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Lane by Lane Analysis of Vehicle Time Headways - Case Study of Izmir Ring Roads in Turkey

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Abstract

The studies on headway characteristics of traffic flow in Turkey are mainly dealing with signalized arterials, intersection approaches or roundabouts. Only a few studies can be found on headway characteristics of uninterrupted flow facilities and nearly none of them are on lane by lane basis. In this study, the authors are modeling headways of vehicles at İzmir ring roads by lane by lane principle. The study demonstrates that lognormal distribution is an effective tool to define headways. In addition, the applicability of Cowan M3 distribution to time headways is investigated. Proportion of free vehicles is modeled for different lanes. The results show that traffic flow in the middle lane is highly affected by the vehicles in other lanes. Vehicles in the outer lane can be assumed to arrive randomly, but they are also disturbed by vehicles in other lanes. These results can be used in capacity and performance analysis of freeway segments, ramp junctions and weaving areas.

Keywords: *freeway, lane by lane analysis, Kolmogorov - Smirnov test, Cowan M3 distribution, proportion of free vehicles*

1. Introduction

Ring roads or freeway passages are found to be efficient solutions for traffic congestion in metropolitan areas in Turkey. Thus in recent years freeways and their macroscopic traffic properties have been subject of detailed research. Most of the studies focus on the Bosporus Bridges' connection arterials whereas others focus on link capacity estimates of freeways in Turkey (Şahin, 2009; Şahin and Altun, 2008; Şahin and Akyıldız, 2005; Dell'orco *et al*., 2009; Öğüt, 2004; Öğüt and Ergün, 2006). Lane utilization characteristics of Turkish drivers have also been a subject of inquiry (Günay, 2004). However, only a few studies can be found on interactions between vehicles and microscopic variables of traffic flow like car following characteristics and headway distributions of uninterrupted flow facilities in Turkey and to the best of authors' knowledge, none of them are on lane by lane basis.

Headway (or time headway) can be defined as the time interval between two vehicles passing a point as measured from the front bumper to the front bumper (Luttinen, 1996). Headways can be used to define characteristics of uninterrupted and interrupted traffic flows; to develop capacity and performance functions for unsignalized intersections, roundabouts, on and off ramp junctions etc. The properties of headways are extensively studied to present a distribution model. Accurate modeling and analysis of vehicle headway distribution helps to minimize vehicle delays and maximize roadway capacity. Headways are also being used as important tools for calibration of different analytical and simulation models (Winkler and Fan, 2011).

There has been an in depth research on headway characteristics of traffic flow (Buckley, 1968, Branston, 1976; Cowan, 1975; Akçelik, 2003; 2006; Wasielewski, 1974; 1979; 1981; Al-Ghamdi, 2001; Griffiths and Hunt, 1991; Luttinen, 1992, 1994, 1996; Hagring, 2002; Zwahlen *et al*., 2007; Dawson and Chimini, 1968; Chen and Gupta, 1997; Archilla and Morrall, 1996; Hoogendorn *et al*., 1997; Sullivan and Troutbeck, 1994; 1997; Akçelik and Chung, 1994; Troutbeck, 1997).

Akçelik (2003; 2006) has used Cowan M3 distribution for modeling headways for uninterrupted flows and proposed a new model for the proportion of bunched vehicles. In his studies he treated all lanes together while developing the model. Another researcher who analyzed headways of uninterrupted flows (freeways) is Bunker (1996). He also used Cowan M3 distribution in modeling headways. However, he suggested different parameters for proportion of free vehicles for inner and outer lanes. He used the results to develop a delay model for freeway merging areas.

In Turkey, the researches on headway characteristics of traffic flow mainly deal with signalized arterials, intersection approaches or roundabouts. For example, Murat and Gedizlioğlu (2007) have modeled headways at signalized intersection approaches. Çalışkanelli and Tanyel (2010) have suggested a model for proportion of unbunched vehicles to be used in Cowan M3 distribution. Tanyel and Yayla (2003) and Çalışkanelli *et al*. (2009) have studied headway

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distribution modeling at single and multi-lane roundabouts. Nehir (2009) has investigated the changes in the properties of headways near bus stops. One of the rare studies on headways at different lanes of an uninterrupted section of İzmir ring road was prepared by Aydın (2007). In that study, she tried to show the effect of reverse-lane usage on headways and also investigated the effect of opening of the new İzmir outer ring road.

In this study, the characteristics of headways at uninterrupted sections of İzmir ring roads, Turkey are aimed to be discussed by lane by lane principle. The characterization of the flow variation between freeway lanes is significant for several reasons. First, lane flow variations and differences of time headway affect the overall capacity of a freeway. Moreover, lane effects are taken into account especially in case of lane selection and lane changing behavior of drivers.

The paper is organized as follows: The following section explains the observation and data collection procedure. This is followed by a presentation and discussion of some of the relations of descriptive statistics. Next, a brief analysis on applicability of simple distributions and calibration of Cowan M3 distribution is presented. Finally, conclusions and suggestions for future research are given.

2. Data Collection

In this research, data was collected from four different sections of İzmir ring roads (Fig. 1). All sights have three lanes at each direction; lane widths are approximately 3.6 m and all sections of ring roads are unsignalized. At each site, data was collected from only one direction, mostly the direction towards the city center. Observations were made during the morning (8:00 to 9:00 am) and evening (6:00 to 7:00 pm) peak hours, and mid-week days (Tuesday, Wednesday or Thursday). In addition, the research was repeated in different times of the year: in winter and in spring. The number of vehicles, percentages of different vehicle types (minibus, bus or trucks), averages and standard deviations of vehicle speeds are given in Table 1.

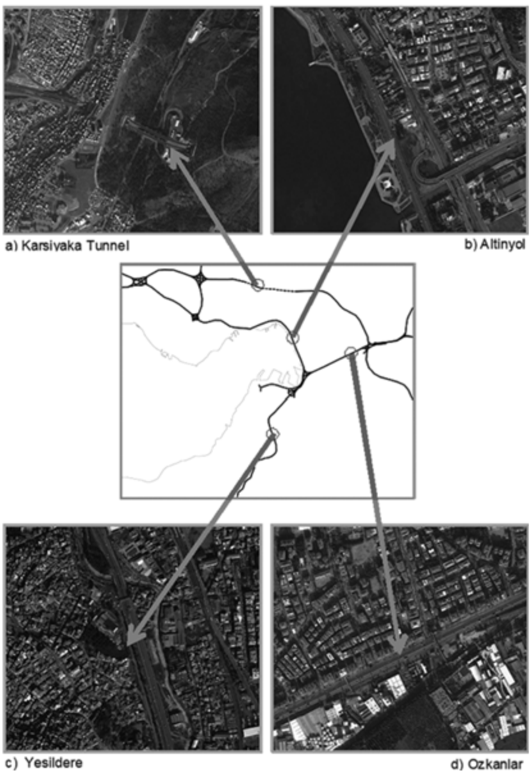

Fig. 1. Locations of Observation Areas

Vehicle headway data was collected using standard video equipment and data was extracted from the recordings by using a counter program. The means, standard deviations, minimum and maximum values of hourly headway data groups are shown in Table 2 and 3.

