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Impacts of Weather on Traffic Flow Characteristics of Urban Freeways in Istanbul

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Abstract

Speed-flow relationships have been established for different free-flow speeds on urban freeways. However, there have been few research efforts relating real-time traffic flow parameters and weather conditions for different levels of heavy vehicle traffic. This study aims at establishing relationships between speed and volume in freeway sections using Remote Traffic Microwave Sensor (RTMS) data as a function of weather conditions. Historical weather and RTMS detector data (i.e., volume and speed) from two highway corridors in the Istanbul metropolitan area are used for this purpose. Empirical relationships between traffic speed and volume are analyzed by weather condition (clear, rain, fog/mist/haze, or snow), surface condition (dry, wet, or icy), and percentage of heavy vehicles in the traffic mix. The findings from the analysis show that rain reduced the average vehicular speeds by 8 to 12% and the capacity by 7-8%. Moreover, wet surface conditions resulted in a reduction of average speeds by 6 to 7% and light snow affected demand leading to a significant reduction in traffic volume.

Keywords: Weather impacts; speed-flow-capacity relationship; RTMs data; heavy vehicles; City of Istanbul

1. Introduction

Inclement weather can significantly affect travel demand, driving behaviour and traffic flow characteristics. Advances in sensor technologies make it possible to collect real-time traffic flow data under various traffic conditions including adverse weather. This study used such data to establish the potential impact of adverse weather on the three fundamental traffic flow characteristics (i.e., speed, volume and density). More specifically, historical weather and RTMS detector volume and speed data from two freeway corridors in the Istanbul metropolitan area (i.e., 1st and 2nd Bosporus Bridge routes) were obtained through the Traffic Control Center of the Istanbul Metropolitan Municipality and used for this purpose. Empirical relationships between traffic speed and volume were established by weather condition (clear, rain, fog/mist/haze, or snow), surface condition (dry, wet, or icy), and proportion of heavy vehicles in the traffic mix.

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1.1. Background

Since the early 1950's (Tanner, 1952), it has been recognized that weather conditions affect driver behavior and traffic flow. Weather phenomena exert significant impacts on traffic flow related parameters, such as free flow speed and capacity (e.g. Kockelman, 1998; Smith et al., 2004; Hranac et al., 2006; Rakha et al., 2007). In addition, adverse weather often affects tripmaker decisions related to the selection of travel mode, route, timing, destination, or even the occurance of the trip. Thus, weather affects both the supply and demand sides of transportation. Studies confirm that adverse weather results in reduced service capacity, diminished reliability of travel, and greater risk of accident involvement. It is estimated that approximately 28% of all highway crashes and 19% of all fatalities involve weather-related adverse road conditions as a contributing factor (Mahmassani et al., 2009).

Researchers have used different classification schemes for weather conditions, because these conditions differ considerably in type and magnitude (Rakha et al., 2007). Some weather conditions are extreme in nature (tornados, floods, typhoons, hurricanes etc.) and thus may trigger a different response by the drivers. Such extreme conditions are outside the immediate focus of the present study. Other inclement weather conditions (such as light and heavy rain, light and heavy snow, etc.) offer a less compressed time frame to the decision makers, and allow drivers to retain an acceptable amount of control. Still this control may be compromised by physical factors such as visibility, physical discomfort (cold or hot temperatures) and reduced pavement friction in the presence of precipitation or icy conditions (Mahmassani et al., 2009).

1.1.1. Traffic Flow Characteristics

The commonly used speed-flow-density relationships do not explicitly take into consideration the effect of weather. In their study, Salomen and Puttonen (1982) found that darkness results in a reduction of operating speed by 5 km/h. In terms of capacity, Jones and Goolsby (1969, 1970) indicated a 14% reduction during rain; however, no information was provided on the severity of the rain conditions. The rain severity has an important impact on such reduction as reported by Kleitsch and Cleveland (1971).

