Proceedings of the Eastern Asia Society for Transportation Studies, Vol. 5, pp. 739 - 749, 2005

THE MARGINAL DECREASE OF LANE CAPACITY WITH THE NUMBER OF LANES ON HIGHWAY

Xiaobao YANG
Student of PhD
School of Economic and Management
Beihang University
Xueyuan Poad 37, Haidian District, Beijing, 100083 China
Fax: +86-01-82028037
E-mail: baoyang0108@tom.com

Ning ZHANG
Professor
School of Economic and Management
Beihang University
Xueyuan Road 37, Haidian District, Beijing, 100083 China
Fax: +86-01-82028037
E-mail: nzhang@buaa.edu.cn

Abstract: This paper attempts to investigate the impact of the number of lanes on highway capacity. Methodologically, we provide a better understanding of the relationship between highway capacity and its number of lanes upon the statistical analysis of the survey. We employ the variance analysis of single factor for modeling the effect of the number of lanes on capacity. The findings show that average capacity per lane decreases with increasing number of lanes on uninterrupted highway segments. The analysis is based on an extensive field survey of traffic flow in Beijing. The implication of the marginal decrease of lane capacity requires that the manuals of highway capacity should be revised for the better plan and design of road network. In addition, the factor of marginal decrease should be incorporated into the decision on adding lanes or constructing a new parallel road when travel demand exceeds road capacity.

Key Words: Highway capacity, Number of lanes, Marginal decrease

1. INTRODUCTION

The design of highway capacity is extremely concerned with the number of lanes. The classical assumption defines that highway capacity is positively proportioned to the number of lanes. Moreover, most of engineering manual of traffic design assumes that average capacity per lane on different highways is equal. However, we find that average capacity per lane decreases with increasing number of lanes through empirical research.

The determination of highway capacity is one of the most important applications of any traffic theory (Kerner, 2004). Many of Transportation Research Boards made significant progress in investigating highway capacity. Some previous theories and empirical researches focused on the interrelationships among the contemporaneous influences of capacity, traffic features, geometric elements, environmental conditions and temporal weather factors on interrupted highway (see for example, Hoban, 1987; Iwasaki, 1991; Ibrahim, A.T. *et al.*, 1994; Shankar, V *et al.*, 1998). Other studies paid much attention to the relationships between speed, density, and capacity on uninterrupted highway. The American Highway Capacity Manual (1994) considered that highway capacity increases with increasing free-speed. These researches of highway capacity are seldom involved into the comparison of lane capacities on highways with different number of lanes. For instance, the manuals of highway capacity in many countries prescribe that average capacity per lane on different highways is equal. They assume that highway capacity is constantly proportioned to its number of lanes. Such as in Japan and

China, their manuals prescribe that average capacity per lane on uninterrupted multilane highway is 2200 PCU (Passenger Car Units), regardless of the number of lanes. However, the increase of lane number incurs some changes of cars' interaction and drivers' behavior. It may lead to the inequality of average capacity per lane on highways with different number of lanes. Based on field survey in Beijing, we find that average capacity per lane on highway with two, three and four lanes is 2104, 1973 and 1848 PCU, respectively. It implies a marginal decrease of average capacity per lane with increasing number of lanes on highway.

The statistical test is used to investigate the impact of the number of lanes on highway capacity. We firstly prove that highway capacity is not constantly proportioned to its number of lanes through empirical method. Then, the variance analysis of single factor and *t*-test are applied to test the inequality. Finally, we find the marginal decrease rate of average capacity per lane with increasing number of lanes is around 6.7%. It is important to recognize that this discussion is based on data from only three highways, in one location every highway. Despite this limitation, it is likely that some useful insights can be gained.

This paper begins by providing an overview of the modeling approach and test technique. The next section gives descriptions of the data-collection and the presentation of model-test results. This is followed by the analyses of the differences of traffic characteristics on different highways and possible explanations. Finally, conclusions and recommendations are drawn.

