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Insight into driver behavior during overtaking maneuvers in disorderly traffic: An instrumented vehicle study

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Abstract

Weak lane discipline and high vehicle heterogeneity are the common characteristics on Indian roads. Overtaking maneuvers are common in non-lane based (disorderly) traffic conditions. A review of available literature shows how driver behavior during overtaking maneuvers is influenced by factors such as shoulder width, lane width, vehicle type and changes in the traffic scene. There are limited studies reported in the literature, which study on-road driver behavior during overtaking maneuvers. Different types of road may have different influence on driver behavior. Lateral gap, longitudinal distance, and relative speed play an important role during such maneuvers. The current study examines the relationship among lateral gap, longitudinal distance, and relative speed during overtaking on different types of roads. The selected roads differ in terms of number of lanes (four-lane and six-lane roads) and vehicle density. Also, the influence of road type on a driver during overtaking is studied. An instrumented vehicle is used for data collection. The vehicle will help to observe instantaneous driver behavior during overtaking. Similar relationship is observed on both the types of road when lateral gap and longitudinal distance are considered. Opposite relationship is observed on the two types of road when relationship between relative speed and lateral gap are considered. Similarly, different relationship is observed between relative speed and longitudinal distance when road type is taken into account. Lastly, different relative speed values are observed on the two types of road, indicating that type of road significantly influences the nature of overtaking maneuver.

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Keywords: Overtaking; Lateral gap; Longitudinal distance; Relative speed; Highway

1. Introduction

Several studies have been carried out to understand overtaking maneuvers on different types of roads and traffic conditions. The studies mainly focus on overtaking distance, overtaking time, influence of opposing traffic, traffic

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volume, type of overtaking maneuver adopted and acceleration-deceleration behavior during overtaking. During overtaking, longitudinal distance, lateral gap, relative speed and speed of the interacting vehicles play an essential role to undertake a safe maneuver. However, the literature on the relationship among these variables during such maneuver is sparse. There is no previous comprehensive comparison of field observation on overtaking maneuvers between different types of roads. The present study aims to get an empirical insight into these aspects of driver behavior during overtaking on different types of road.

2. Literature review

Overtaking maneuvers help the drivers to attain their desired speed. If such maneuvers are not allowed, it will lead to the formation of vehicle platoons, which in turn will reduce the level of service of that particular facility. Besides, it will also lead to an increase in fuel consumption and vehicle emissions. Several studies have focused on observing overtaking maneuvers on divided and undivided roads. The driver's desire to pass and the decision to accept or reject a particular gap are the two main factors that decide whether to undertake an overtaking maneuver (Farah et al., 2009; Farah and Toledo, 2010). The decision to pass also depends on the existing traffic volume and passing sight distance (Takemoto et al., 2009; Bella, 2011), type of overtaking maneuver driver wants to perform (Wilson and Best, 1982; Matson and Forbes, 1938) and waiting time for an opportunity to overtake (Pollatschek and Polus, 2005; Summala, 1980). Jenkins and Rilett (2005) classified overtaking maneuvers into different categories (accelerative and decelerative) based on the relative speed between the vehicles during the maneuver. Studies are conducted to understand the influence of lane marking, lane width and shoulder width on overtaking (Shackel and Parkin, 2014).

Overtaking maneuvers can occur anywhere on the road. Hence, field studies with the help of static data collection methods, such as videography (Polus et al., 2000; Llorca and Gracia, 2011; Hardwood et al., 2008) to collect data on such maneuvers become expensive and time-consuming. Driving simulators have become a reliable source of data collection for such maneuvers (Farah et al., 2009; Farah and Toledo, 2010; Bella, 2011). Simulators offer many advantages such as repeatability of scenarios, time efficient and ability to control variables. However, real traffic scenarios cannot be replicated inside the laboratory. Besides, it cannot be guaranteed that drivers will behave the same way in the simulator as they do on roads. Recently, instrumented vehicles are used to observe driver behavior through naturalistic driving experiments. In such type of data collection, drivers are asked to drive vehicles equipped with different sensors on various road sections. Many studies are conducted on driver behavior using data from the instrumented vehicle (Sultan et al., 2002; Ko et al., 2009, 2010; Papakostopoulos et al., 2015). However, not many studies on overtaking maneuvers are reported using data from an instrumented vehicle. Llorca and Farah (2016) carried out a comprehensive comparative study between two databases of overtaking maneuvers. The first database is obtained from a field study and the second database is obtained using a driving simulator. The results show similarities between overtaking time and overtaking distance of completed maneuvers. However, drivers pass faster in the driving simulator, keeping higher clearances. Gap acceptance decisions are also found to be similar, as the distributions of both accepted and rejected gaps are similar, although critical gaps are found to be lower in the driving simulator.