Ibrahim and Hall (1994) used a dummy variable multiple regression analysis technique to test the significance in the differences in traffic operating conditions among different weather conditions. The light rain caused a drop in the free-flow speed of a maximum of 2 km/h. At a maximum flow of 2400 veh/hr, an average drop of 13 km/h was observed compared to clear conditions. Under light snow conditions, the free-flow speed dropped on average by 3 km/h (8km/h at the 2400 veh/h level). During heavy rain, the free-flow speeds dropped by 5 to 10 km/h whereas heavy snow caused a drop of free-flow speed of 38 to 50 km/h. Rakha et al. (2007) reported that the impact of weather conditions on traffic flow relationships and parameters at freeway sections varied depending on the road types.

1.1.1.1. Capacity

Adverse weather conditions can significantly reduce the operating speed and capacity in a given road segment. Compared to fair conditions the HCM 2000 reports a 30% reduction of capacity due to snowfall and 15% due to rain or fog (HCM, 2000). Lamm et al., (1990) reported that speeds were not influenced by the presence of wet pavement until visibility was affected. Accordingly, light rain did not appeat to have noticeable impacts on traffic flow compared to heavy rain that resulted in 10% to 15% reduction in capacity. Similar to heavy rain, heavy snow was reported to have a potentially large impact on the operating speed (Ibrahim and Hall, 1994). A 30% drop in capacity was attributed to heavy snow compared to a 10% reduction in the case of light snow. The main explanatory reason behind such drop is the search for a greater lateral clearance and longer headways since the lane markings are obscured by snow accumulation.

Smith et al. (2004) studied the impact of different rainfall intensity levels on freeway capacity and operating speeds. The corresponding traffic (volume, time mean speed and occupancy) and weather (rainfall intensity) data were collected for a one-year period. The rainfall was classified into light rain (0.01 to 0.25 inch per hour) and heavy rain (greater than 0.25 inch per hour). The mean of the highest 5% flow rates was used to determine the change in capacity. It was found that light rain decreased capacity by 4 to 10% while heavy rain led to a capacity decrease in the range of 25 to 30%.

1.1.1.2. Traffic Volume and Demand

Adverse weather may also reduce demand for trips when drivers cancel or postpone their activities. However, an increase in demand of vehicle trips may also be observed as travelers switch from transit or non-motorized modes to private vehicle use. Furthermore, adverse weather can also shift the peak-hour demand if the drivers choose to leave earlier or later due to unsafe driving conditions (Mahmassani et al., 2009).

Hanabali and Kuemmel (1992) quantified the reduction in traffic volumes during snowstorms in rural areas of Illinois, Minnesota, New York, and Wisconsin using automatic vehicle detectors data collected during the first three months of 1991. These data included annual average daily traffic and 24-hour counts. Comparing hourly traffic volumes during every snowstorm to the "normal" hourly traffic volume, a correlation between volume reduction and snowfall was found. The study concluded that the volume reduction was less pronounced during peak-hours and during weekdays. This may be attributed to the non-discretionary type of trips (home to work and work to home trips).

The winter weather impact on traffic volume and safety was also studied by Knapp et al. (2000). Traffic and weather data were collected on an hourly basis along interstate highways in Iowa during from 1995 to 1998 focusing on 64 significant winter storm events (618 hours). The analysis showed a traffic volume reduction ranging from 16% to 47% with average reduction of 22.3%. Based on regression analysis, the study concluded that the volume reduction had a significant correlation with total snowfall and the square of the maximum wind speed.