2. MODELING APPROACH

A statistical test model is developed to analyze the relationship between highway capacity and its number of lanes on multilane highway. In the past, average capacity per lane on different highways is considered as equal in many countries' manuals. However, we can suggest average capacity per lane on different highways have some difference. The appropriate procedure for testing the equality of several means is the variance analysis. We apply the variance analysis of single factor to model the effect of the number of lanes on highway capacity. Let c_{ij} be the j-th observation of average capacity per lane on i-lane highway. Then, the linear statistical model of average capacity per lane on different highways can be written as:

$$c_{ij} = c + \tau_i + \varepsilon_{ij} \qquad \begin{cases} i = 1, 2, 3, \cdots, m \\ j = 1, 2, 3, \cdots, n \end{cases} . \tag{1}$$

Where c is a parameter common to all treatments called the overall mean of lane capacity on different highways, τ_i is a parameter unique to the i-th treatment called the i-th treatment effect, that is, the random effect on i-lane highway, and ξ_{ij} is a random error component.

Our objectives will be to test appropriate hypotheses about the average capacity per lane on different highways. For hypothesis testing, the model errors are assumed to be normally and independently distributed random variables with mean zero and variance σ^2. The variance σ^2 is assumed to be constant for all levels of the factor. Let c_i be average capacity per lane on

i-lane highway, and $c_i = c + \tau_i$, i=1, 2, 3…, m. Thus, the mean on i-lane highway consists of the overall mean plus the random effect on i-lane highway. The null hypothesis and alternative hypothesis can be expressed as:

$$H_0 : c_2 = c_3 = c_4 = c$$

$$H_1 : c_i \neq c_j, \quad \forall i, j \text{, and } j \neq i. \tag{2}$$

Note that if H_0 is true, average capacity per lane on different highways have a common mean c.

The null hypothesis assumes that highway capacity is proportioned constantly to its number of lanes. That is to say, average capacities per lane on highways with different number of lanes have no difference ($c_2 = c_3 = c_4 = c$). Then, the variance analysis of single factor is applied to test the null hypothesis. Finally, we use the one-sided t-test of independent samples to test the decrease of c_2 and c_3, c_3 and c_4. In these problems, we wish to reject H_0 only if one mean is larger than the other. Thus, their null hypotheses and alternative hypotheses can be written as:

$$H_0 : c_2 = c_3, \quad H_1 : c_2 > c_3; \tag{3}$$

and $$H_0 : c_3 = c_4, \quad H_1 : c_3 > c_4. \tag{4}$$

If both of null hypotheses are not true, there exists a gradual decrease of c_2, c_3 and c_4.

3. EMPIRCAL SETTING

3.1 Field Capacity Survey

The survey areas are urban locations in the north of Beijing in China. After panel observations, we finally choose three types of divided and uninterrupted highway sections respectively which have two, three and four lanes to collect data. Capacities on these highways are little interrupted by other factors except the number of lanes.

Table 1 summarizes the conditions of the field highway capacity survey in the summer and fall of 2004. From Table 1, geometric characteristics on different highway sections can be obtained. The lane width, lateral clearance, and design speed, etc is consistent on three highway sections. The horizontal curvature is less than 2%, and the gradient is less than 1%. The entrance, exit or curvature is over one kilometer from each surveyed location. Therefore, geometric characteristics have little influence upon highway capacity. Furthermore, Weather conditions on our surveyed dates are clear and wind speed is not more than 3 mph. It is shown that weather conditions can not influence capacity on surveyed highways. Finally, all of the surveyed jobs are chosen on workday from 7.00 a.m. to10.00 a.m. The activity types of travelers are mostly work and go-to-work.