As already mentioned, a driver's decision to overtake not only depends on the driver's desire to undertake the overtaking maneuver but also, it is governed by gap available and traffic volume. During overtaking, longitudinal distance, lateral gap, relative speed, and driving speed play an important role for a safe maneuver. The relationship between these variables also depends on the type of road. Overtaking maneuvers frequently occur in weak lane disciplined traffic in an attempt to utilize the road space efficiently and to attain the desired speed. More frequently, overtaking occurs on highways. Highways can be either divided or undivided. Overtaking maneuvers on divided highways are comparatively easier than on undivided highways where vehicles have to take into account the on-coming vehicle in the opposing lane. Overtaking can also differ depending on the number of lanes on the highway. More the number of lanes on a divided road, lesser will be the interaction between overtaken and overtaking vehicles due to the presence of wider space to maneuver. Examination of the existing literature shows that there has been no previous comprehensive comparison of field observations during overtaking maneuvers on different types of road. Hence, in this study, an attempt is made to understand different aspects of overtaking on four-lane divided and six-lane divided highways in India.

3. Objectives

The primary goal of this study is to get an insight into driver behavior during overtaking on different types of roads using data from an instrumented vehicle. In this study, overtaking maneuvers are observed on four-lane divided and six-lane divided highways in India. More specifically, the following objectives are determined:

- To observe the relationship among longitudinal distance, lateral gap and relative speed between interacting vehicles during overtaking on different types of roads.
- To compare driver behavior during overtaking on different types of roads.

4. Method

As mentioned in the literature review, not many studies are reported to understand on-road instantaneous driver behavior during overtaking maneuvers. Overtaking is a complicated maneuver, and accurate, instantaneous information on headway, lateral gap and relative speed are required. Hence, in this study, an instrumented vehicle is developed to collect traffic and driver data. The instrumented vehicle is run on selected roads and instantaneous driver behavior is collected during overtaking. In order to avoid observational bias, only data on other vehicles overtaking the instrumented vehicle are considered. For analyses, both overtaken and overtaking vehicles belonging to the vehicle category of passenger car is considered.

4.1. Instrumented vehicle

An instrumented vehicle is used for data collection. The instrumented vehicle is an SUV (Sports Utility Vehicle), which is 1.75 meters wide and 3.9 meters long. This vehicle is equipped with various sensors such as VLP-16 LiDAR, four video cameras, IMU-GPS unit, onboard diagnostic (OBD) scanner and steering angle sensor. The sampling frequency of the sensors is 10 Hz. The functions of the sensor are described below:

- VLP-16 LiDAR records relative position coordinates of objects near the instrumented vehicle
- Video-camera collects information on feature type in the surrounding
- IMU-GPS unit records location coordinates and acceleration of the instrumented vehicle
- OBD-scanner records engine RPM and speed of the instrumented vehicle
- Steering angle sensor records steering angle value of the instrumented vehicle

4.2. Test track

Data are collected on four-lane and six-lane divided highways in India. The four-lane highway has two lanes in each direction of travel. The two lanes are termed as shoulder lane and median lane. The six-lane highway has three lanes in each direction of travel. The lanes are termed as shoulder lane, middle lane and median lanes. The six-lane divided highway was recently opened to traffic due to which the vehicle traffic was relatively less as compared to the four-lane highway. Certain experimental setups are designed for the six-lane highway based on the location of the overtaken vehicle on the road and approach side of overtaking vehicle. The different experimental setups are shown in Table 1. Six drivers with at least five years of driving experience are used to collect data on four-lane and six-lane divided highways.

Table 1. Experimental set-ups for the six-lane highway

Overtaken vehicle position on the highway	Overtaking vehicle approach side with respect to overtaken vehicle
Shoulder lane	Right-hand side
Median lane	Left-hand side
Middle lane	Right-hand side Left-hand side

4.3. Variables considered

Lateral gap, longitudinal distance and relative speed between the interacting vehicles are the variables considered in the study. Lateral gap is defined as the clear distance between the nearest edges of the interacting vehicles and longitudinal distance is defined as the distance from the front bumper of the following vehicle to the rear bumper of the leading vehicle. The definitions of lateral gap and longitudinal distance are shown in Figure 1 and given by equations (1) and (2).

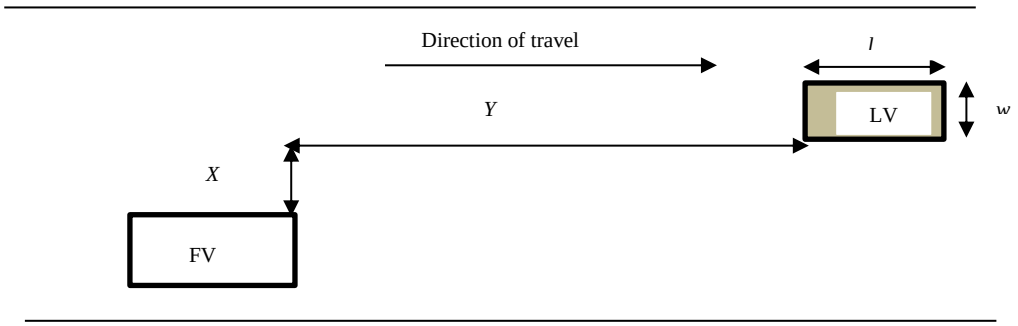

Figure 1. Schematic diagram to show lateral gap and longitudinal distance

Where,
LV: leading vehicle
FV: following vehicle
l: length of the leading vehicle
w: width of the leading vehicle
X: lateral gap between the vehicles
Y: longitudinal distance between the vehicles