Observed data were grouped for outer, middle and inner lanes separately and evaluated for each lane group. Luttinen (1996) has compared three different trend analysis tests, weighted sign test, Kendall's rank correlation test and exponential ordered scores trend test. He stated that, exponential ordered scores test give better results than other two tests. As a result trends in data groups were analyzed by using exponential ordered scores test. The sample size was incremented by 50 vehicles until the test reported trend 5% level of significance and sampling periods were 10-20 minutes (Luttinen, 1996). As a result, a total of 64 trend free data groups were obtained for each lane type. Randomness and autocorrelation were also investigated for each sub data sets. According to the results of the analysis, hypothesis of randomness was accepted for all subsets and no significant autocorrelation was found.

3. Investigation on Relations between Some Descriptive Statistics

To have a better understanding of the differences between lane usage behaviors, the relations between some descriptive statistics of data groups are investigated. Griffiths & Hunt (1991) and Al-Ghamdi (2001) stated that the relationship between mean of headways and standard deviation have important consequences due to the estimation of the standard deviations of headways directly from the mean of observed flow, which is the reciprocal of the mean headway ($\bar{t} = 1/q$). Similar analyses were performed for the observed data and the outcome is shown in Fig. 2.

The regression equations of the lines shown in Fig. 2 can be written as follows:

$$S_L = 0.9899\bar{t} - 0.0285 \qquad R^2 = 0.90 \tag{1}$$

$$S_M = 0.824\bar{t} - 0.2565 \qquad R^2 = 0.91 \tag{2}$$

$$S_R = 0.7964\bar{t} - 0.3413 \qquad R^2 = 0.95 \tag{3}$$

where, S_L, S_M and S_R are the standard deviations of time headways for each lane, respectively. Fig. 2 indicates that mean of headways of all lanes changes between 2.0-13.0 sec. The values under the mean time headway of 6.0 sec, the standard deviation of inner lane is greater than the standard deviation of other lanes. The mean

Table 1. Number of Vehicles, Percentages of Different Vehicle Types (minibus, bus or trucks), Averages and Standard Deviations of Vehicle Speeds for each Data Group

Location		Observation Period		Flow rate (vph)	$P_{minibus}$ (%)	P_{bus} (%)	P_{Truck} (%)	Average Speed (km/h)	Std. Dev. of Speed (km/h)
Section	Lane	Date	Time						
Altinyol	Inner	Dec, 2009	08:00-09:00	952	10.8	1.6	2.2	66	8.623
	Middle			1635	11.7	0.5	1.8	56	7.516
	Outer			2021	7.7	0.2	0.0	66	9.300
	Inner	Dec, 2009	17:00-18:00	319	17.9	2.2	9.7	59	9.159
	Middle			1018	20.9	1.9	5.7	63	5.342
	Outer			1107	13.7	1.4	0.4	58	4.383
	Inner	May, 2010	08:00-09:00	1536	10.7	5.3	1.0	42	17.217
	Middle			1666	5.0	2.5	1.6	40	14.098
	Outer			1746	5.4	0.3	0.7	28	13.218
	Inner	May, 2010	17:00-18:00	427	18.3	9.1	19.9	64	9.505
	Middle			1047	18.1	3.1	4.8	63	16.922
	Outer			1101	13.0	1.1	0.2	80	8.882
Ozkanlar	Inner	Dec, 2009	08:00-09:00	507	8.5	0.8	25.4	41	11.161
	Middle			1062	3.5	0.3	9.7	55	17.154
	Outer			1221	2.7	0.3	1.5	71	24.840
	Inner	Dec, 2009	17:00-18:00	338	16.0	1.5	21.3	45	10.739
	Middle			1109	9.6	1.0	13.3	65	5.363
	Outer			1487	7.1	1.3	0.9	80	4.536
	Inner	May, 2010	08:00-09:00	309	12.0	1.9	9.7	56	8.207
	Middle			926	9.5	0.4	10.6	62	4.670
	Outer			1020	9.5	0.7	1.7	78	4.623
	Inner	May, 2010	17:00-18:00	371	10.5	5.7	11.1	56	6.967
	Middle			897	10.0	3.2	10.9	64	3.481
	Outer			1194	8.8	1.2	1.5	73	3.278
Yesildere	Inner	Dec, 2009	08:00-09:00	859	27.2	4.1	1.7	41	7.878
	Middle			1343	23.2	0.3	1.8	50	17.812
	Outer			1669	12.3	0.1	0.2	59	11.870
	Inner	Dec, 2009	17:00-18:00	448	39.5	6.0	1.6	47	3.463
	Middle			1021	21.3	1.2	3.9	48	3.386
	Outer			1348	15.6	0.4	0.4	68	4.962
	Inner	May, 2010	08:00-09:00	786	20.9	1.8	3.8	51	7.785
	Middle			1211	17.1	0.1	4.0	47	9.899
	Outer			1593	11.6	0.0	0.0	73	43.044
	Inner	May, 2010	17:00-18:00	404	32.7	1.2	3.7	58	7.000
	Middle			817	22.0	0.6	3.7	54	5.498
	Outer			1085	13.3	0.7	0.2	80	8.483
Karsiyaka Tunnel	Inner	Dec, 2009	08:00-09:00	243	17.7	0.8	68.3	64	31.304
	Middle			526	6.8	0.8	6.5	76	17.434
	Outer			542	4.4	0.0	0.4	94	11.717
	Inner	Dec, 2009	17:00 -18:00	212	28.8	0.5	28.3	71	13.924
	Middle			602	17.6	3.0	4.2	82	12.540
	Outer			280	8.6	0.4	0.4	81	17.416
	Inner	May, 2010	08:00-09:00	240	12.1	2.1	69.2	71	5.473
	Middle			552	13.6	2.7	6.5	69	8.934
	Outer			233	7.3	2.6	65.2	77	10.817
	Inner	May, 2010	17:00-18:00	374	17.1	2.9	38.5	44	7.996
	Middle			1042	7.1	1.9	4.6	52	11.389
	Outer			714	4.5	0.3	1.0	59	13.316

headways in the middle lane are much lower than other lanes.