Table 1.Summary of the Field Capacity Survey

Objective	to collect data on the capacities of three highway sections and to explore the relationship between highway capacity and the number of lanes			
Common characteristics of highway sections	a) lane width: 3.75 m, lateral clearance: 1.85m, paved shoulders: 0.75m b) sight distance: >500m (no restriction on overtaking) c) horizontal curvature: <2%, gradient: <1% d) design speed: 100km/h e) road surface: good condition			
Different characteristics of highway sections		northbound	southbound	
	2-lane	an entrance, 1.1 km away	an exit, 1.3 km away	
	3-lane	an entrance, 1.3 km away	a curvature, 1.1 km away	
	4-lane	an entrance, 1.3 km away (west)	an exit, 1.2 km away (east)	
Date and time	date: (workday) a) 2-lanes: Sept 9, Sept 10, Sept 14, Sept 17, Sept 21, Sept 22 of 2004 b) 3-lanes: May 12, May 14, May 17, Aug 11, Aug 13, Oct 20 0f 2004 c) 4-lanes: May 10, July 19, Sept 6, Sept 13, Sept 27, Oct 8 0f 2004			
	time: 7.00 a.m. – 10.00 a.m. on each day			
Number of samples	six (each surveyed highway section)			
Weather	conditions: clear, wind: ≤ 3mph			
Composition of vehicle		passenger car	medium vehicle	heavy vehicle
	2-lane	97.09%	2.91%	0%
	3-lane	96.16%	3.75%	0.09%
	4-lane	96.97%	2.98%	0.06%

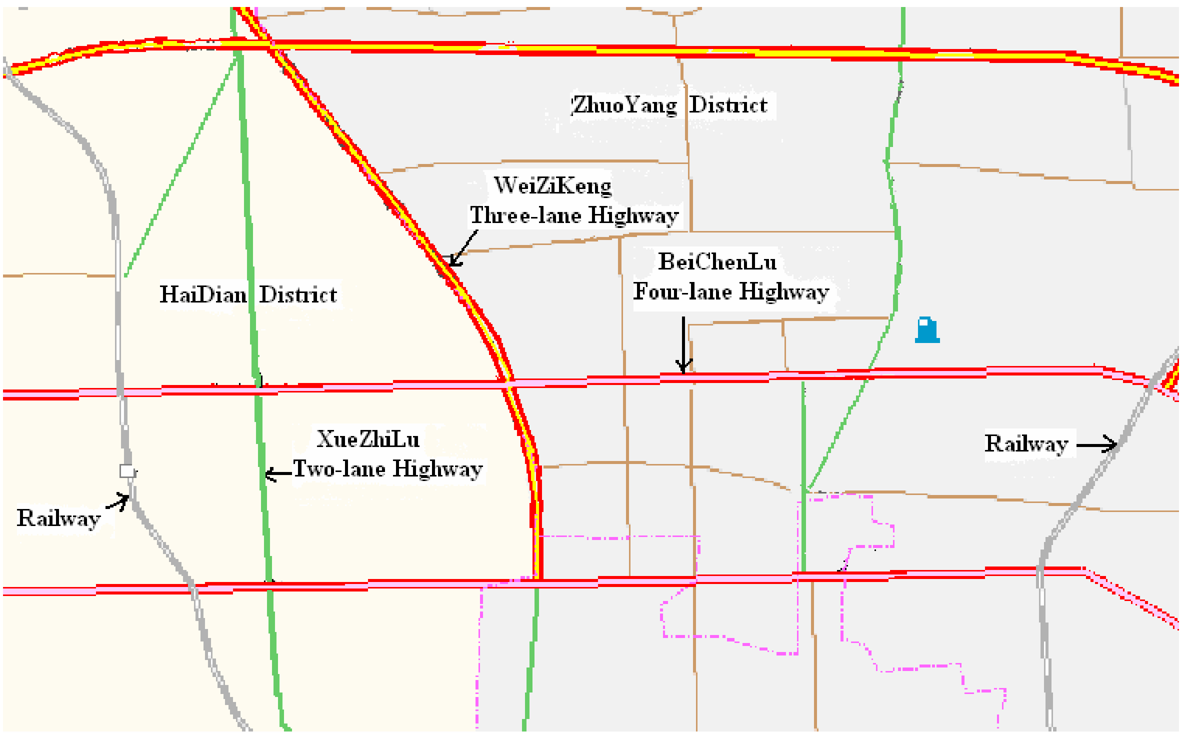

Figure 1.Three Highways and Observation Stations

To test the relationship between highway capacity and the number of lanes in these locations, the data were collected using the Panasonic digital video camera with a precision of 1/25th per second. XueZhiLu, WeiZiKeng and BeiChenLu are the highway segments with two-lane, three-lane, and four-lane highways respectively. Figure 1 shows the locations where the measurements were taken. The junctions of these three highways are cloverleaf. Figure 2 gives three pictures of surveyed highway sections. Data on spot flows, speeds, densities and vehicle classifications by lane were collected in the summer and fall of 2004 in one direction over 15 minutes categorized into a group.

