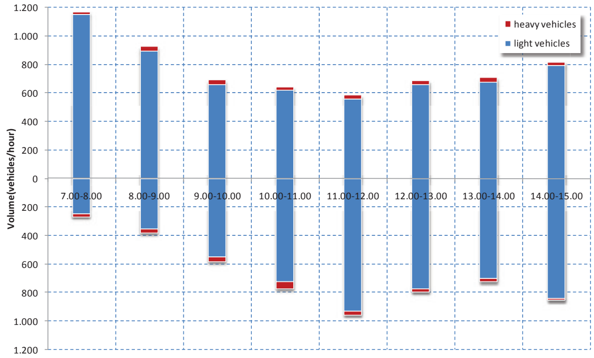
Tab. 1 - Duration of traffic surveys and main characteristics of traffic data.

Section code	Date	Time Interval	Duration (hours)	Total Vehicles	Heavy Vehicles (%)	Directional Split (%)
VNTSR011h4088	Wed 20/06/2007	6.30 a.m.–5.00 p.m.	10.30	12,148	6.1	44/56
xVESP043h0024	Sun 29/07/2007	7.00 a.m.–3.00 p.m.	8.00	11,576	3.7	54/46
	Wed 29/07/2009	8.00 a.m.–2.00 p.m.	6.00	8,841	3.2	55/45
xVESP074h0117	Sun 29/07/2007	7.00 a.m.–3.00 p.m.	8.00	9,896	1.3	63/37
	Wed 29/07/2009	8.00 a.m.–2.00 p.m.	6.00	9,554	1.4	51/49
ANASS014h0168	Tue 13/06/2009	8.00 a.m.–12.00 a.m.	4.00	7,750	3.1	45/55

The temporal evolution of the traffic volumes measured during the survey is shown in the following diagrams. Vehicles longer than 7.5 meters were considered “heavy” vehicles.



Cross-section VNTSR011h4088



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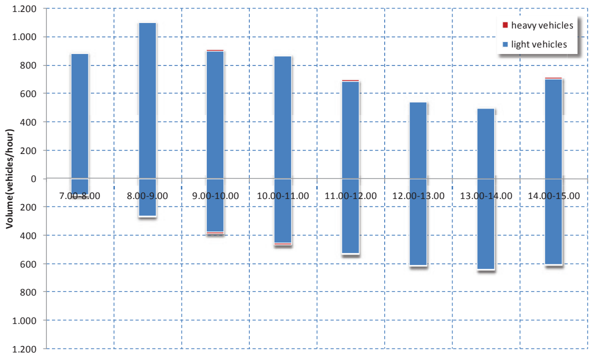

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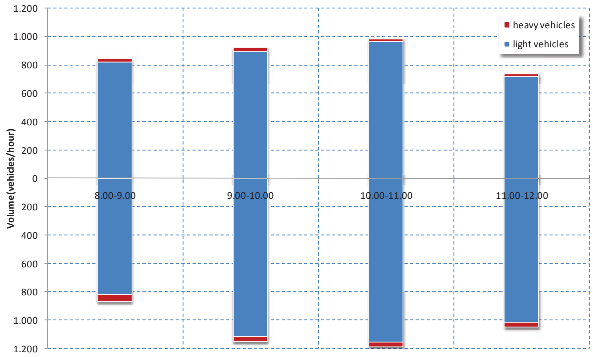

Cross-section ANASS014h0168

Fig. 2 - Analysed cross-sections. Temporal evolution of traffic volumes observed by direction.

With reference to all sections, the percentage of heavy vehicles must be viewed as very low (less than 6.1%, see Tab. 1).

The traffic conditions represented cover a range of values from 100 to 1,200 vehicles/lane/hour. In some peak periods meta-stable conditions were observed (volumes close to 1,200 vehicles/lane/hour). These findings match previous data about this kind of road, where capacity values are usually around 1,400 pce/lane/hour.