1.1.1.3. Speed

A study sponsored by Federal Highway Administration (FHWA) confirmed a decrease in speeds during inclement weather (FHWA, 2006). In the HCM 2000 (HCM, 2000), the reported weather impact on speed is based on Ibrahim and Hall's (1994) study. Conducting a regression analysis on the clear weather data, a quadratic model was found to best fit the flow-occupancy relationship; and a simple linear model suited the speed-flow relationship. Moreover, comparing different relationships under different weather conditions, the differences in slope and intercept of the speed-flow function during the rainy (snowy) conditions were more significant that those between clear and rainy weather. In light rain, a 1.9 km/h reduction in operating speeds was found during free-flow conditions and 6.4 to 12.9 km/h for capacity conditions. In heavy rain, a 4.8 to 6.4 km/h reduction in speed was reported for free-flow conditions and a 12.9 to 16 km/h reduction under congested conditions. Finally, light snow resulted in a minor drop in free-flow speeds (0.96 km/h), contrary to heavy snow that led to a 37.0 to 41.8 km/h drop (Mahmassani et al., 2009). Another related study by Smith et al. (2004) concluded that although operating speed reductions were not as dramatic as was the case with capacity reductions, statistically significant reductions (3 to 5 %) in operating speed were observed under rainfall conditions compared to no rain at all.

In another research study, Padget et al. (2001) investigated whether drivers of SUVs, pickup trucks, and passenger cars choose different vehicle speeds during winter weather at an urban arterial street in Ames, Iowa, between November 1999 and April 2000. The results indicated that winter-weather vehicle speeds for all three vehicle types were significantly less than their normal weather speeds, and that during the day a large percentage of the speed reduction occured after snow began to accumulate in the gutter pans of the roadway. They also found that speed variability between vehicles types increased during winter-weather conditions and the magnitude of the speed differences between SUVs, pickups and passenger cars increased with roadway snow cover, but remained below 5.6 km/h (Mahmassani et al., 2009).

2. Data and Methodology

This study used historical weather, surface condition data and detector data captured by RTMS in 2009 along two main highway corridors in the Istanbul metropolitan area (i.e., 1st and 2nd Highway Bridges crossing the Bosporus Strait) to develop empirical relationships among traffic speed, density and volume and pertinent parameters. These include road classification (6 or 8-lane freeway sections with 90 or 120 km/h speed limits respectively), weather condition (clear, rain, fog/mist/haze, or snow), surface condition (dry, wet, or icy), and heavy vehicles presence in the traffic mix (large vehicle percentages, LV% <10%, 10-20%, 20-30%, 30-40%, 40-50%, >50%).

The findings from this study were compared with the HCM 2000 values and recommendations were offered for future potential improvements.

3. Results

3.1. Speed-Density-Volume Relationships by Highway Sections (1st and 2nd Highway Bridges)

In order to obtain some background information about the operating conditions of the two study sites and the potential differences between them, speed-density-volume (V-K-Q) relationships for the 1st and 2nd Bosporus Bridge routes for all study data combined are plotted in Figure 1. Table 1 shows the related data statistics.