Figure 2.Three Pictures of Surveyed Highway Sections

Classification of vehicle types was based on three vehicle-length classes of up to less than 5, 5 to 8, and more than 8 m. All vehicles are classified into passenger car, medium vehicle and heavy vehicle and their passenger car equivalents are 1.0, 1.5 and 2.0, respectively. The detailed vehicle classification for highway capacity analysis is shown in Table 2.

Table 2.The Vehicle Classification for Highway Capacity Analysis

Labels of vehicle-type	description of the vehicle classification	length of vehicle (m)
Passenger car	mini-buses, jeeps, vans, passenger cars, light vehicles, and microbuses(<12 p), etc.	<5
Medium vehicle	medium bus(12-25 p), trucks(2.5-7 t), etc.	5-8
Large vehicle	large trucks(>7 t) large buses(>25 p), trailers, heavy vehicles, and container-vehicles, etc.	>8

On the basis of Table1, the percentages of vehicle type can be obtained. The percentage of medium vehicles on each highway is lower than 4% and the differences of them are less than 1%. Meanwhile, the percentage of heavy vehicles is very small, less than 0.1% on each highway. It implies that the differences to the percentages of each vehicle type on different highways are indifferent. The Passenger Car Equivalents might give birth to little error of highway capacity.

3.2 Average Capacity per Lane on Highways

The American HCM (Highway Capacity Manual, 1994) defines highway capacity as: “The maximum sustained 15-minute rate of flow which can be accommodated by a uniform highway segment under prevailing and roadway conditions in the specified direction of interest (Smith, W. S. *et al.*, 1996)”. Therefore, we use 15-minute flow rate to assess highway capacity.

Table 3.Summary of Average Capacity per Lane on Each Highway (PCU/ln/h)

Lane number *i*	observations							
	1	2	3	4	5	6	mean	STD
2	2129	2054	2094	2118	2081	2150	2104	34.83
3	1928	1938	1965	1995	2010	2002	1973	32.66
4	1876	1821	1860	1883	1805	1845	1848	30.79
Total							1975	112.06

The observations that we obtains on average capacity per lane on different-lane highways are shown in Table 3. We can see that the means of observations on different highways are significantly different. The means of observations on different highways are 2104, 1973, 1848, respectively. They are gradually decreasing with increasing number of lanes. Meanwhile, the standard deviations on different highways undergo a little change, varying from 30.79 to 34.83. However, the standard deviation of overall observations is as nearly 3.5 times as that of each highway. The mean of overall observations on highways is 1975, nearly equal to that of three-lane highway, less than the mean of two-lane highway and more than that of four-lane highway.