Another analysis which can be performed for the descriptive statistics of observed data is to investigate the relation between modes of headway data groups and traffic volumes. Summala and

Table 2. Fundamental Statistical Analysis of the Collected Headways on Uninterrupted Multi-Lane Freeways in Winter

Location		Average flow rate (vph)		Mean of headways (sec)		Std deviation of headways (sec)		Minimum Value (sec)		Maximum value (sec)	
		Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening
Altinyol	Inner	952	319	3.803	11.347	3.224	9.805	0.631	0.610	20.900	72.434
	Middle	1635	1018	2.253	3.582	1.369	2.445	0.591	0.590	15.402	17.656
	Outer	2021	1107	1.828	3.291	1.097	3.162	0.521	0.410	10.735	21.721
Ozkanlar	Inner	507	338	6.648	10.840	5.941	9.614	0.594	0.594	46.940	76.562
	Middle	1062	1109	3.190	3.369	2.457	2.481	0.109	0.297	26.750	19.266
	Outer	1221	1487	2.782	2.524	2.540	2.135	0.328	0.281	22.469	19.203
Yesildere	Inner	859	448	4.286	6.585	4.183	6.638	0.150	0.297	38.844	51.930
	Middle	1343	1021	2.744	2.917	2.273	2.481	0.150	0.219	25.540	17.157
	Outer	1669	1348	2.212	2.683	2.457	2.964	0.469	0.422	37.812	37.390
Karsiyaka Tunnel	Inner	243	212	12.419	13.597	9.762	9.955	0.904	0.680	66.463	58.740
	Middle	526	602	5.815	4.946	4.088	4.241	1.359	0.337	28.546	33.281
	Outer	542	280	5.560	10.527	8.815	10.907	0.422	0.188	70.687	68.599

Table 3. Fundamental Statistical Analysis of the Collected Headways on Uninterrupted Multi-Lane Freeways in Spring

Location		Average flow rate (vph)		Mean of headways (sec)		Std deviation of headways (sec)		Minimum value (sec)		Maximum value (sec)	
		Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening
Altinyol	Inner	1536	427	2.385	8.419	1.509	6.775	0.282	0.718	16.844	45.510
	Middle	1666	1047	2.214	3.486	1.371	2.342	0.310	0.471	21.125	14.831
	Outer	1746	1101	2.105	3.295	1.583	2.929	0.234	0.200	31.860	20.536
Ozkanlar	Inner	309	371	7.751	9.682	5.892	8.393	0.721	0.561	37.464	71.573
	Middle	926	897	3.900	4.014	2.925	2.973	0.611	0.391	25.827	20.340
	Outer	1020	1194	3.543	3.064	3.016	2.656	0.400	0.270	24.576	21.250
Yesildere	Inner	786	404	3.769	7.868	3.315	18.108	0.302	0.672	23.444	350.328
	Middle	1211	817	2.480	3.608	1.609	3.167	0.302	0.235	14.637	31.160
	Outer	1593	1085	1.913	2.727	1.323	2.728	0.344	0.406	24.907	28.688
Karsiyaka Tunnel	Inner	240	374	13.233	8.897	11.667	6.930	0.867	0.594	74.790	38.750
	Middle	552	1042	5.241	3.228	4.155	2.473	0.703	0.447	33.328	16.406
	Outer	233	714	12.383	4.757	10.695	5.070	0.985	0.515	57.391	37.313

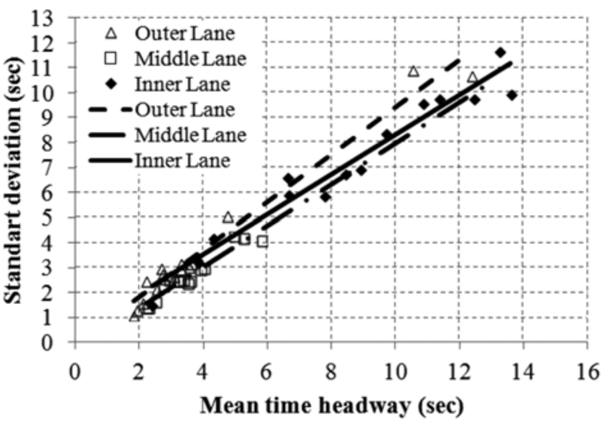

Fig. 2. Standard Deviation of Time Headways versus Mean with Best Fit Line for each Lane at Three-Lane Freeway

Vierimaa (1980) describe the mode as an approximation of the headway that most drivers select when they are following the vehicle ahead (Luttinen, 1996). As known, the bin width can have a considerable effect on the shape of the estimate (and also the mode of the sample group), especially at low volumes of headways (Luttinen, 1996). Using wider headway bins where the density is low reduces noise due to sampling randomness; on the other hand using narrower headway bins where the density is high gives greater accuracy to the density estimation. In this study, bin widths of 0.5 seconds were chosen for analysis. The mode of time headways versus volume for each lane separately are shown in Fig. 3.

Figure 3 indicates that at low volumes mode varies between 1.0 and 8.0 sec in inner lanes. The mode varies between 1.0 and 5.0 sec in middle lanes whereas it varies around 1.0 sec in outer lanes. The mode of the inner lanes may be greater than the other lanes because of the high proportion of heavy vehicles and/or slow moving vehicles.

The last step which includes descriptive statistics of data groups is analyzing the results of coefficient of variations. The Coefficient of Variation (CV) is the proportion of the standard deviation to the mean of a random variable (T):

$$C(T) = \frac{\sigma(T)}{\mu(T)} \tag{4}$$

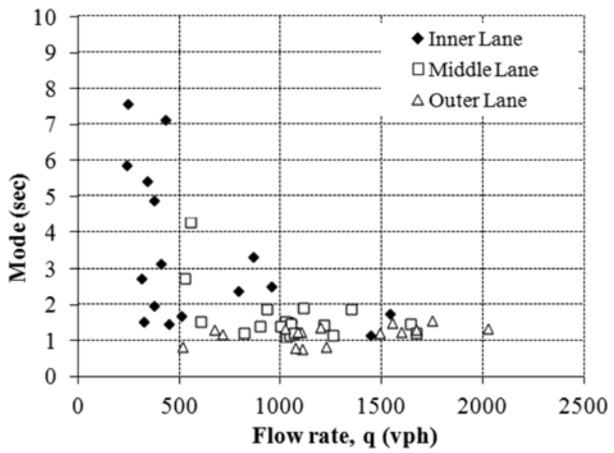

Fig. 3. Lane by Lane Collation of Mode of Freeway Headways vs. Flow Rate

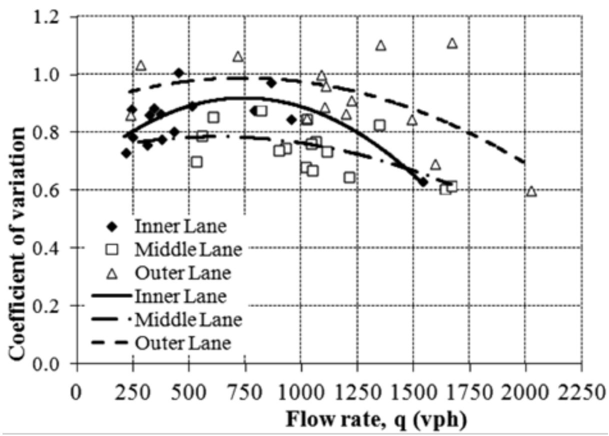

Fig. 4. Lane by Lane Collation of Coefficient of Variation of Freeway Headways versus Flow Rate

The sample CV is the proportion of the sample standard deviation to the sample mean:

$$C = \frac{s}{\bar{t}} \tag{5}$$

Luttinen (1996) defined coefficient of variation as a scaled measure of variation in headways and a useful measure of dispersion in the headway distribution. Luttinen (1996) uses data sets from low-speed roads (speed limit 50-70 km/h) and high speed roads (speed limit 80-100 km/h). In his study, CV of the samples are found to be around 1.0 at low-speed roads and between 1.0-2.0 at high-speed roads. Several other authors discuss the CV and traffic flow rate relation in different studies of which the work of Breiman *et al.* (1977), May (1965) and Buckley (1968) focus on freeway lanes. The CV is less than 1.0 in the freeway samples of May (1965) and Breiman *et al.* (1977) (lanes one and two), and near 1.0 in the samples of Buckley (1968) and Breiman *et al.* (1977) from three-lane freeway.