$$\text{Lateral gap} = \begin{cases} X, \text{ if } X > w/2 \\ 0, \text{ if } X <= w/2 \end{cases} \qquad \text{Lateral gap} = \begin{cases} -X, \text{ if } -X < (-w/2) \\ 0, \text{ if } -X >= (-w/2) \end{cases} \tag{1}$$

$$\text{Longitudinal distance} = \begin{cases} Y, \text{ if } Y > l/2 \\ 0, \text{ if } Y <= l/2 \end{cases} \qquad \text{Longitudinal distance} = \begin{cases} -Y, \text{ if } -Y < (-l/2) \\ 0, \text{ if } -Y >= (-l/2) \end{cases} \tag{2}$$

Positive and negative values of lateral gap indicate that the following vehicle approaches the leading vehicle from right-hand side and left-hand side respectively. Similarly, positive and negative values of longitudinal distance indicate before and after overtaking scenarios respectively.

5. Analysis

Linear regression analysis is performed to understand the nature of the relationship (direct or inverse) between different pairs of variables. Three pairs of variables are considered during regression; lateral gap and longitudinal

distance, relative speed and lateral gap and relative speed and longitudinal distance. Nature of relationship is determined from the sign of the estimate obtained from the regression analysis between a considered pair of variables. The estimate in tables 2(a), 2(b), 3(a) and 3(b) represents the coefficient obtained from regression analysis for a pair of dependent and independent variables. For analysis, the longitudinal distance is divided at an interval of 10 meters: (0 to 10) m, (10 to 20) m, (20 to 30) m and (30 to 40) m. Within each longitudinal distance interval, observations are further grouped based on speed of the overtaken vehicle at an interval of 10kmph such as (20 to 30) kmph, (30 to 40) kmph, (40 to 50) kmph, (50 to 60) kmph, (60 to 70) kmph, (70 to 80) kmph and more than 80 kmph. For each longitudinal distance range, at each speed interval, regression analysis is carried out for different pairs of dependent and independent variables. Hypothesis testing is conducted to compare driver behavior on different types of roads during such maneuvers.

6. Results

6.1. Overtaking on four-lane highway

Tables 2(a) and 2(b) present the results of the regression analysis on four-lane divided highway when the overtaken vehicle is present on the median lane and shoulder lane respectively. The regression analysis is carried out for the three pairs of variables at different intervals of speed and longitudinal distance. The results of regression analysis are discussed below:

6.1.1. Relationship between lateral gap and longitudinal distance

Lateral separation between interacting vehicles is a function of lateral discomfort (Gunay, 2007). Lateral gap between vehicles depends on the longitudinal distance between them. Usually, at a longer longitudinal distance, smaller lateral gap is acceptable; at a shorter longitudinal distance, larger lateral gap is preferred. However, beyond a particular value of longitudinal distance, lateral gap does not depend on longitudinal separation between the interacting vehicles.

When the overtaken vehicle is present in median lane: For a longitudinal distance less than 30 meters, an inverse relationship is observed indicating that as longitudinal distance decreases lateral gap increases and vice versa. However, for a longitudinal distance greater than 30 meters, no specific relationship is observed. It could be inferred that on four-lane highways at a longitudinal distance greater than 30 meters, lateral gap is not influenced by longitudinal distance.

When the overtaken vehicle is present in shoulder lane: The relationship between lateral gap and longitudinal distance is found to be inconsistent, indicating that both direct and inverse relationships are observed. Data showed that when overtaken vehicle is present in shoulder lane, the average lateral gap at different longitudinal distances and different speed intervals is relatively higher in comparison to when the overtaken vehicle is present in the median lane. Average higher lateral gap might be the reason for the inconsistent relationship between the variables. Figure 2 shows the lateral gap values at different speed intervals for 0 to 10 meters longitudinal distance interval on four-lane highway.

6.1.2. Relationship between relative speed and lateral gap

Results show a direct relationship between relative speed and lateral gap indicating that as the lateral gap increases, the relative speed increases, and as the lateral gap decreases, the relative speed decreases. As the following vehicle prepares for the overtaking maneuver from behind the leading vehicle, the lateral gap between the vehicles begin to increase. In such a scenario, the leading vehicle might reduce its speed and the following vehicle might increase its speed, thus leading to an increase in relative speed with increase in lateral gap.