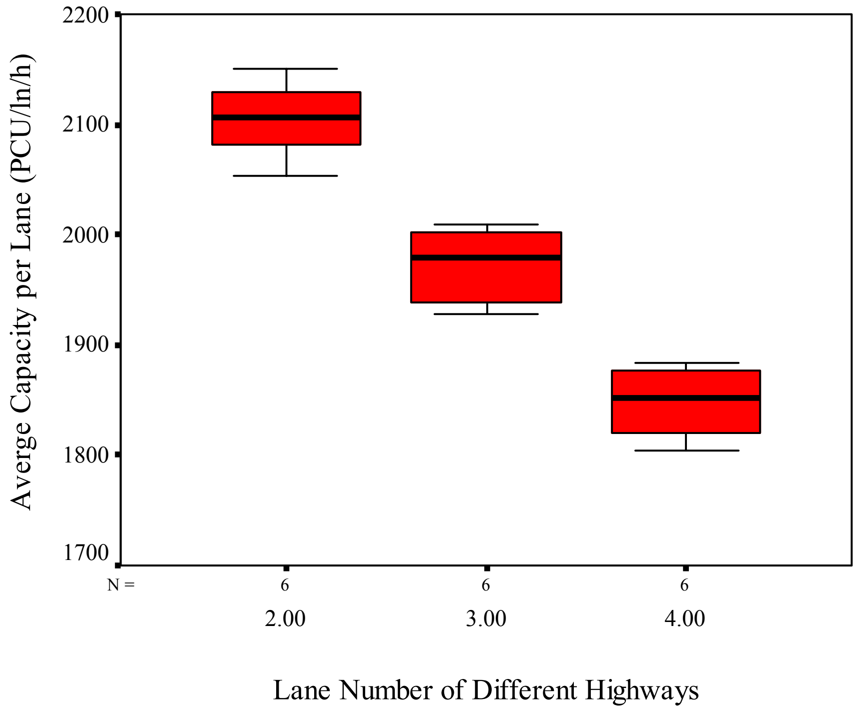

Figure 3.Box Plots of Average Capacity per Lane versus Different Highways

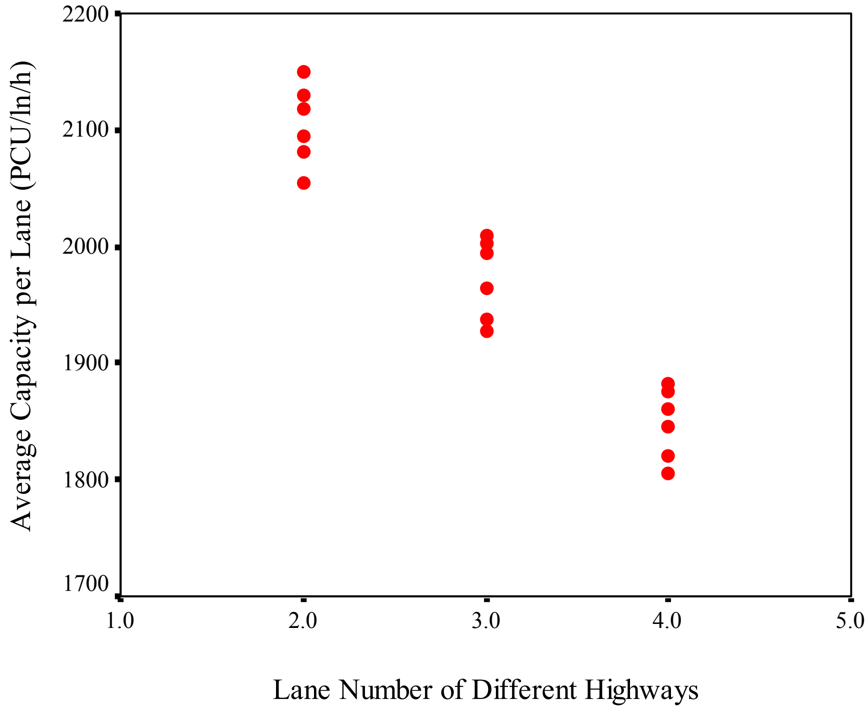

Figure 4.Scatter Diagram for Average Capacity per Lane versus Different Highways

It is always a good idea to examine survey data graphically. Figure 3 presents box plots for average capacity per lane on different highways, and Figure 4 is a scatter diagram of average capacity per lane versus different highways. In Figure 4, the solid dots are the individual observations. Both graphs indicate that average capacity per lane decreases as lane number increases. Based on this simple graphical analysis, we strongly suggest that average capacity per lane decrease with increasing number of lanes on highway.

3.3 Variance Analysis of Single Factor and *t*-test

In order to analysis more objectively the inequality of average capacity per lane on different highways, we use variance analysis of single factor and the *t*-test to test the effect. The variance analysis is summarized in Table 4. Note that the between-treatment mean square (98326.22) is many times larger than the within-treatment mean square (1120.84). Due to F=87.73>$F_{0.05,2,15}$=3.68, we reject H_0 and conclude that lane number significantly affects the average capacity per lane on highway. Then, we apply the one-sided *t*-test of independent samples to test the marginal decrease.