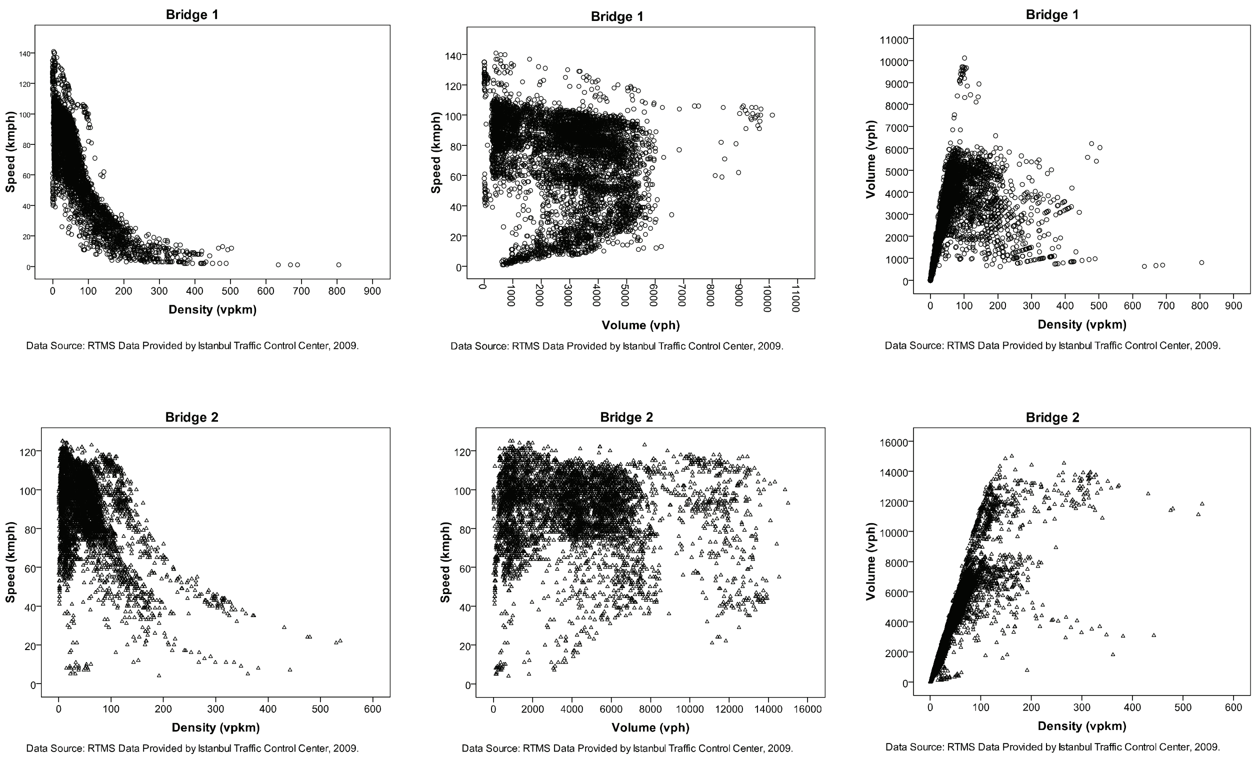

Figure 1. Speed-density-volume relationships for the two study routes.

Table 1. Speed-density-volume data statistics for the 1st and 2nd Bosporus Bridges

DESCRIPTIVES									ANOVA				
	Sections	N	Mean		Std. Dev.	Std. Error	Max.		Comparison	df	Mean Square	F	Sig.*
			value	%			value	%					
Speed (kmph)	1st Bridge	5353	71.93	na	28.206	0.386	141	na	Btw Groups	1	721658.841	1210.177	0.000
	2nd Bridge	5232	88.45	23	19.811	0.274	125	-11	Within Groups	10583	596.325		
	Total	10585	80.09	na	25.777	0.251	141	na	Total	10584			
Volume Per Lane (vphpl)	1st Bridge	5370	944.28	na	534.35	7.292	3372	na	Btw Groups	1	6010406849.755	994.050	0.000
	2nd Bridge	5233	1084.69	15	775.15	10.716	3752	11	Within Groups	10601	6046381.430		
	Total	10603	1013.58	na	667.87	6.486	3752	na	Total	10602			
Density (vpkm)	1st Bridge	5370	61.60	na	70.31	0.960	805	na	Btw Groups	1	119032.174	30.850	0.000
	2nd Bridge	5232	54.90	-11	52.37	0.724	538	-33	Within Groups	10600	3858.395		
	Total	10602	58.30	na	62.20	0.604	805	na	Total	10601			

*: All flow parameters (V-K-Q) are significantly different along the 1st and 2nd Bridge Sections at the 0.05 level (all $p<0.05$).

The V-K-Q relationships observed from the analysis of the two study corridors agree with traffic stream models documented in the literature (Prevedouros and Kongsil, 2003). As seen in Table 1, both the average speed (kmph) and the average volume per hour per lane (vphpl) of the 1st Bridge section are lower than that of the 2nd Bridge section (23% and 13% respectively) and the differences are significant at the 0.05 level.