In this analysis, the authors examine CV values versus flow rate for each lane in three-lane freeway sites in İzmir. CV is found to be an important tool to compare drivers' behavior in different lanes. To compare the differences between inner, middle and outer lanes, second-degree polynomial curves were fitted to the CV data which is found the best curve that may be used for each data set (Fig. 4).

The regression equations of each lane are:

$$C_L = -2\times10^{-7}q^2 + 0.0003q + 0.8848 \tag{6}$$

$$C_M = -2\times10^{-7}q^2 + 0.0002q + 0.7261 \tag{7}$$

$$C_R = -5\times10^{-7}q^2 + 0.0007q + 0.6599 \tag{8}$$

where, q is flow rate (vph) and C_L, C_M, C_R are coefficient of variation of each lane, respectively.

Figure 4 depicts that CV is less than 1.0 for most of the samples. In the inner lanes over the range of volume 210 to 1500 vph, the CV values are between 0.6 and 0.9. In the middle lanes the CV values are between 0.6 and 0.8 over the range of volume 500 and 1700 vph. In the outer lanes CV varies between 0.6 and 1.1 over the range of volume 250 and 2000 vph and it is approximately 1.0 at volume 750 vph. The curves have maxima approximately at volumes 750 vph (outer lanes), 500 vph (middle lane) and 700 vph (inner lanes).

The results show that, drivers tend to follow each other with analogous headways in the middle lane more than other lanes. This may be mainly because drivers' (or vehicles') interactions with each other is much higher because of drivers' who change lanes from inner and outer lanes. Al Ghamdi (2001) stated that the motorists in developing countries leave shorter headways from the car ahead than corresponding drivers in the developed world. The aggressive drivers who tend to follow each other in short headways affect the characteristics of traffic behavior which is a typical accident reason in Turkey. Hence is the expected difference in CV values between this study and other international studies.

All freeway data curves are convex for each lane which are similar to Luttinen's (1996) results; but, this result is not consistent with the analysis of Al Ghamdi's (2001) which concave curves are fitted to freeway headways.

4. Applicability of Statistical Distributions

The headways between vehicles can be defined by using simple statistical distributions like negative exponential, shifted negative exponential, Erlang, gamma, Pearson Type III and lognormal distributions. Negative exponential distribution is the most common distribution used in traffic engineering analysis. The probability density function of negative exponential distribution is given below:

$$f(t) = qe^{-qt} \tag{9}$$

where, q is the traffic flow rate in veh/sec and t is the headway value. Luttinen (1996) states that the negative exponential distribution is the interarrival time distribution of the Poisson process. It is quite simple and its parameters can be predicted quite easily. However, the frequency of unrealistically short headways in the negative exponential distribution is too large (Luttinen, 1996). Another commonly used simple distribution is the gamma distribution:

$$f(t) = \frac{\lambda}{\Gamma(K)}(\lambda.t)^{K-1}e^{-\lambda.t} \tag{10}$$

where, *f(t)* is the probability density function, λ is the parameter that is a function of the mean headway and *K* is a user-selected parameter between 0 and ∞ that affects the shape of the distribution and *Γ(K)* is the gamma function which is equivalent to (*K-1*)! (May, 1990). When *K* is chosen as any positive value then Eq. (10) can be rewritten as:

$$f(t) = \frac{\lambda}{(K-1)!}(\lambda.t)^{K-1}e^{-\lambda.t} \tag{11}$$

which is named as Erlang distribution (May, 1990). If *K* is assumed as 1.0 then equation turns into negative exponential distribution. Another statistical distribution which is preferred by researchers is the lognormal distribution:

$$f(t) = \frac{1}{\sigma(t-\Delta)\sqrt{2\pi}}e^{\left\{-\frac{[ln(t-\Delta)-\mu^2]}{2\sigma^2}\right\}} \tag{12}$$

where, "μ" and "σ" are mean and standard deviation of observed data.

Initially, the authors investigated the applicability of negative exponential, gamma and lognormal distributions to the headway data. The Kolmogorov–Smirnov test (K–S test) is used to determine the distance between the distribution functions of the measured data. According to the analysis, it is found that 11 data sets fit to negative exponential distribution, 4 data sets can be defined with gamma distribution and 33 data sets can be defined with lognormal distribution (Table 4).

Considering the results, it is clear that in most cases lognormal distribution is found to be an appropriate distribution for headway modeling purposes. Negative exponential distribution is the second best distribution.

However, the most significant disadvantage of simple distributions is their inability to describe the sharp peak and the long tail of the sample headway distribution (Luttinen, 1996). Studies have shown that near the mode of the distribution there is a high accumulation between vehicles even at very low volumes while the long tail can be modeled by using negative exponential distribution. This leads us to conclude that the vehicles can be categorized as free flowing and bunched vehicles.

In one of the early studies on headways, Dawson & Chimini (1968) have defined free vehicles as "the vehicles' headways are of "adequate" duration; which are able to pass so that they do not have to modify their time-space trajectories, as they approach preceding vehicles and as passing vehicles which have sustained a positive speed difference after the passing maneuver so that they are still able to operate as independent units". When vehicles in a traffic flow are categorized as free and bunched vehicles, mixed statistical distributions should be used. The general form of probability density function of mixed distributions can be written as:

$$f(t) = \theta.f_1(t) + \alpha.f_2(t) \tag{13}$$

where, *f(t)* is the probability distribution of composite distribution model, $f_1(t)$ is the probability distribution of constrained headways, $f_2(t)$ is the probability distribution of free headways, α is the proportion of free vehicles and θ is the proportion of bunched vehicles. The most known mixed distributions can be listed as hyper-exponential, Hyperlang, Cowan M3 (M/D/1 queuing model), Cowan M4 (generalized queuing model) and Semi-Poisson distributions.

In this study, Cowan M3 distribution is chosen to model headways at İzmir ring roads for its ability to represent long tails of observed data and for comparison with other similar models studied by different researchers like Akçelik (2003) and Çalı şkanelli and Tanyel (2010). The advantages of Cowan M3 distribution are its simplicity and its effective usage for analyzing traffic flow

Table 4. Distributions Fitting the Data of each Lane at Different Sections of İzmir Ring Roads