Table 2a. Values of estimates of regression analysis when overtaken vehicle was present in median lane (four-lane highway)

Overtaken vehicle in median lane, overtaking vehicle approaches from LHS							
Longitudinal gap (meters)	Speed (kmph)	Relation between lateral gap and longitudinal distance		Relation between relative speed and lateral gap		Relation between relative speed and longitudinal distance	
		Estimate	p-value	Estimate	p-value	Estimate	p-value
(0 to 10)	<30						
	30-40	0.000	0.988	-1.337	0.093	-0.263	0.081
	40-50	-0.118	0.000	3.278	0.000	-0.403	0.000
	50-60	-0.045	0.035	0.814	0.154	-0.225	0.020
	60-70	-0.083	0.000	-0.713	0.175	0.097	0.274
	70-80	-0.112	0.000	0.741	0.000	-0.185	0.000
(10 to 20)	<30						
	30-40	-0.014	0.542	0.550	0.326	0.068	0.546
	40-50	-0.048	0.009	2.125	0.000	0.005	0.914
	50-60	-0.022	0.003	-0.936	0.093	0.131	0.000
	60-70	-0.030	0.007	1.169	0.000	0.048	0.175
	70-80	0.128	0.000	2.382	0.000	0.270	0.000
(20 to 30)	<30	-0.051	0.000	3.882	0.001	-0.032	0.708
	30-40	-0.068	0.018	1.006	0.068	0.308	0.023
	40-50	-0.033	0.331	1.689	0.000	-0.043	0.565
	50-60	0.001	0.942	0.651	0.049	-0.018	0.222
	60-70	0.017	0.424	0.410	0.108	0.150	0.000
	70-80						
(30 to 40)	<30						
	30-40	-0.001	0.854	4.544	0.303	-0.129	0.314
	40-50	0.212	0.000	0.669	0.000	0.165	0.001
	50-60	-0.003	0.674	0.087	0.589	-0.038	0.000
	60-70						
	70-80						

Significance level of the estimates: 5%

6.1.3. Relationship between relative speed and longitudinal distance

On the four-lane highway, for a longitudinal distance less than 10 meters, an inverse relationship is observed between relative speed and longitudinal distance. It might be because when the longitudinal distance reduces to 10 meters the overtaken vehicle driver might realize that the overtaking vehicle wants to perform the maneuver. In such a scenario, the overtaken vehicle might reduce its speed, and overtaking vehicle might increase its speed in order to complete the maneuver quickly. Hence, as the longitudinal distance decreases, the relative speed might increase. For longitudinal distance greater than 10 meters no specific relationship is observed when the overtaken vehicle is present in the median lane. On the other hand, when the overtaken vehicle is present in the shoulder lane, for longitudinal distance greater than 10 meters, a direct relationship is observed between relative speed and longitudinal distance.

Table 2b. Values of estimates of regression analysis when overtaken vehicle was present in shoulder lane (four-lane highway)

Overtaken vehicle in shoulder lane, overtaking vehicle approaches from RHS							
Longitudinal gap (meters)	Speed (kmph)	Relation between lateral gap and longitudinal distance		Relation between relative speed and lateral gap		Relation between relative speed and longitudinal distance	
		Estimate	p-value	Estimate	p-value	Estimate	p-value
(0 to 10)	<30	0.045	0.063	0.648	0.005	0.291	0.000
	30-40	-0.064	0.001	1.155	0.000	-0.190	0.002
	40-50	0.033	0.001	1.714	0.000	0.478	0.000
	50-60	-0.055	0.000	0.147	0.074	-0.200	0.000
	60-70	-0.068	0.000	0.691	0.000	-0.464	0.000
	70-80	-0.021	0.000	1.161	0.000	-0.034	0.000
(10 to 20)	<30	0.033	0.023	0.605	0.000	0.051	0.113
	30-40	0.023	0.255	1.244	0.000	-0.001	0.982
	40-50	0.059	0.000	2.011	0.000	0.269	0.000
	50-60	0.087	0.000	1.708	0.000	0.223	0.000
	60-70	0.128	0.000	1.503	0.000	0.286	0.000
	70-80						
(20 to 30)	<30	-0.020	0.134	1.724	0.000	0.025	0.525
	30-40	0.007	0.804	0.740	0.000	0.147	0.004
	40-50	-0.008	0.414	1.309	0.000	0.057	0.044
	50-60	0.022	0.118	-0.690	0.025	0.118	0.047
	60-70	-0.045	0.071	0.521	0.000	-0.061	0.097
	70-80	0.070	0.029	2.986	0.000	0.199	0.046
(30 to 40)	<30	0.058	0.001	1.302	0.000	0.055	0.345
	30-40	0.016	0.604	0.547	0.000	0.072	0.226
	40-50	-0.007	0.573	1.780	0.000	0.070	0.109
	50-60	0.011	0.017	-0.721	0.000	-0.019	0.000
	60-70	0.018	0.763	4.560	0.000	0.734	0.012
	70-80	0.000	0.974	0.192	0.825	0.066	0.000

Significance level of the estimates: 5%

6.2. Overtaking on six-lane highway

Tables 3(a) and 3(b) present the results of regression analysis on six-lane divided highway when the overtaken vehicle is present in median lane and shoulder lane respectively. The regression analysis is carried out for the three pairs of variables at different intervals of speed and longitudinal distance. The results of the regression analysis are discussed below:

6.2.1. Relationship between lateral gap and longitudinal distance

When the overtaken vehicle is present in median lane: For longitudinal distance less than 20 meters, an inverse relationship is observed indicating that as the longitudinal distance decreases lateral gap increases and as longitudinal distance increases lateral gap decreases. At a longitudinal distance less than 20 meters, the following vehicle might prepare for lane change maneuver before overtaking. This might be the reason for increase in lateral gap with decrease in longitudinal distance. However, for a longitudinal distance greater than 20 meters, no specific relationship is observed. It could be inferred lateral gap is not influenced when longitudinal distance is greater than 20 meters. A similar relationship is observed when the overtaken vehicle is present in the middle lane and the overtaking vehicle approaches the overtaken vehicle from LHS.

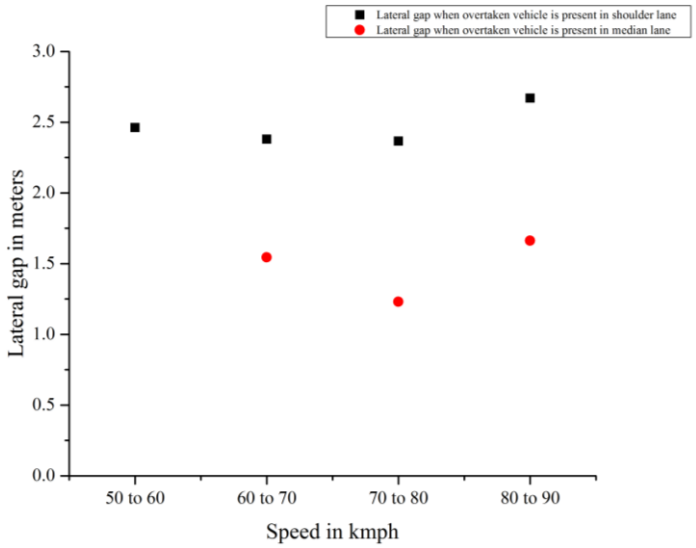

Figure 2. Lateral gap on four-lane highway for 0 to 10 meters longitudinal distance interval

When the overtaken vehicle is present in shoulder lane: The relationship between lateral gap and longitudinal distance is found to be inconsistent, indicating that both direct and inverse relationships are observed. Data showed that when overtaken vehicle is present in shoulder lane, the average lateral gap at different longitudinal distances and for different speed intervals is relatively higher in comparison to when the subject vehicle is present in the median lane. Average higher lateral gap might be the reason for the inconsistent relationship between the variables. Figure 3 shows the lateral gap values at different speed intervals for 0 to 10 meters longitudinal distance interval on six-lane highway.

6.2.2. Relationship between relative speed and lateral gap

When the overtaken vehicle is present in median lane and middle lane, overtaking vehicle approaches from LHS: Inverse relationship is observed between relative speed and lateral gap for most of the observations indicating that as the lateral gap increases, relative speed decreases, and as the lateral gap reduces relative speed increases. The traffic density is less on the six-lane highway. Drivers prefer to lead or lag behind the vehicles in the adjacent lanes (Gunay and Erdemir, 2011). More the number of lanes on the road, higher is the tendency to drive at the speed limit of the road (Shackel and Parkin, 2014). On the six-lane highway, drivers might view the increase in lateral gap to drive at their desired speed irrespective of the presence of other vehicles. Hence, as the lateral gap increases, both the overtaken and overtaking vehicle drivers might prefer to drive at the speed limit of the road thus decreasing the relative speed.

When the overtaken vehicle is present in shoulder lane and middle lane, overtaking vehicle approaches from RHS: Inconsistent relationship is observed. Average lateral gap is higher when the overtaken vehicle is present in the shoulder and middle lanes. Driving speed of the vehicles present in the adjacent lanes might be independent of each other due to the high average lateral gap. Higher lateral gap might be the reason for the inconsistent relationship between the variables.

6.2.3. Relationship between relative speed and longitudinal distance

On the six-lane highway, for a longitudinal distance less than 20 meters, a direct relationship is observed indicating that as the longitudinal distance increases, there is an increase in relative speed and as the longitudinal distance decreases, there is a decrease in relative speed. Due to less traffic and wide road, the vehicles can drive at their desired speed on the six-lane highway. The overtaken vehicle might not consider the need to reduce its speed even in the presence of approaching following vehicle. This might lead to a decrease in relative speed with decrease in longitudinal distance

Table 3a. Values of estimates of regression analysis when overtaken vehicle was present in median and middle lanes (six-lane highway)