The 1st Bridge section has a free flow speed (FFS) of 140 kmph and capacity of approximately 2000 vphpl during 2x3 lane operations. When a lane is added to the higher demand direction (in the morning from Asia to Europe and in the afternoon from Europe to Asia), capacity reaches 2500 vphpl. As far as the 2nd Bridge section is concerned, FFS is 125 kmph and capacity is 2200 vphpl for 2x4 lane operations and 2800-3000 vphpl when an additional lane becomes available during peak times. The observed jam density is approximately 450-500 vpkm.

3.2. Speed-Density-Volume Relationships by Weather Condition

Figure 2 depicts the V-K-Q relations for the 1st and 2nd Bosporus Bridge routes for various weather conditions (clear, rain, fog/haze/mist, snow), and Tables 2 and 3 present the related data statistics. Snow conditions represent only a few hours (small number of observations, N=36) and did not affect the traffic operations during February of 2009.

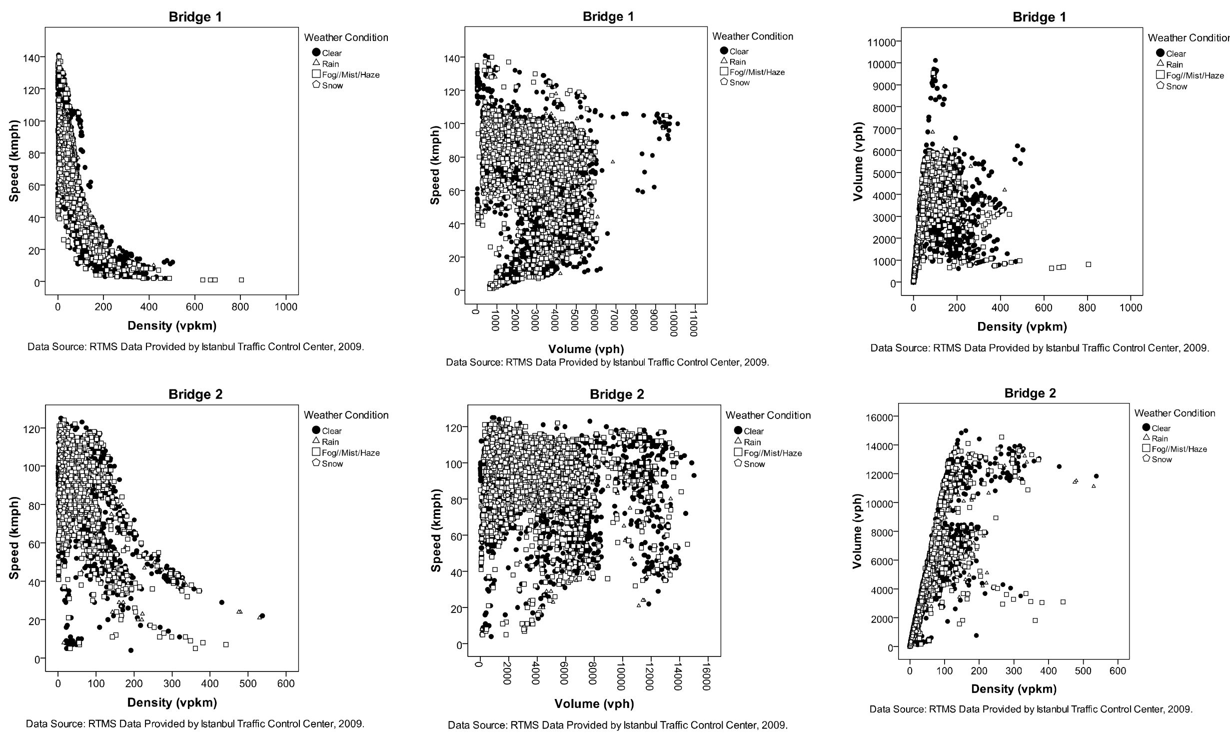

Figure 2. Speed-density-volume relationships for various weather conditions for the two study routes.