2.3. Estimation of time headway pdf

In order to create the samples to be used for estimation, the following assumptions were made:

- headways are analysed separately among lanes;
- for each road section, the observation time period is divided into 15-minute sub-intervals (hypothesis of steady flow conditions);
- the corresponding traffic volumes are converted in pce with an equivalence factor for heavy vehicles of 2.0 pce;
- each sub-interval is classified on the basis of its traffic volume (flow rate in pce) into eight volume ranges: [0-200], (200-400], (400-600], (600-800], (800-1,000], (1,000-1,200], (1,200-1,400] and (1,400-1,600);
- for each section/lane and each flow rate range, time headway samples were created by joining the subsets containing the headways belonging to subsequent sub-intervals of that range. Fig. 3 shows an example: joining

time headway subsets (each formed by the time headways observed in the corresponding 15-minute time intervals) for the same flow rate range yields two samples for the flow rate range 600-800 pce/hour (blue, called 600-800 s1 and 600-800 s2), two samples for the flow rate range 800-1,000 pce/hour (green, called 800-1,000 s1 and 800-1,000 s2) and one sample for the flow rate range 1,000-1,200 pce/hour (orange, called 1,000-1.200 s1).

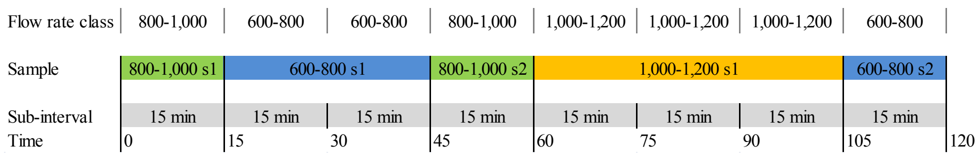

Fig. 3 - Time headway sampling criteria based on flow rate range and joining of subsequent sub-intervals.

A set of pdf's was estimated for each sample with reference to each section/lane. The estimation was carried out with Stat::Fit® software (Stat::Fit, 2001): which can evaluate the goodness-of-fit by the well-known Kolmogorov-Smirnov test (K-S test). The estimation used the Maximum Likelihood method; in all the estimations the condition of left-bounded (at zero) pdf's was set up. In the case of very large samples (up to 2,000 headways), a set of randomly extracted sub-samples containing about 200 headways was used. In this way, we were able to avoid cases in which the K-S test becomes over-sensitive, occasionally rejecting distributions which are actually significant. The 15-minute sub-intervals used as base guaranteed that sample size was large enough for all flow rate ranges. For each section/lane and each range of flow rates, a set of statistically significant pdf's (at 0,05 level) was identified. The tests allowed us to assess the statistical validity of each estimated distribution and to identify a ranking over the accepted distributions for each section/lane and each range of flow rate considered.

The final aim of our analysis was to create a catalogue of pdf's typical for the analysed road segments, providing information about the most efficient distributions for different flow rate ranges. Results for one section are presented in the following section, as an example.

2.3.1. Section xVESP043h002 - Sun 29/07/2007. Estimated time headway distributions

The traffic conditions observed at cross-section xVESP043h002 during the 8-hour period considered are well described by the flow rate/space mean speed diagram of Fig. 4: the set of pairs representing flow rate/space mean speed were estimated with 5-minute sub-intervals and then represented in plan *(Q, Vs)*. As a consequence of the second assumption listed above, the space mean speed was estimated as the harmonic average of vehicle speeds recorded at the section during the 5-minute sub-intervals.

The distribution of points representing the state of the system shows how the sampled time period covers the whole domain of the flow rate, ranging from free-flow conditions to a probable value of road segment capacity of about 1,400 vehicles/lane/hour at an average speed of 70 km/hour.

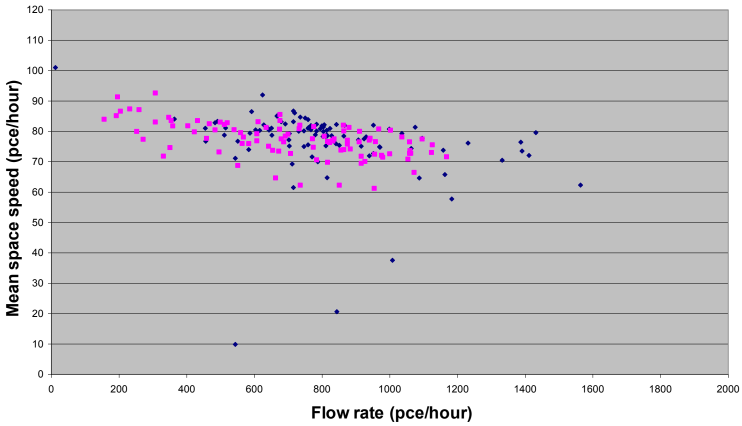

Fig. 4 – Section xVESP043h002 - Sun 29/07/2007. Space mean speed / flow rate pairs by lane.