D-STATISTIC VALUE (K-S TEST)													
		Winter						Spring					
		Inner		Middle		Outer		Inner		Middle		Outer	
		Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening
ALTINYOL	Exponential Distr.	0.034	0.043	0.267	0.098	0.234	0.037	0.281	0.078	0.105	0.205	0.102	0.033
	Gamma Distr.	0.084	0.041	0.090	0.066	0.082	0.113	0.090	0.026	0.092	0.063	0.131	0.099
	Log-Normal Distr.	0.061	0.039	0.052	0.049	0.044	0.068	0.057	0.014	0.049	0.045	0.056	0.060
OZKANLAR	Exponential Distr.	0.029	0.032	0.066	0.083	0.040	0.046	0.074	0.045	0.113	0.101	0.034	0.031
	Gamma Distr.	0.055	0.043	0.061	0.057	0.081	0.109	0.022	0.048	0.042	0.050	0.083	0.103
	Log-Normal Distr.	0.009	0.035	0.028	0.030	0.029	0.060	0.025	0.031	0.029	0.037	0.054	0.060
YESILDERE	Exponential Distr.	0.051	0.028	0.065	0.039	0.047	0.596	0.047	0.002	0.248	0.042	0.085	0.073
	Gamma Distr.	0.062	0.059	0.090	0.091	0.011	0.142	0.076	0.002	0.092	0.076	0.117	0.153
	Log-Normal Distr.	0.013	0.020	0.052	0.044	0.018	0.076	0.056	0.002	0.057	0.052	0.075	0.103
KARSIYAKA TUNNEL	Exponential Distr.	0.109	0.101	0.245	0.077	0.121	0.021	0.106	0.072	0.105	0.165	0.036	0.043
	Gamma Distr.	0.030	0.046	0.093	0.058	0.088	0.017	0.044	0.039	0.044	0.065	0.060	0.056
	Log-Normal Distr.	0.033	0.080	0.061	0.036	0.067	0.048	0.034	0.014	0.033	0.032	0.040	0.022

characteristics. Especially it can be used in modeling proportion of free vehicles or percentage of vehicles in platoon. The probability distribution function of Cowan M3 distribution can be written as below:

$$F(t) = \begin{cases} 0 & , \quad if\ t<0 \\ 1-\alpha\ exp[-\lambda(t-\Delta)], & if\ t\geq 0 \end{cases} \quad (14)$$

where, λ is the shape parameter (Luttinen, 2003; 2004). "λ" can be found by using the following equation:

$$\lambda = \alpha.q/(1-\Delta.q) \quad (15)$$

This equation was developed from the requirement that the mean headway is equal to *1/q* (Troutbeck, 1997). In this paper, the parameters of Cowan M3 distribution are predicted by using least square method. The procedure can be listed as follows:

a) As a first step, "λ" is calculated by:

$$\lambda = \frac{1}{\Sigma_i t_i/n-\xi} \quad (16)$$

where, "ξ" is a headway value limit at which the vehicles are assumed to be free. In different studies "ξ" is accepted as 3 or 4 seconds (Troutbeck, 1997; Hagring, 1998). In this analysis, the best results are obtained when "ξ" is assumed as 3 seconds.

b) Again in Eq. (16), $\Sigma_i t_i/n$ is the average of headways which are greater than ξ. The location parameter Δ was substituted with an exponential threshold, which does not introduce any bias to scale parameter estimate if $F(t|t>\xi)$ follows exponential distribution (Luttinen, 1999). For $t>\xi$, the distribution function can be rewritten as:

$$F(t) = 1-\alpha e^{-\lambda(t-\Delta)} = 1-\gamma e^{-\lambda t} \quad (17)$$

where,

$$\gamma = \alpha e^{\lambda\Delta} \quad (18)$$

c) Minimizing the sum of squares of the difference between the measured and expected distributions an estimate of γ can be calculated by using the following function (Hagring, 1996):

$$\gamma = \frac{\Sigma_i\{1-H(t_i)\}e^{-\lambda\Delta_i}}{\Sigma_i e^{-2\lambda\Delta_i}} \quad (19)$$

where, $H(t_i)$ is the measured cumulative distribution.

d) Satisfying the condition that the mean headway must be equal to the reciprocal of the flow, proportion of free vehicles α can be calculated by solving the following equality (Çalışkanelli and Tanyel, 2010):

$$\alpha e^{-\alpha} = \gamma e^{-\lambda/q} \quad (20)$$

e) After the proportion of free vehicles is obtained, shape parameter (Δ) can be calculated by using:

$$\bar{t} = \Delta + \frac{\alpha}{\lambda} \quad (21)$$

where, $\bar{t}$ is the mean of observed headways.

Observations show that "Δ" parameter varies between 0.5 sec and 2.5 sec (Akçelik and Chung, 1994). The headway values under 1.0 sec are mostly observed at intersections or roadways where there is more than one lane and the value is observed between vehicles at different lanes (Hagring, 1996b). If observations are made at a single lane "Δ" values mostly change between 1.5 sec and 2.0 sec (Çalışkanelli and Tanyel, 2010). In this research, "Δ" varies between 1.0 sec and 4.0 sec in inner lanes, 1.0 sec and 3.0 sec in middle lanes and 0.5 sec. and 2.5 sec in outer lanes.

Proportion of free vehicles, α is one of the parameters which give information about the differences in traffic characteristics. Tanner (1962) has defined "α" as:

$$\alpha = 1-\Delta.q \quad (22)$$

Plank (1982) states that Tanner's formula may underestimate the proportion of free vehicles for low flow rates in the major flow and can overestimate for higher major flow rates. Various researchers have suggested different models for prediction of "α" (Tanner, 1962; Troutbeck, 1989; Sullivan and Troutbeck, 1997; Akçelik and Chung, 1994; Akçelik, 1998, 2003; Plank, 1982; Tanyel and Yayla, 2003; Çalışkanelli and Tanyel, 2010).

The authors categorize the lane types of ring roads and suggest an appropriate "α" model for each lane in this paper. For this purpose two different approaches are defined in the literature: (a) models which relate α only with the major flow rate, q. (b) models which relate α with $q\Delta$. In this study, approach (b) is preferred since calculated Δ values may give an idea of the capacity of each lane. Sullivan & Troutbeck (1994) explains the background to approach (a) as follows:

"The distribution of larger headways will be unchanged if the shape parameter λ and the term α. exp(λΔ) remains constant. Using the same value for λ, a number of sets of values of α and Δ can then be used so that α. exp(λΔ) has the same value. It's then convenient to set Δ to some constant value Δ_c and to use an appropriate α_c value so that α_c exp(λ. Δ_c) remains the same. With choosing a Δ_c value, the cumulative density function will not be affected for the larger headway values. Setting the tracking headway to Δ_c, the proportion of free vehicles at each site can be compared to determine changes in the flow characteristics at each site."

By this way values for the proportion of free vehicles, α can be compared at different flow rates and different locations. As a result decay constant, λ becomes a function of flow rate, q and α (Sullivan and Troutbeck, 1994). This approach was tested for the observed data sets however, no significant results could be obtained. Therefore, models which depend on the relation between α and Δq are investigated.

Although there are some studies which assume approach (a) for prediction of "α" (Sullivan and Troutbeck, 1997), researchers like Plank (1992), Akçelik (2003), Akçelik and Chung (1994) prefer approach (b) in their studies. Çalışkanelli and Tanyel (2010) have examined both approaches and have found out that approach (b) gives better results. They have also investigated the usage of Akçelik (2003) function for each lane which can be written as:

$$\alpha = \frac{1-\Delta q}{(1-(1-k_d)\Delta q} \quad subject\ to\ \alpha \geq 0.001 \tag{23}$$

In Eq. (23), k_d is defined as the traffic delay/bunching parameter which can be used for different traffic analysis like speed-flow relationships and travel time functions (Akçelik, 2003).