The results show that rain reduced the average speed (kmph) by 12 and 8% at the 1st and 2nd Bridges, respectively. This is a speed reduction of about 7 to 8 km/h. Light snow resulted in 65-66% less traffic volume which, in turn, led to a speed increase by 4 and 5%. Fog, mist or haze did not have significant impacts on the average speeds as well as FFS on either bridge sections. The results are in overall agreement with findings by Snowden et al. (1998) and other earlier studies. Differences in all three flow measures with respect to various weather conditions were statistically significant at the 0.05 level.

Table 2. Speed-density-volume data statistics for various weather conditions for the 1st Bosporus Bridge route

DESCRIPTIVES										ANOVA				
Weather Condition		N	Mean value	Mean Change	Std. Dev.	Std. Error	Maximum value	Maximum Change	Comparison	df	Mean Square	F	Sig.*
Speed (kmph)	Clear	3146	71.42	na	29.576	0.527	141	na	Between Groups	3	11663.021	14.773	0.000
	Rain	298	63.18	-12%	30.681	1.777	132	-6%					
	Fog//Mist/Haze	1873	73.99	4%	25.119	0.580	140	-1%	Within Groups	5349	789.456		
	Snow	36	81.72	14%	17.700	2.950	110	-22%					
	Total	5353	71.93	na	28.206	0.386	141	na	Total	5352			
Volume Per Lane (vphpl)	Clear	3163	926.49	na	562.180	9.996	3372	na	Between Groups	3	6568057.558	23.289	0.000
	Rain	298	1056.37	14%	505.297	29.271	3128	-7%					
	Fog//Mist/Haze	1873	968.44	5%	482.009	11.137	3180	-6%	Within Groups	5366	282025.567		
	Snow	36	323.68	-65%	304.890	50.815	1296	-62%					
	Total	5370	944.28	na	534.358	7.292	3372	na	Total	5369			
Density (vpkm)	Clear	3163	63.29	na	71.997	1.280	503	na	Between Groups	3	86954.961	17.751	0.000
	Rain	298	81.56	29%	75.645	4.382	426	-15%					
	Fog//Mist/Haze	1873	56.51	-11%	66.142	1.528	805	me**	Within Groups	5366	4898.727		
	Snow	36	13.10	-79%	14.161	2.360	63	-87%					
	Total	5370	61.60	na	70.318	0.960	805	na	Total	5369			

*: All flow parameters (V-K-Q) are significantly different under various weather conditions at the 0.05 level. **me=measurement error.

Table 3. Speed-density-volume data statistics for various weather conditions for the 2nd Bosporus Bridge route

DESCRIPTIVES										ANOVA				
Weather Condition		N	Mean value	Mean Change	Std. Dev.	Std. Error	Max value	Max Change	Comparison	df	Mean Square	F	Sig.*
Speed (kmph)	Clear	3112	88.34	na	19.526	0.350	125	na	Between Groups	3	5588.993	14.349	0.000
	Rain	293	81.67	-8%	21.638	1.264	117	-6%					
	Fog//Mist/Haze	1788	89.65	1%	19.852	0.469	124	-1%	Within Groups	5228	389.508		
	Snow	39	92.69	5%	15.651	2.506	118	-6%					
	Total	5232	88.45	na	19.811	0.274	125	na	Total	5231			
Volume Per Lane (vphpl)	Clear	3113	1088.67	na	797.794	14.299	3752	na	Between Groups	3	10758809.301	18.081	0.000
	Rain	293	1279.18	17%	773.576	45.193	3437	-8%					
	Fog//Mist/Haze	1788	1061.60	-2%	729.708	17.257	3637	-3%	Within Groups	5229	595044.301		
	Snow	39	365.18	-66%	344.381	55.145	1440	-62%					
	Total	5233	1084.70	na	775.159	10.716	3752	na	Total	5232			
Density (vpkm)	Clear	3112	54.28	na	50.849	0.912	538	na	Between Groups	3	64205.427	23.707	0.000
	Rain	293	75.84	40%	73.587	4.299	530	-1%					
	Fog//Mist/Haze	1788	53.40	-2%	50.322	1.190	442	-18%	Within Groups	5228	2708.289		
	Snow	39	16.03	-70%	14.993	2.401	69	-87%					
	Total	5232	54.90	na	52.379	.724	538	na	Total	5231			