Statistical analysis identified a set of pdf's for each flow rate range.

In this analysis a wide set of pdf's was evaluated, including well-known functions in the field of headway analysis such as, Negative Exponential, Lognormal, Gamma, Erlang, etc.. Other functions were also analysed.

Time headway distributions estimated for the section examined are listed in Tab. 2.

Tab. 2 - Section xVESP043h002. Statistically significant pdf's for headways.

pdf	Equation	Distribution parameters
Inverse Gaussian	$f(x)=\left(\frac{\alpha}{2\pi(x-min)^3}\right)^{1/2} exp\left[-\frac{\alpha(x-min-\beta)^2}{2\beta^2(x-min)}\right]$	min = minimum time headway x α = shape parameter > 0 β = mixture of shape and scale > 0
Inverse Weibull	$f(x)=\alpha\beta\left(\frac{1}{\beta(x-min)}\right)^{\alpha+1} exp\left(-\left(\frac{1}{\beta(x-min)}\right)^{\alpha}\right)$	min = minimum time headway x α = shape parameter > 0 β = mixture of shape and scale > 0
Log-Logistic	$f(x)=\frac{p\left(\frac{x-min}{\beta}\right)^{p-1}}{\beta\left[1+\left(\frac{x-min}{\beta}\right)^{p}\right]^2}$	min = minimum time headway x p = shape parameter > 0 β = scale parameter > 0
Pearson 5	$f(x)=\frac{\beta^{\alpha}}{\Gamma(\alpha)(x-min)^{\alpha+1}} exp\left(-\frac{\beta}{[x-min]}\right)$	min = minimum time headway x α = shape parameter > 0 β = scale parameter > 0
Pearson 6	$f(x)=\frac{\left(\frac{x-min}{\beta}\right)^{p-1}}{\beta\left[1+\left(\frac{x-min}{\beta}\right)\right]^{p+q} B(p,q)}$	min = minimum time headway x β > 0 p > 0 q > 0

The reported functions are those estimated as statistically significant (0.05 level) and the corresponding parameters are listed in Tab. 3. Blank cells refer to non-statistically significant functions. Orange cells correspond to functions which, for each sample, were the best in terms of goodness-of-fit (maximum p-value of K-S statistic).

The data show clearly that, regardless of lane, the Inverse Weibull distribution fits the time headways observed for the majority of situations analysed (flow rate ranges). Only in the case of the highest flow rates (1,200-1,400 and 1,400-1,600) does the Inverse Weibull distribution not fit the observed data. In these ranges, Pearson 5 and Log Logistic pdf's turned out to be the best in terms of fit.

Tab. 3 - Section xVESP043h002 - Sun 29/07/2007. Estimated parameters of headway pdf's by range of flow rate and lane. Rows correspond to headway sample used in estimation process.