In Akçelik's function, intrabunch headway is treated as the average headway at capacity ($\Delta = 1/q$, where q is in veh/sec). Although selecting Δ on the basis of the best headway distribution prediction is still an important objective, Δ should be treated as the average headway at capacity flow.

Initially, regression analysis was performed for each lane between Δq (independent variable) and "α" (dependent variable) in this research. The results are shown in Figs. 5, 6 and 7.

The derived equations from Figs. 5, 6 and 7 are listed below:

$$\alpha_L = 1.08 - 1.05\Delta q \quad R^2 = 0.78 \tag{24}$$

$$\alpha_M = 1.28 - 1.23\Delta q \quad R^2 = 0.85 \tag{25}$$

$$\alpha_R = 1.15 - 1.06\Delta q \quad R^2 = 0.89 \tag{26}$$

where, α_L, α_M and α_R are proportion of free vehicles for each lane, respectively.

All three models are shown and compared in Fig. 8 with respect to traffic flow rate, q. It is clear that, for low and moderate traffic flows, proportion of free vehicles in the middle lane is greater than the other lanes. This may be a result of the fluctuations in the traffic flow caused by other vehicles passing from or to other lanes. "α" values for the inner lanes are also greater than the outer lanes and this may be a result of proportion of heavy vehicles since they occupy larger areas and gaps.

Following the regression analysis, applicability at Akçelik function is also examined. Çalışkanelli and Tanyel (2010) state that although Akçelik (2003) has suggested different values of k_d for different facilities (0.20 for uninterrupted flows and 2.20 for roundabouts), the α parameter may show different characteristics for different values of k_d. This may be assumed as an advantage of this model.

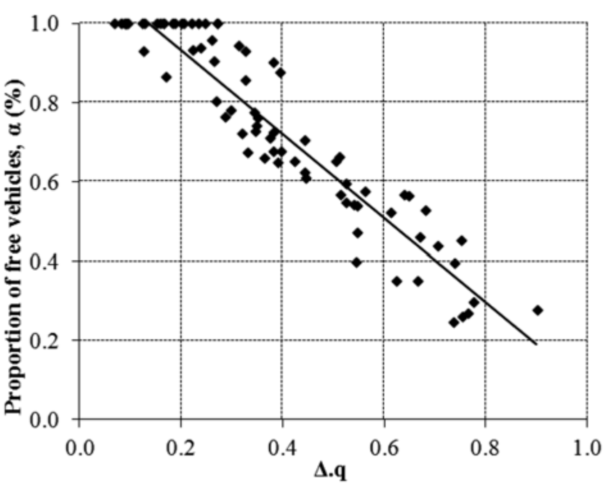

Fig. 5. Graphical Representation of Relation between $\Delta.q$ and α for Inner Lanes

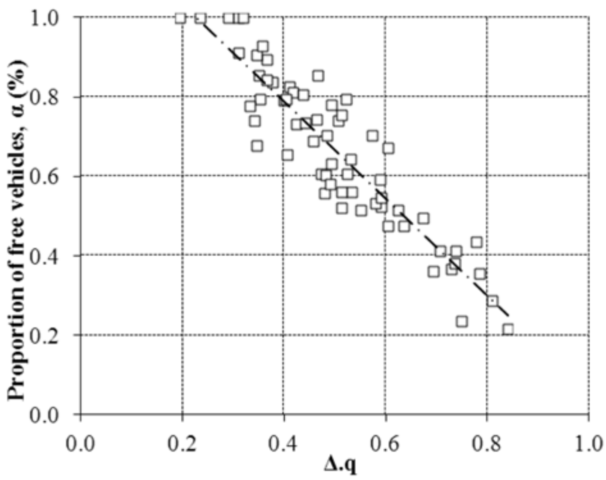

Fig. 6. Graphical Representation of Relation between $\Delta.q$ and α for Middle Lanes

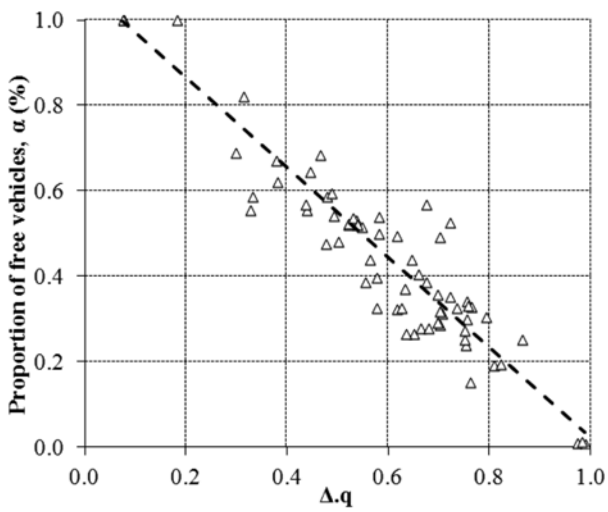

Fig. 7. Graphical Representation of Relation between $\Delta.q$ and α for Outer Lanes

By using Eq. (23), k_d values for inner, middle and outer lanes are found as 0.53, 0.49 and 0.85 respectively. "α" values which are computed by using k_d parameters defined above are shown in Fig. 9. Figure denotes that the proportion of free vehicles at middle lanes is higher than the proportion of vehicles at both inner and outer lanes at certain flow rate values. Thus, the results of middle and inner lanes are very close.

Due to the higher proportion of heavy vehicles which create larger gaps in inner lanes, α value increases. Furthermore, drivers who are cruising at high speeds in outer lanes tend to follow each other with small headways, and this causes a reduction in the proportion of unbunched vehicles. On the other hand, the results show that vehicles in the middle lane are affected by the vehicles which are changing lanes from either outer lane or inner lane.

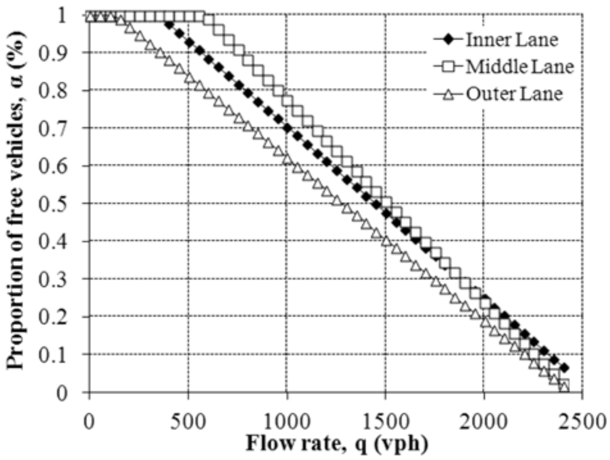

Fig. 8. Comparison of Models with respect to Traffic Flow Rate (vph)