*: All flow parameters (V-K-Q) are significantly different under various weather conditions at the 0.05 level (all $p<0.05$). **me=measurement error.

3.3. Speed-Density-Volume Relationships by Surface Condition

Drivers take extra precautions during their course of driving on surfaces that are wet or icy. Such driver behaviour in believed to impact speed-density-volume (V, K and Q) relationships. Figure 3 shows V-K-Q graphs for the two study routes for various surface conditions (dry, wet, icy), and Tables 4 and 5 present relevant data statistics. It should be noted that only a small sample of icy conditions (N=12 hrs) was available in the database.

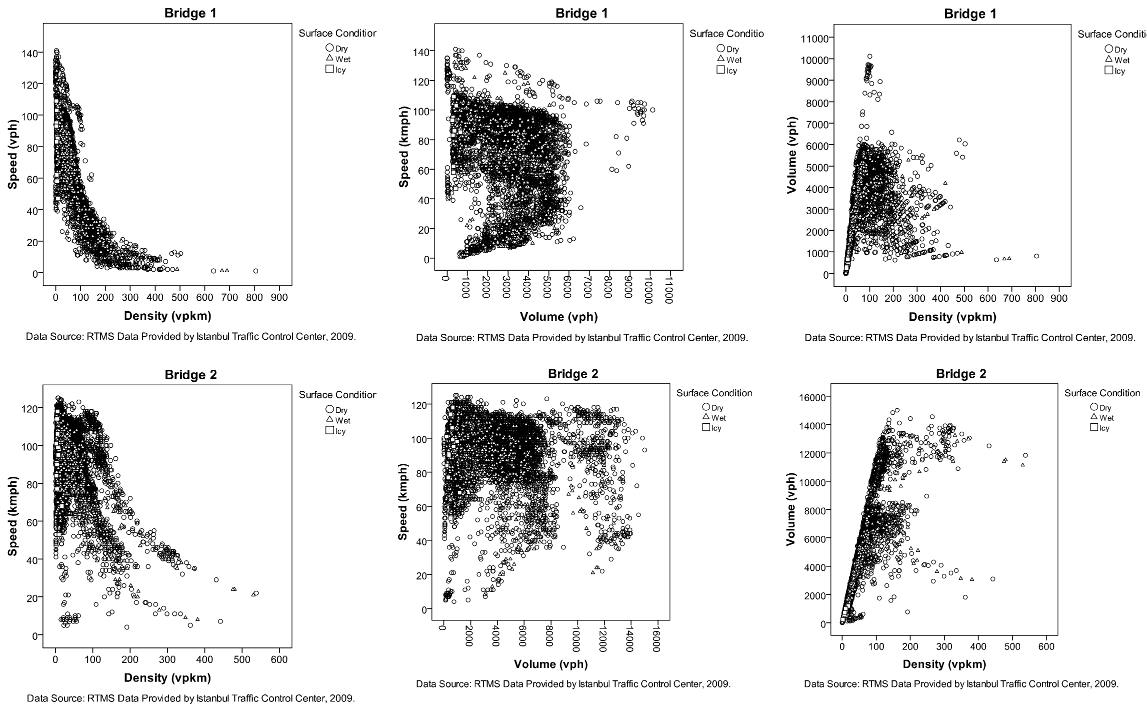

Figure 3. Speed-density-volume relationships for various surface conditions for the two study routes.