		Probability density function				
Flow rate (pce/hour)	Lane	Inverse Gaussian (min,α,β)	Inverse Weibull (min,α,β)	Log Logistic (min,p,β)	Pearson 5 (min,α,β)	Pearson 6 (min,β,p,q)
0-200	2	(0., 3.08, 14.8)	0., 0.813, 0.352)	(0., 1.07, 5.54)	(0., 0.724, 1.85)	(0., 1.18, 2.3, 0.783)
400-600	1		(0., 1.22, 0.523)	(0., 1.68, 2.75)	(0., 1.33, 2.71)	(0., 0.0473, 58.8, 1.35)
400-600	1		(0., 1.2, 0.531)	(0., 1.63, 2.71)	(0., 1.29, 2.57)	(0., 0.0642, 42., 1.32)
400-600	1	(0., 3.92, 6.25)	(0., 1.21, 0.443)	(0., 1.69, 3.38)	(0., 1.36, 3.27)	(0., 0.349, 11.1, 1.48)
400-600	2		(0., 1.29, 0.539)			
400-600	2		(0., 1.33, 0.493)			
600-800	1		(0., 1.43, 0.521)			
600-800	1		(0., 1.24, 0.515)		(0., 1.38, 2.87)	
600-800	1		(0., 1.34, 0.547)	(0., 1.92, 2.6)	(0., 1.62, 3.24)	(0., 0.0984, 35., 1.68)
600-800	1		(0., 1.33, 0.522)	(0., 1.92, 2.74)	(0., 1.61, 3.37)	
600-800	2		(0., 1.38, 0.519)	(0., 1.92, 2.7)	(0., 1.65, 3.47)	(0., 0.111, 33.1, 1.7)
600-800	2		(0., 1.37, 0.602)	(0., 1.92, 2.27)	(0., 1.59, 2.89)	(0., 0.03, 97.5, 1.61)
600-800	2		(0., 1.31, 0.553)		(0., 1.48, 2.9)	(0., 0.0657, 46.3, 1.52)
600-800	2		(0., 1.37, 0.62)	(0., 1.93, 2.22)	(0., 1.61, 2.84)	(0., 0.131, 23.8, 1.71)
800-1,000	1		(0., 1.51, 0.575)	(0., 2.16, 2.32)	(0., 1.94, 3.73)	
800-1,000	1		(0., 1.49, 0.643)	(0., 2.08, 2.07)	(0., 1.82, 3.12)	(0., 0.0234, 139, 1.87)
800-1,000	1		(0., 1.37, 0.585)	(0., 1.92, 2.42)	(0., 1.65, 3.08)	(0., 0.0309, 101, 1.66)
800-1,000	2		(0., 1.69, 0.541)	(0., 2.43, 2.38)		
800-1,000	2		(0., 1.77, 0.564)	(0., 2.53, 2.28)	(0., 2.46, 4.9)	(0., 1.29e-002, 381, 2.47)
800-1,000	2		(0., 1.48, 0.586)			
800-1,000	2		(0., 1.67, 0.674)			
1,000-1,200	1		(0., 1.84, 0.525)	(0., 2.66, 2.44)	(0., 2.68, 5.75)	(0., 0.213, 29.2, 2.82)
1,000-1,200	2		(0., 1.64, 0.611)	(0., 2.43, 2.13)	(0., 2.25, 4.11)	(0., 0.142, 31.1, 2.35)
1,000-1,200	2		(0., 1.61, 0.61)	(0., 2.29, 2.15)	(0., 2.09, 3.82)	(0., 0.073, 53.6, 2.12)
1,200-1,400	1			(0., 2.85, 2.15)	(0., 2.85, 5.28)	(0., 0.341, 19.1, 3.33)
1,400-1,600	1			(0., 3.11, 2.02)	(0., 3.23, 5.68)	(0., 0.743, 11.6, 4.49)

For a clear interpretation of the results, the Inverse Weibull fitted curves are shown in Fig. 5. For each flow rate range, the thick lines correspond to curves plotted with the average values of the estimated parameters.

The Inverse Weibull distribution fits the headways frequency well, and is characterized both by a peak in the left part of the positive domain and a long positive tail. As expected, the curves tend to increase as the flow rate rises.