Table 4.The Result of Variance Analysis of Single Factor

Source of variation	sum of squares	degrees of free	mean square	*F*
Between treatments	196652.40	2	98326.22	87.73
Within treatments	16812.67	15	1120.84	
Total	213465.10	17		

Table 5.The Result of The Unilateral *t*-test of Independent Samples

Independent samples	degrees of free	the value of *t*-test	the threshold with the significance level 97.5%
c_2, c_3	10	6.55	2.23
c_3, c_4	10	6.59	2.23
c_2, c_4	10	13.49	2.23

Table 5 presents the result of the one-sided *t*-test of independent samples. The upper 2.5 percent point of the t distribution with n_1+n_2-2=6+6-2=10 degrees of freedom is $t_{0.025,10}$=2.23. Since the numerical values of *t*-test of c_2 and c_3, c_3 and c_4, c_2 and c_4, are 6.55, 6.59 and 13.49, respectively. Every of them are larger than the threshold 2.23 with the significance level 97.5%. We reject H_0 and conclude that the decrease of c_2, c_3 and c_4 is statistically significant. Thus, average capacity per lane decreases with increasing number of lanes on highway. We can easily calculate that the marginal decrease rate is about 6.7%.

4. THE DIFFERENCES OF TRAFFIC CHARACTERISTICS AND POSSIBLE EXPLANATIONS

4.1 Lane Capacity

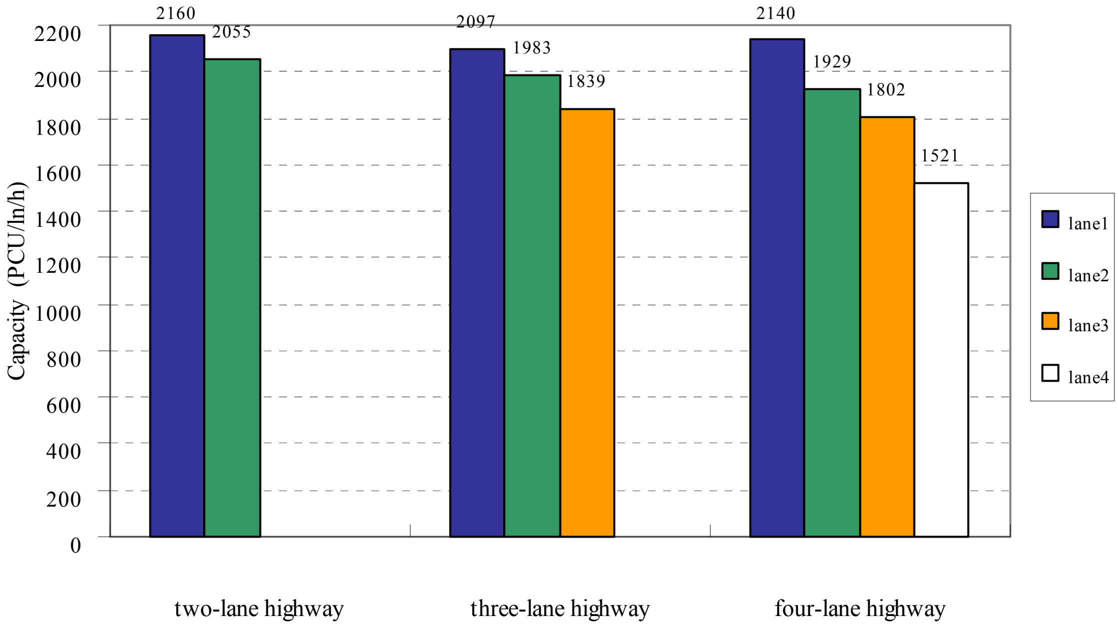

Figure 5.Lane Capacity on Three Highways

Figure 5 is given with the results of lane capacity on different highways. It can be seen that lane capacity decreases with the change of lane position from lane 1 to 4 on each highway, which is consistent with a common observation in many countries. This phenomenon should be attributed to the driving habits and speed limit of lanes on highway. The left lane is dedicated to a high-speed lane and right lane is a low-speed lane in vehicle right-way-forward countries, i.e. China.