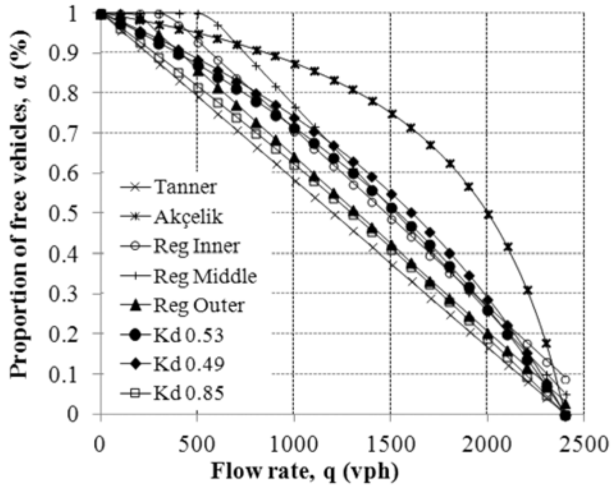

Fig. 10. Comparison of Models with Tanner and Akçelik Models

The drivers in the outer lane may choose to change their location or lane under some circumstances like:

- Motorists who are driving at much higher speeds may force them to move to the middle lane (in Turkey, most of the drivers tend to use the outer lane although it is not permitted to use the outer lanes for a long period.)
- They may choose to use the middle lane but for a short period while they may be passing a slower vehicle.
- They may exit the freeway from the next off-ramp so they may begin to move to the inner lane.

On the other hand, motorists on the inner lane may move to the middle lane if:

- The middle lane is their preference for travel.
- He/she is passing a slower vehicle in the inner lane.
- He/she wants to move to the outer lane.

In all those circumstances, it is clear that the motorists who prefer the middle lane can be defined as the most disturbed drivers in the road section. For this reason, motorists who prefer to travel in middle lanes may tend to choose different speeds in order not to slow down because of lane changing vehicles from different lanes.

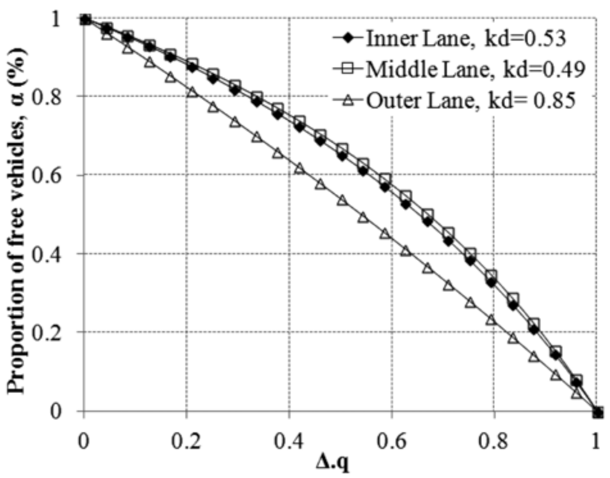

Fig. 9. Graphical Representation of Relation between $\Delta.q$ and α

Although the results given in Figs. 8 and 9 show some differences, especially for middle lanes, they provide useful information for engineers which will design uninterrupted facilities. Both functions for outer lanes give very close results to Tanner's equation. This indicates that, vehicles in outer lanes may assume to arrive at the observation points randomly. However, the same result cannot be defined for middle and inner lanes. It is clear that both lanes are affected by other vehicles which change lanes. This also explains the difference of constants from "1" for outer lanes.

In Fig. 10, suggested models are compared with Tanner and Akçelik models. In the figure, Reg_{inner}, Reg_{middle} and Reg_{outer} shows the regression functions for each lane and Kd 0.53, Kd 0.49 and Kd 0.85 represent the k_d values used in Akçelik's function for inner, middle and outer lanes, respectively.

Figure 10 indicates that, Akçelik function when k_d parameter is chosen as 0.20, give much higher results than other models. Generally, all other models give close results although they may show some small differences. Tanner's function provides a lower limit for uninterrupted flow models. All other models give higher values than Tanner's function.

5. Conclusions

In this study, the authors model the vehicle time headways at the ring roads in İzmir, Turkey and discuss the differences between lanes caused by driver behaviors. The research reveals the following results:

- Lognormal distribution is found to be an effective tool to define headways. However, its applicability is a concern.
- Traffic flow in the middle lane is highly affected by the vehicles in the other lanes. To have a better understanding of drivers' behavior in the middle lane, speed characteristics at different lanes and lane changing attitudes should be investi-

gated in future studies.

- Vehicles in the outer lane can be assumed to arrive randomly but they are also disturbed by vehicles in other lanes. These results should be evaluated in capacity and performance analysis of freeway segments, ramp junctions and weaving areas.
- Although heavy vehicle effect has not been taken into account in this study, its presence is visible especially in the results obtained for the inner lanes. This effect will be investigated in our future project.
- Proportion of free vehicles in different lanes is found to give rather close values especially for high traffic volumes but they should be considered separately for more precise results.

References

Akçelik, R. (1998). "Roundabouts: Capacity and performance analysis." *ARRB Research Report, ARR 321,* Vermont, Australia.

Akçelik, R. (2003). "Speed-flow and bunching relationships for interrupted flows." *Proceedings of 25th Conference of Australian Institute of Transportation Research (CAITR 2003)*, 3-5 December, University of South Australia, Adelaide, Australia.

Akçelik, R. (2006). *Speed-flow and bunching models for uninterrupted flows*, Transportation Research Board 5th International Symposium on Highway Capacity and Quality of Service, July 2006, Yokohama, Japan.

Akçelik, R. and Chung, E. (1994). "Calibration of the bunched exponential distribution of arrival headways." *Road and Transport Research*, Vol. 3, No. 1, pp. 42-59.

Al-Ghamdi, A. S. (2001). "Analysis of time headways on urban roads: Case study from Riyadh." *Journal of Transportation Engineering,* Vol. 127, No. 4, pp. 289-294.

Archilla, A. R. and Morrall, J. F. (1996). "Traffic characteristics on two-lane highway downgrades." *Transportation Research Part A: Policy and Practice*, Vol. 30 A, No. 2, pp. 119-133.

Aydın, D. (2007). *Predicting the effect of İzmir ring road on traffic flow at Altınyol*, MSc Thesis, Dokuz Eylül University Graduate School of Natural and Applied Sciences, İzmir.

Braston D. (1976). "Models of single lane time headway distributions." *Transportation Science*, Vol. 10, No. 2, pp. 125-148.

Breiman, L., Lawrence, R., Goodwin, D. and Bailey, B. (1977). "The statistical properties of freeway traffic." *Transportation Research Part A,* Vol. 11, No. 4, pp. 221-228.

Buckley, D. J. (1968). "A semi-Poisson model of traffic flow." *Transportation Science*, Vol. 2, No. 2, pp. 107-133.

Bunker, J. M. (1996). *Microscopic modelling of freeway operations*, PhD Thesis, Queensland University of Technology, School of Civil Engineering, Brisbane, Australia.

Chen, J. and Gupta, J. (1997). "Estimation of shift parameter of headway distributions using cross correlation function method." *IEEE conference on Intelligent Transport Systems*, pp. 741-746.

Cowan, R. C. (1975). "Useful headway models." *Transportation Research,* Vol. 9, No. 6, pp. 371-375.

Çalışkanelli, S. P. and Tanyel, S. (2010). "Investigation of vehicle bunching at signalized arterials in Turkey." *Canadian Journal of Civil Engineering,* Vol. 37, No. 3, pp. 380-388.