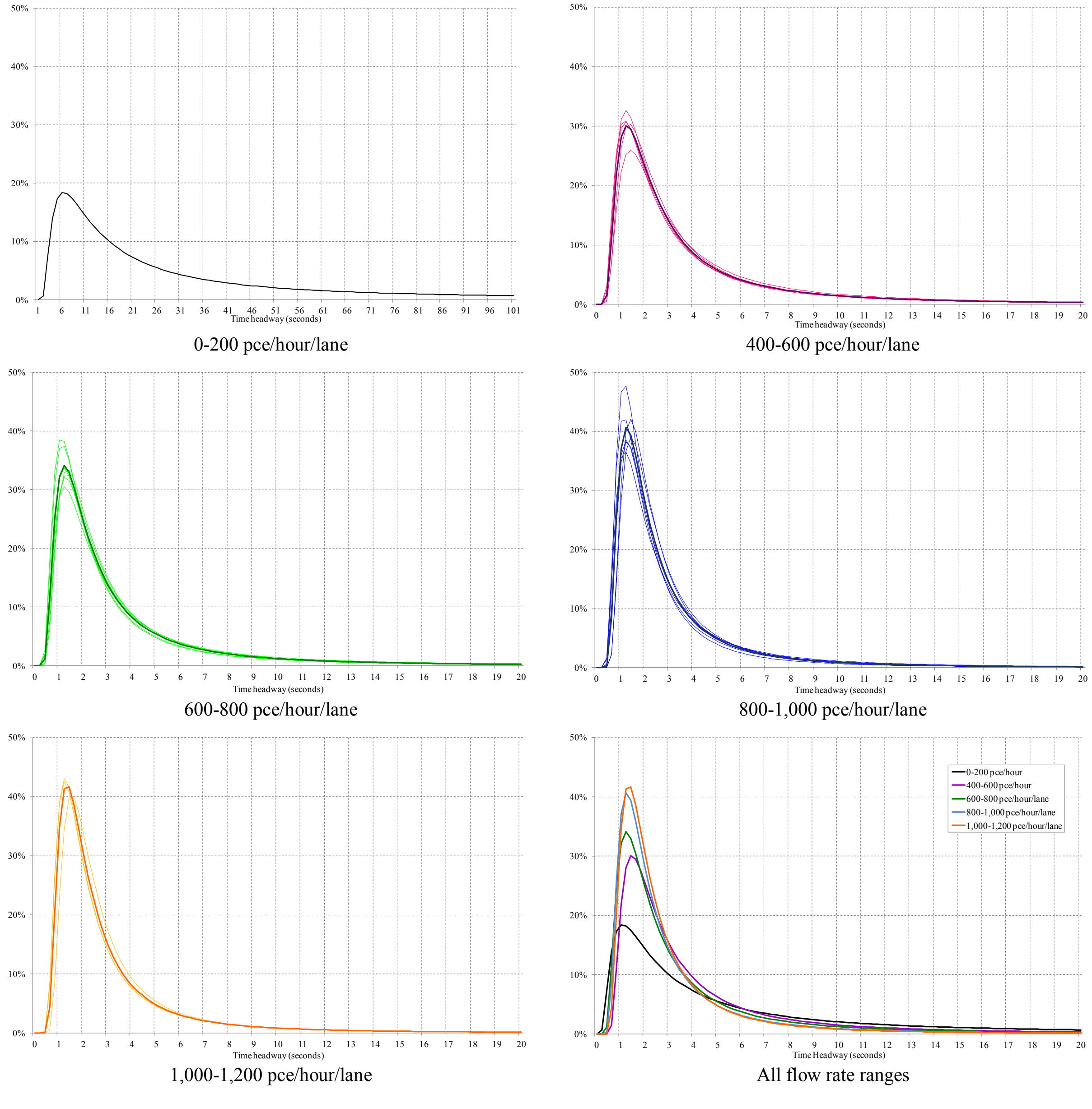

Fig. 5 - Section xVESP043h002 - Sun 29/07/2007. Inverse Weibull headway pdf's by range of flow rate and lane.

3. Main results

The above analysis was performed for all sections and periods considered. A total of 77 samples of headways were analysed.

In the following diagrams, the results are presented concisely; in view of the limited number of cases in the range 0-400 pce/hour/lane, we decided to exclude the relative results from the discussion.

Considering all the road sections analysed, for each flow rate range the blue bars represent the frequency of cases in which each pdf was significant, and the orange bars cases in which each pdf was the best fit. The pdf's presented are those shown to be significant in at least one case.