Longitudinal gap (meters)	Speed (kmph)	Relation between lateral gap and longitudinal distance		Relation between relative speed and lateral gap		Relation between relative speed and longitudinal distance	
		Estimate	p-value	Estimate	p-value	Estimate	p-value
Overtaken vehicle in median lane, overtaking vehicle approaches from LHS							
(0 to 10)	50-60	-0.059	0.002	-5.932	0.000	0.587	0.000
	60-70	-0.016	0.056	-2.071	0.000	0.059	0.005
	70-80	-0.076	0.000	-0.363	0.000	0.049	0.000
	80-90	-0.105	0.000	-0.477	0.000	0.144	0.000
(10 to 20)	50-60						
	60-70	-0.058	0.000	-0.047	0.774	0.012	0.530
	70-80	-0.069	0.018	-0.891	0.000	0.133	0.001
	80-90	-0.053	0.000	-0.339	0.278	0.162	0.000
(20 to 30)	50-60						
	60-70						
	70-80	-0.011	0.441	0.345	0.641	0.010	0.459
	80-90	-0.002	0.455	-0.067	0.662	-0.005	0.002
Overtaken vehicle in middle lane, overtaking vehicle approaches from LHS							
(0 to 10)	50-60	-0.135	0.385	1.212	0.002	-0.348	0.164
	60-70	-0.016	0.667	-0.676	0.000	0.287	0.000
	70-80	-0.073	0.000	-0.496	0.000	0.157	0.000
	80-90	-0.040	0.000	-0.961	0.000	0.237	0.000
(10 to 20)	50-60						
	60-70	-0.066	0.001	-0.040	0.275	-0.002	0.941
	70-80	-0.059	0.000	-0.237	0.004	0.052	0.000
	80-90	-0.061	0.000	-1.174	0.147	0.072	0.086
(20 to 30)	50-60						
	60-70						
	70-80	-0.011	0.441	0.557	0.000	0.010	0.459
	80-90	-0.037	0.129	2.019	0.000	-0.082	0.097

Significance level of the estimates: 5%

Table 3b. Values of estimates of regression analysis when overtaken vehicle was present in shoulder and middle lanes (six-lane highway)

Longitudinal gap (meters)	Speed (kmph)	Relation between lateral gap and longitudinal distance		Relation between relative speed and lateral gap		Relation between relative speed and longitudinal distance	
		Estimate	p-value	Estimate	p-value	Estimate	p-value
Overtaken vehicle in shoulder lane, overtaking vehicle approaches from RHS							
(0 to 10)	50-60	-0.146	0.000	1.186	0.000	-0.135	0.005
	60-70	0.025	0.000	0.569	0.393	0.085	0.038
	70-80	-0.054	0.000	-0.081	0.223	0.011	0.401
	80-90	0.034	0.000	0.269	0.138	0.075	0.000
(10 to 20)	50-60	0.002	0.598	0.047	0.476	-0.001	0.341
	60-70	0.029	0.328	2.094	0.011	0.194	0.003
	70-80	0.025	0.014	0.357	0.282	0.013	0.767
	80-90	0.024	0.370	3.362	0.000	-0.021	0.858
(20 to 30)	50-60						
	60-70	0.002	0.763	-3.545	0.000	0.012	0.667
	70-80	-0.013	0.600	3.189	0.000	-0.172	0.139
	80-90	-0.039	0.266	6.099	0.000	-0.200	0.374
Overtaken vehicle in middle lane, overtaking vehicle approaches from RHS							
(0 to 10)	50-60						
	60-70	-0.100	0.002	0.323	0.018	-0.080	0.011
	70-80	-0.015	0.051	-0.008	0.868	0.146	0.000
	80-90	0.011	0.546	0.075	0.239	0.119	0.000
(10 to 20)	50-60						
	60-70	0.047	0.027	1.327	0.017	0.123	0.000
	70-80	-0.189	0.000	0.407	0.000	-0.121	0.000
	80-90	0.071	0.011	-1.104	0.037	0.237	0.004
(20 to 30)	50-60	-0.013	0.532	0.465	0.652	-0.111	0.335
	60-70	-0.004	0.810	0.476	0.027	0.016	0.385
	70-80	-0.027	0.054	-1.025	0.166	-0.051	0.507
	80-90	0.003	0.738	0.660	0.001	0.006	0.595

Significance level of the estimates: 5%

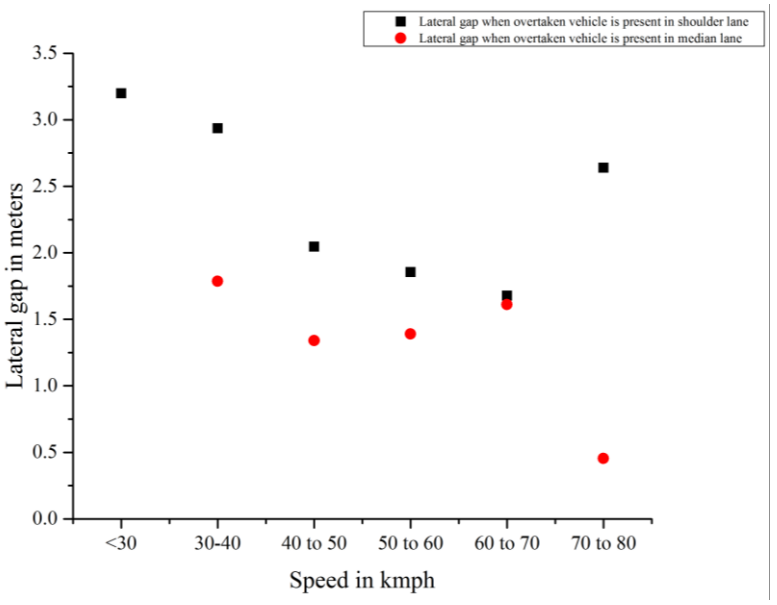

Figure 3. Lateral gap on six-lane highway for 0 to 10 meters longitudinal distance interval