Çalışkanelli, S. P., Özuysal, M., Tanyel, S., and Yayla, N. (2009). "Comparison of different capacity models for traffic circles." *Transport,* Vol. 24, No. 4, pp. 257-264.

Dawson, R. F. and Chimini, L. A. (1968). "The hyperlang probability distribution - A generalized traffic headway model." *Characteristics of Traffic Flow*, Highway Research Board, pp. 1-14.

Dell'orco, M., Çelikoğlu, H. B., and Gürcanlı, G. E. (2009). "Evaluation of traffic pollution through a dynamic link loading model." *International Symposium on Environmental Science and Technology,* 2-5 June, Shanghai, China.

Griffiths, J. D. and Hunt, J. G. (1991). "Vehicle headways in urban areas." *Traffic Engineering and Control,* Vol. 32, No. 10, pp. 458-462.

Günay, B. (2004). "An investigation of lane utilisation on Turkish highways." *ICE Journal of Transport*, Vol. 157, No. 1, pp. 43-49.

Hagring O. (1996). "The use of the Cowan M3 distribution for modelling roundabout flow." *Traffic Engineering & Control*, Vol. 37, No. 5, pp. 328-332.

Hagring, O. (1998). *Vehicle-vehicle interactions at roundabouts and their implications for the entry capacity,* Lund Institute of Technology, Sweden.

Hagring, O. (2002). "Estimation of parameters in distribution of headways in roundabouts." *Journal of Transportation Engineering*, Vol. 128, No. 5, pp. 403-411.

Hoogendoorn, S. P., Bovy, P. H. L., and Van der Zijpp, N. P. (1997). *Co-ordinated traffic control in freeway corridors: A proposed evaluation approach, Faculteit der Civiele Techniek*, Vakgroep Infrastructuur, Sectie Verkeerskunde, TU Delft.

Luttinen, R. T. (1992). "Statistical properties of vehicle time headways." *Highway Capacity and Traffic Flow*, Transportation Research Board, pp. 92-98.

Luttinen, R. T. (1994). "Identification and estimation of headway distributions." *Second International Symposium on Highway Capacity,* Australian Road Research Board, Transportation Research Board, pp. 427-446.

Luttinen, R. T. (1996). "Statistical analysis of vehicle time headways." *Teknillien korkeakoulu, Liikennetekniikka*: Julkaisu 87, Otaniemi, Finland.

Luttinen, R. T. (1999). "Properties of Cowan M3 headway distribution." *Transportation Research Board 1999 Annual Meeting Preprints*, TRB, Washington, D.C.

Luttinen, R. T. (2003). "Capacity of unsignalized intersections." *TL Research Report*, No.3, TL Consulting Engineers, Lahti, Finland.

Luttinen, R. T. (2004). "Capacity and level of service at Finnish unsignalized intersections." *Finnish Road Administration Finnra Reports*.

May, A. D. (1965). "Gap availability studies" *Traffic Flow Characteristics 1963 and 1964,* Highway Research Board, pp. 101-136.

May, A. D. (1990). *Traffic flow fundamentals*, Prentice-Hall, Inc., Englewood Cliffs, N.J.

Murat, Y. Ş. and Gedizlioğlu, E. (2007). "Investigation of vehicle time headways in Turkey." *Transport Journal,* Vol. 160, No. 2, pp. 73-78.

Nehir, Y. (2009). *A study on the effective usage of bus stops in İzmir*, MSc Thesis, Dokuz Eylül University Graduate School of Natural and Applied Sciences, İzmir.

Öğüt, K. S. (2004). "Toll plazas at bosphorus bridge." *ACE 2004, Sixth International Congress in Civil Engineering*, İstanbul, pp. 1759-1768.

Öğüt, K. S. and Ergün, M. (2006). "Modelling bosphorus bridge crossing with spectral analysis." *ACE2006, Seventh International Congress* *in Civil Engineering*, pp. 407, İstanbul.

Plank, A. W. (1982). "The capacity of a priority intersection - Two approaches." *Traffic Engineering and Control,* Vol. 23, No. 2, pp. 88-92.

Sullivan, D. P. and Troutbeck, R. J. (1994). "The use of Cowan's M3 distribution for modeling urban traffic flow." *Traffic Engineering & Control,* Vol. 35, No. 7/8, pp. 445-450.

Sullivan, D. P. and Troutbeck, R. J. (1997). "An exponential relationship for the proportion of free vehicles on arterial roads." *Transportation Research Part A, Policy and Practice*, Vol. 31, No. 1, pp. 21-33.

Summala, H. and Vierimaa, J. (1980). *Vehicle speeds, speed differences and headways at 10 locations in autumn 1978: Analyses of driver behavior*, Finnish National Board of Public Roads and Waterways, Helsinki (in Finnish).

Şahin, İ. (2009). "Some observed features of freeway traffic oscillations." *Transportation Research Record,* 2124, pp. 186-193.

Şahin, İ. and Akyıldız, G. (2005). "Bosporus Bridge toll plaza in İstanbul, Turkey-Upstream and downstream traffic features." *Transportation Research Record*, 1910, pp. 99-107.

Şahin, İ. and Altun, İ. (2008). "Empirical study of behavioral theory of traffic flow: Analysis of recurrent bottleneck." *87th Annual Meeting of the Transportation Research Board Proceedings*, January 13-17, Washington, D.C.

Tanner, J. C. (1962). "A theoretical analysis of delays at an uncontrolled intersection." *Biometrika,* Vol. 49, Nos. 1-2, pp. 163-170.

Tanyel, S. and Yayla, N. (2003). "A discussion on the parameters of Cowan M3 distribution for Turkey." *Transportation Research Part A,* Vol. 37, No. 2, pp. 129-143.

Troutbeck, R. J. (1989). *Evaluating the performance of a roundabout*, Special Report SR 45. ARRB Transport Research Ltd., Vermont South, Australia.

Troutbeck, R. J. (1997). "A review on the process to estimate the Cowan M3 headway distribution parameters." *Traffic Engineering & Control,* Vol. 38, No. 11, pp. 600-603.

Wasielewski, P. (1974). "An integral equation for the semi-Poisson headway distribution model." *Transportation Science*, Vol. 8, No. 3, pp. 237-247.

Wasielewski, P. (1979). "Car-following headways on freeways interpreted by the semi-Poisson headway distribution." *Transportation Science*, Vol. 13, No. 1, pp. 36-55.

Wasielewski, P. (1981). "The effect of car size on headways in freely flowing freeway traffic." *Transportation Science*, Vol. 15, No. 4, pp. 364-378.

Winkler, M. and Fan, W. D. (2011) "Evaluating impacts on freeway capacity using VISSIM: Accounting for truck lane restrictions, driver behavior, and interchange density." *Advances in Transportation Studies,* Section A 25, pp.15-28.

Zwahlen, H. T., Öner, E., and Suravaram, K. (2007). "Approximated headway distributions of free-flowing traffic on Ohio freeways for work zone traffic simulations." *Transportation Research Record,* 1999, pp. 131-140.