The difference must be emphasized from the decreasing step of lane capacity from left to right lane on different highways. The lane capacity decreases about 100 PCU from left to right lane on two-lane highway and three-lane highway. On four-lane highway the lane capacity of lane 2 is less about 200 PCU than the one of lane 1. The lane capacity of lane 4 is less about 300 PCU than the one of lane 3.

4.2 Density at Capacity

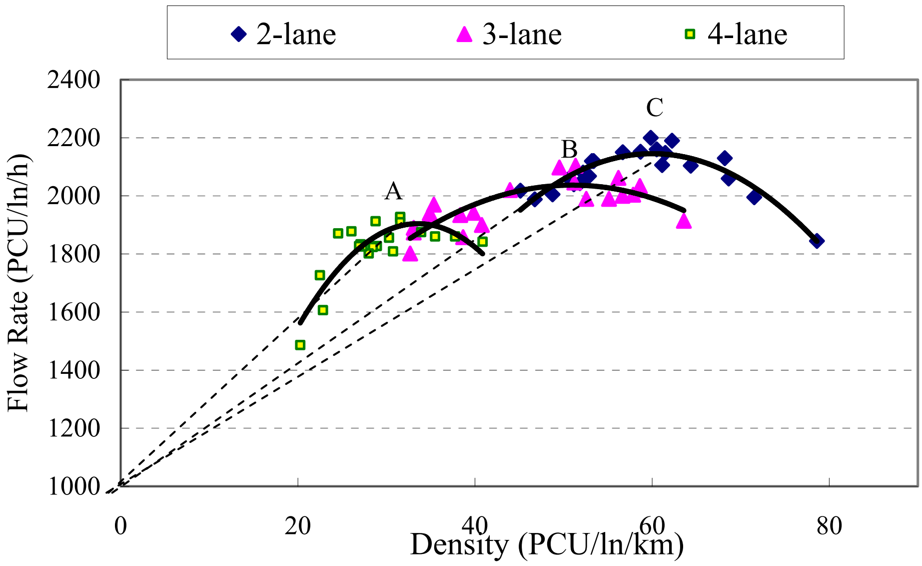

Figure 6.Density versus Capacity on Different Highways

In order to demonstrate the marginal decrease of lane capacity, we employ the density-flow relationship with 5-minute average flow, which is shown in figure 6. The peak flows on the density-flow curve are marked by the point A, B and C subsequently for four-lane, three-lane and two-lane highway respectively. Because that the density divides flow equals to the average speed, the speed at point A is greater than the one at point B whereas the speed at point B is greater than the one at point C. However, both the flow and density at point A are less than the ones at point B whereas both the flow and density at point B are less than the ones at point C. It implies that the more the number of lanes is, the stronger the vehicle interruption on the lane flow is even if the vehicle density is the same. Hence, the density-flow curve shifts up-right along with the decrease of lane number. It leads to the marginal decrease of lane capacity. It may be the effect of increasing interruption with increasing number of lanes on highways. The observed phenomena by video camera show that lane-changing frequencies increase with increasing number of lanes on highway.

4.3 The Standard Deviation of Speed at Capacity

As shown in the survey, the standard deviation of speed at its lane capacity increases with the increase of lane number for different highways. The standard deviation of speed can be referred as to the indicator of cars' interaction. The larger deviation of speed must lead to stronger cars' interaction. The increase of lane number on highways incurs increasing cars' interaction and hence the marginal decrease of lane capacity.

5. CONCLUSIONS AND RECOMMENDATIONS

Endogenous impact of the number of lanes on average capacity per lane of highway was found to be statistically significant. We surveyed three highway segments with the scenes of two, three and four lane cases. The conclusions show that average capacity per lane on highway is 2104, 1971 and 1848 PCU, respectively. It is obvious that there exists a marginal decrease of average capacity per lane with increasing lane number. Through analysing the differences of traffic characteristics on different highways, we explored possible explanations of the decrease. It may be the effect of increasing lane-changing opportunities and cars' interaction with increasing lanes' number on highway.