6.3. Comparison of overtaking maneuver observations on four-lane and six-lane highways

In Table 4, a comparison of the nature relationship between different pairs of variables on four-lane and six-lane highways is shown. The discussions on the comparison are mentioned below:

Table 4. Comparison between four-lane and six-lane highways on the nature of the relationship between different pairs of variables

Location of LV	Nature of relationship between lateral gap and longitudinal distance		Nature of relationship between relative speed and lateral gap		Nature of relationship between relative speed and longitudinal distance	
	Four-lane highway	Six-lane highway	Four-lane highway	Six-lane highway	Four-lane highway	Six-lane highway
SL	Inconsistent (Both direct and inverse)	Inconsistent (Both direct and inverse)	Direct	Inconsistent (Both direct and inverse)	Inverse (Y<10 meters)	Not Sig
MeL	Inverse (Y<30 meters)	Inverse (Y<20 meters)	Direct	Inverse (Y<10 meters)	Inverse (Y<10 meters)	Direct (Y<20meters)
ML-R	N/A	Inconsistent (Both direct and inverse)	N/A	Inconsistent (Both direct and inverse)	N/A	Direct (Y<20meters)
ML-L	N/A	Inverse (Y<20 meters)	N/A	Inverse (Y<10 meters)	N/A	Direct (Y<20meters)

N/A: Not Applicable, Not Sig: No Significant relation, LV: Leading vehicle (Overtaken vehicle)
SL: Overtaken vehicle present in shoulder lane MeL: Overtaken vehicle present in median lane Y: Longitudinal gap
ML-R: Overtaken vehicle present in middle lane, overtaking vehicle approached overtaken vehicle from RHS
ML-L: Overtaken vehicle present in middle lane, overtaking vehicle approached overtaken vehicle from LHS

6.3.1. Relationship between lateral gap and longitudinal gap

An inverse relationship is observed between lateral gap and longitudinal distance during overtaking on both the types of road (four-lane and six-lane divided highways). The nature of relationship between lateral gap and longitudinal distance remains same irrespective of the type of road.

6.3.2. Relationship between relative speed and lateral gap

Opposite relationship is observed on four-lane and six-lane highways between relative speed and lateral gap. The possible explanations for the conflicting nature of relationship on the two types of road are mentioned below:

- On the four-lane highway, there is a direct relationship between relative speed and lateral gap. On the four-lane highway, traffic density is higher as compared to the six-lane highway. Hence, in order to allow the overtaking maneuver to be completed safely and quickly, the overtaken vehicle might reduce its speed and overtaking vehicle might increase its speed, thus leading to an increase in relative speed with increase in lateral gap.
- An inverse relationship is observed between relative speed and lateral gap on the six-lane highway indicating that as the lateral gap increases, relative speed decreases, and as the lateral gap decreases relative speed increases. Less vehicle density coupled with greater space on the road to maneuver, drivers might view the increase in lateral gap as an opportunity to drive at the speed limit of the road thus reducing the relative speed.

6.3.3. Relationship between relative speed and longitudinal distance

Opposite relationship is observed on four-lane and six-lane highways between relative speed and longitudinal distance. On the four-lane highway, for longitudinal gap less than 10 meters, an inverse relationship is observed. It might be because when the longitudinal distance reduces to 10 meters, the overtaken vehicle driver might realize that the overtaking vehicle wants to perform the overtaking maneuver. In such a scenario, the overtaken vehicle might reduce its speed, and overtaking vehicle might increase its speed in order to allow the maneuver to be completed quickly. This might lead to an increase in relative speed with decrease in longitudinal distance. On the six-lane highway, for a longitudinal distance less than 20 meters, a direct relationship is observed between relative speed and longitudinal distance. Due to greater space on the six-lane highway, the overtaken vehicle might not consider the need to reduce its speed even in the presence of the overtaking vehicle in the close vicinity. This might lead to a decrease in relative speed with decrease in longitudinal distance.