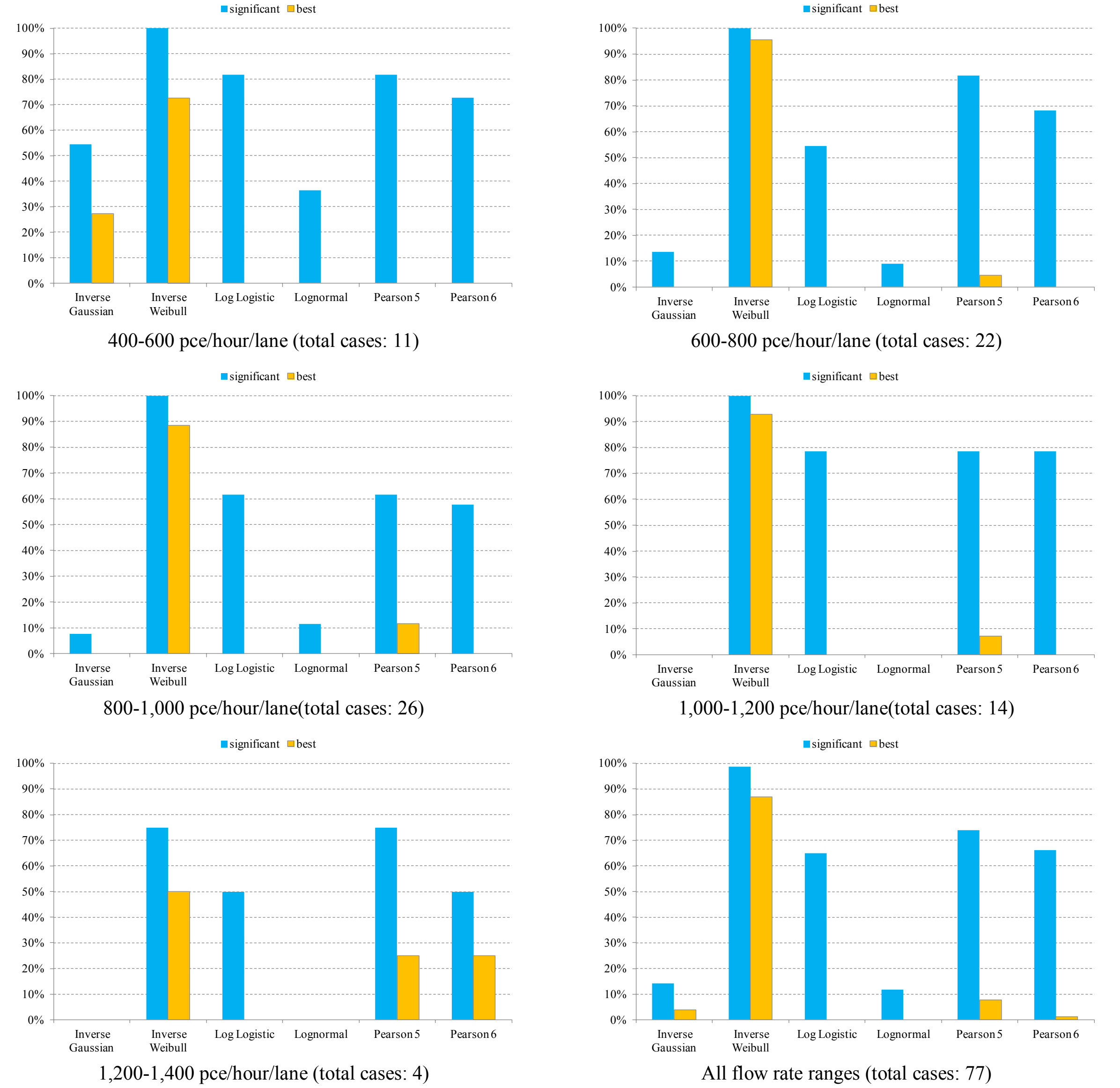

Fig. 1 – All sections, all samples. Frequency of cases with significant pdf's (blue bars) and best fit (orange bars).

These diagrams illustrate a "law" describing how headway distributions relate to flow rate (whereas road segments must be considered similar in terms of traffic volumes and composition).

With regard to analysed cases, note that:

- the Inverse Weibull pdf appears to be the most suitable for representing real headway distributions for most of the flow rate ranges; some lacks arise only in the impeded-free regime (Kim & Keller, 2008) placed realistically in the 1,000-1,200 pce/hour/lane. In this condition, Person 5 and Person 6 pdf's become more suitable;
- Log Logistic, Person 5 and Person 6 appear to fit the observed headway distributions quite well, although they do not fit as easily as the Inverse Weibull, regardless of flow rate range;
- well-known pdf's such as Negative Exponential, Lognormal, Gamma and Erlang do not appear to be suitable to represent time headway distributions in the analysed cases.

4. Concluding remarks and future directions

The main aim of the analysis presented here was to identify typical headway pdf's representing empirical time headway distributions usually observed on cross-sections belonging to two-way two-lane rural roads with different flow rate ranges. This aim was directly connected to the need to simulate these phenomena, both in micro-simulation models and driving simulator virtual environments.

In this first stage of our research, we report traffic observations on four cross-sections placed in the rural road network of the Province of Venice (Northern Italy).

With reference to all the analysed road-sections, the results allow us to draw the following conclusions:

- Inverse Weibull pdf appears to be the most suitable to represent real headway distributions for most of the flow rate ranges;
- Log Logistic, Person 5 and Person 6 appear to fit the observed headway distributions quite well, although they do not fit as easily as the Inverse Weibull, regardless of flow rate range.

Future research directions will focus on the following issues:

- extension of field observations to other sections in different contexts (urban and rural areas) with the aim of generalizing results for all flow rate ranges (also under 400 pce/hour/lane) and different traffic compositions;
- improvement in the analysis, considering statistical procedures useful for determining trendless time intervals;
- application of results to driving simulator experiments (e.g., gap-acceptance analysis) and micro-simulation models.

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