Although these conclusions are based on the observations in China, we think they may be applicable to many other countries. The increase of lane number should bring about the changes of cars' interaction and drivers' behavior, which would finally result in the difference of average capacity per lane on highway.

The conclusion of the marginal decrease modifies the assumption that average capacity per lane is equal on highways with different number of lanes proposed by many countries' HCM (highway Capacity Manual). It requires that the manuals of highway capacity should be revised for the better plan and design of road network. We can not ignore the impact of lane number on lane capacity in future road network plan and design. In addition, we should consider the factor of the marginal decrease of average capacity per lane in the decision on adding lanes or constructing a new parallel road when travel demand exceeds road capacity.

Some future extensions of research work are suggested. Through collecting more samples, the method of orthogonal designs should be used to analysis the marginal decrease of average capacity per lane with increasing number of lanes on highway. We can find other factors of affecting capacity and the accuracy of the conclusions will be enhanced. The rational explanations of the marginal decrease and the behavioral distinctions of different-lane highways should be more completely explored. The road network plan and design problems with the impact of the marginal decrease of average capacity per lane should also be further researched.

ACKNOWLEDGEMENTS

The work described in this paper was supported by the National Natural Science Foundation of China (70131160744) and the Doctorial Research Foundation of Education Bureau of China (20010006003) to the Beihang University.

REFERENCES

Del Castillo, J.M. and Benitez, F.G. (1995) On the functional form of the speed-density relationship-I: general theory, **Transportation Research, 29B,** 373-389.

Del Castillo, J.M. and Benitez, F.G. (1995) On the functional form of the speed-density relationship-II: empirical investigation, **Transportation Research, 29B,** 391-406.

Hoban, C.J. (1987) **Evaluating traffic capacity and improvements to road geometry.** World Bank, Washington, DC.

Guo, J.F., Quan, Y.S., Zheng, M. and Li, X. (2000) Study on the traffic flow of the expressway system in Beijing, **Urban Transport of China, 42,** 42-44.

Ibrahim, A.T. and Hall, F.L. (1994) Effect of adverse weather conditions on speed-flow-occupancy relationships, **Transportation Research Record 1457,** 184-191.

Iwasaki, M. (1991) Empirical analysis of congested traffic flow characteristics and free speed affected by geometric factors on an intercity expressway, **Transportation Research Record 1320,** 242-250.

Koshi, M., Nishinari, K., Takahashi, D. and Ishibashi, Y. (2002) Metastable flows in a two-lane traffic model equivalent to extended Burgers cellular automaton, **Physica A, 303,** 226-238.

Kerner, B.S. (2004) Three phase traffic theory and highway capacity, **Physica A, 333,** 379-440.

Kerner, B.S. and Rehborn, H. (1996) Experimental properties of complexity in traffic flow, **Physica E, 53,** R4275-R4278.

Lee, H.Y., Lee, H.W. and Kim, D. (2000) Traffic states of a model highway with on-ramp, **Physica A, 281,** 78-86.

Momtgomerey, .C. (1991) **Design and analysis of experiments.** John Wiley & Sons, NewYork.

Nagatani, T. (1997) Kinetic segregation in a multilane highway traffic flow, **Physica A, 237,** 67-74.

Rong, J., Liu, X. M. and Ren, F. T. (2000) Vehicle classification for expressway capacity analysis in China, **Fourth International Symposium on Highway Capacity,** Transportation Research Board, Hawaii, June 27-July 1, 2000.

Smith, W. S., Hall, F. L. and Montgomery, F.O. (1996) Comparing the speed-flow relationship for Motorways with new data from the M6, **Transportation Research 30A,** 89-101.

Shankar, V. and Manneriing, F. (1998) Modeling the Endogeneity of Lane-mean Speeds and Lane-speed Deviations: A Structural Equations Approach, **Transportation Research, 32A,** 311-322.

Wagner, P., Nagel, K. and Wolf, D.E. (1997) Realistic multi-lane traffic rules for cellular automata, **Physica A, 234,** 687-698.

Zhang, H.M. (2001) A note on highway capacity, **Transportation Research, 35B,** 929-937.