6.4. Comparison of driver behavior on different road types: Observations from relative speed

Highway design and posted speed limit influence driving speed. In this section, driver behavior during overtaking is compared on the two types of road, four-lane divided and six-lane divided, based on relative speed. Higher the value of relative speed between the overtaking and overtaken vehicles, higher is the driver yielding behavior because higher relative speed will enable to complete the overtaking maneuver quickly. Hypothesis testing at 95% confidence level is conducted to understand the influence of the type of road on the driver during overtaking. The null hypothesis is that the relative speeds on the four-lane and six-lane highways are same. The alternative hypothesis is that the relative speeds on the four-lane and six-lane highways are different. The null and alternative hypothesis are given by equations (3) and (4) as follows:

$$H_o : \mu_{rel.speed\,(four-lane)} = \mu_{rel.speed\,(six-lane)} \quad (3)$$

$$H_a : \mu_{rel.speed\,(four-lane)} \neq \mu_{rel.speed\,(six-lane)} \quad (4)$$

Where, $\mu_{rel.speed\,(four-lane)}$: Mean relative speed between the interacting vehicles on the four-lane highway

$\mu_{rel.speed\,(six-lane)}$: Mean relative speed between the interacting vehicles on the six-lane highway

Tables 5 and 6 show the mean and standard deviations of relative speed and hypothesis test results when the overtaken vehicle is present in median lane and shoulder lane respectively. Hypothesis test results reveal that the null hypothesis is rejected, indicating that the relative speed during overtaking on the two types of road are different. From mean values of relative speed, as seen in tables 5 and 6, it is observed that relative speed on the four-lane highway is

higher than relative speed on the six-lane highway during overtaking. The traffic density on the four-lane highway is higher as compared to on the six-lane highway. During overtaking, in order to allow the maneuver to be completed safely and quickly, the overtaken vehicle might reduce its speed, and the overtaking vehicle might increase its speed. This might lead to an increase in relative speed between the interacting vehicles during overtaking. On the other hand, less traffic density coupled with greater space on the six-lane highway, both the interacting vehicle drivers drive at their preferred speed, leading to a decrease in relative speed. It could be inferred that on four-lane highway drivers are more careful during overtaking as compared to drivers on the six-lane highway.

Table 5. Hypothesis test results on the relative speed when overtaken vehicle is present in the median lane

Longitudinal distance (meters)	Speed (kmph)	Relative speed on four-lane highway (m/sec)		Relative speed on six-lane highway (m/sec)		*t*-statistic	*p*-value	H_0
		Mean	SD	Mean	SD			
0 to 10	50 to 60	3.593	0.217	0.578	0.276	11.308	0.000	Reject
	60 to 70	3.596	0.195	0.440	0.065	14.859	0.000	Reject
	70 to 80	0.832	0.055	0.507	0.031	7.738	0.000	Reject
	80 to 90			0.465	0.036			
10 to 20	50 to 60	3.802	0.086					
	60 to 70	2.570	0.106	1.589	0.053	2.635	0.013	Reject
	70 to 80	3.308	0.185	2.026	0.147	12.879	0.000	Reject
	80 to 90			1.298	0.158			
20 to 30	50 to 60	4.171	0.042					
	60 to 70	2.901	0.115	2.182	0.185	37.377	0.000	Reject
	70 to 80			2.114	0.006			
	80 to 90							

Table 6. Hypothesis test results on the relative speed when overtaken vehicle is present in the shoulder lane

Longitudinal distance (meters)	Speed (kmph)	Relative speed on four-lane highway (m/sec)		Relative speed on six-lane highway (m/sec)		*t*-statistic	*p*-value	H_0
		Mean	SD	Mean	SD			
0 to 10	50 to 60	2.261	0.059					
	60 to 70	2.071	0.111	2.207	2.209	12.305	0.000	Reject
	70 to 80	6.245	0.027	0.477	0.034	14.42	0.000	Reject
	80 to 90			0.345	0.048			
10 to 20	50 to 60	2.265	0.103	-1.684	0.002	19.064	0.000	Reject
	60 to 70	2.464	0.125	1.608	0.057	6.221	0.000	Reject
	70 to 80	6.019	0.063	0.808	0.157	32.714	0.000	Reject
	80 to 90			0.435	0.177			
20 to 30	50 to 60	3.770	0.160	-0.942	0.415	10.584	0.000	Reject
	60 to 70	2.734	0.101	2.064	0.047	5.993	0.000	Reject
	70 to 80	4.981	0.244	-0.483	0.263	15.142	0.000	Reject
	80 to 90			-2.067	0.031			

7. Summary and conclusion

The present study is carried out to understand the driver behavior during overtaking maneuvers on different types of road using data from instrumented vehicle. The main objectives are to understand the relationship between different pairs of variables during overtaking and differences in driver behavior during overtaking based on the type of road. The selected road types are different in terms of number of lanes and traffic density. The two types of roads is four-lane and six-lane divided highways.

Results from the study show similar nature of relationship between lateral gap and longitudinal distance on both the types of highways, indicating that type of road has no influence on the relationship between lateral gap and longitudinal distance. Opposite relationship is observed between relative speed and lateral gap and relative speed and longitudinal distance on the two types of road. Differences in the available maneuvering road space and vehicular density on four-lane and six-lane highways might lead to the difference like relationship between the two pairs of

variables. Hypothesis test results show that drivers on the four-lane highway are more careful as compared to drivers on the six-lane highway during overtaking as evident from higher values of relative speed maintained during the maneuver.

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