Table 4. Speed-density-volume data statistics for various surface conditions for the 1st Bosporus Bridge route

DESCRIPTIVES									ANOVA				
	Surface Condition	N	Mean value	Mean Change	Std. Dev.	Std. Error	Max value	Max Change	Comparison	df	Mean Square	F	Sig.*
Speed (kmph)	Dry	4766	72.37	na	28.164	.408	141	na	Between Groups	2	5591.476	7.04	0.001
	Wet	575	68.03	-6%	28.406	1.185	132	-6%	Within Groups	5350	793.759		
	Icy	12	83.08	15%	18.574	5.362	109	-23%					
	Total	5353	71.93	na	28.206	.386	141	na	Total	5352			
Volume Per Lane (vphpl)	Dry	4783	958.43	na	535.571	7.744	3372	na	Between Groups	2	7459145.5	26.37	0.000
	Wet	575	843.79	-12%	505.151	21.066	1911	-43%	Within Groups	5367	282864.74		
	Icy	12	119.97	-87%	35.562	10.266	217	-94%					
	Total	5370	944.28	na	534.358	7.292	3372	na	Total	5369			
Density (vpkm)	Dry	4783	61.28	na	68.499	.990	805	na	Between Groups	2	24102.43	4.88	0.008
	Wet	575	65.50	7%	84.116	3.508	689	-14%	Within Groups	5367	4937.43		
	Icy	12	4.61	-92%	1.939	.560	9	-99%					
	Total	5370	61.60	na	70.318	.960	805	na	Total	5369			

*: All flow parameters (V-K-Q) are significantly different under various surface conditions at the 0.05 level (all p<0.05). **me=measurement error.

Based on the available data, ice did not affect the traffic operations at the study sites. On the other hand, wet surface was found to reduce the average speed (kmph) by 6% and 7% in the 1st and 2nd Bridges, respectively. Differences in all three flow measures with respect to surface conditions are statistically significant at 0.05 level.

Table 5. Speed-density-volume data statistics for various surface conditions for the 2nd Bosporus Bridge route

DESCRIPTIVES									ANOVA				
Surface Condition			Mean			Std.	Maximum						
		N	value	Change	Std. Dev.	Error	value	Change		df	Mean Square	F	Sig.
Speed (kmph)	Dry	4651	89,07	na	19,678	0,289	125	na	Between Groups	2	8753,539	22,486	0,000
	Wet	568	83,22	-7%	20,190	0,847	118	-6%	Within Groups	5229	389,292		
	Icy	13	91,85	3%	18,078	5,014	118	-6%					
	Total	5232	88,45	na	19,811	0,274	125	na	Total	5231			
Volume Per Lane (vphpl)	Dry	4652	1103,79	na	777,304	11,396	3752	na	Between Groups	2	11777002,560	19,740	0,000
	Wet	568	949,89	-14%	739,421	31,025	3437	-8%	Within Groups	5230	596598,293		
	Icy	13	142,67	-87%	71,557	19,846	296	-92%					
	Total	5233	1084,70	na	775,159	10,716	3752	na	Total	5232			
Density (vpkm)	Dry	4651	54,71	na	50,061	0,734	538	na	Between Groups	2	17305,552	6,321	0,002
	Wet	568	57,58	5%	68,540	2,876	530	-1%	Within Groups	5229	2737,989		
	Icy	13	6,56	-88%	4,088	1,134	17	-97%					
	Total	5232	54,90	na	52,379	0,724	538	na	Total	5231			

*: All flow parameters (V-K-Q) are significantly different on various surface conditions at 0.05 level (all $p<0.05$).

3.4. Speed-Density-Volume Relationships by Large Vehicle Presence

Due to their dynamics, the presence of large vehicles in the traffic stream reduces the capacity of a rodway, and affects the speed-density-volume relationships. Figure 4 shows V-K-Q graphs for the 1st and 2nd Bosporus Bridge routes for various surface conditions (dry, wet, icy), and Tables 6 and 7 summarize data statistics.

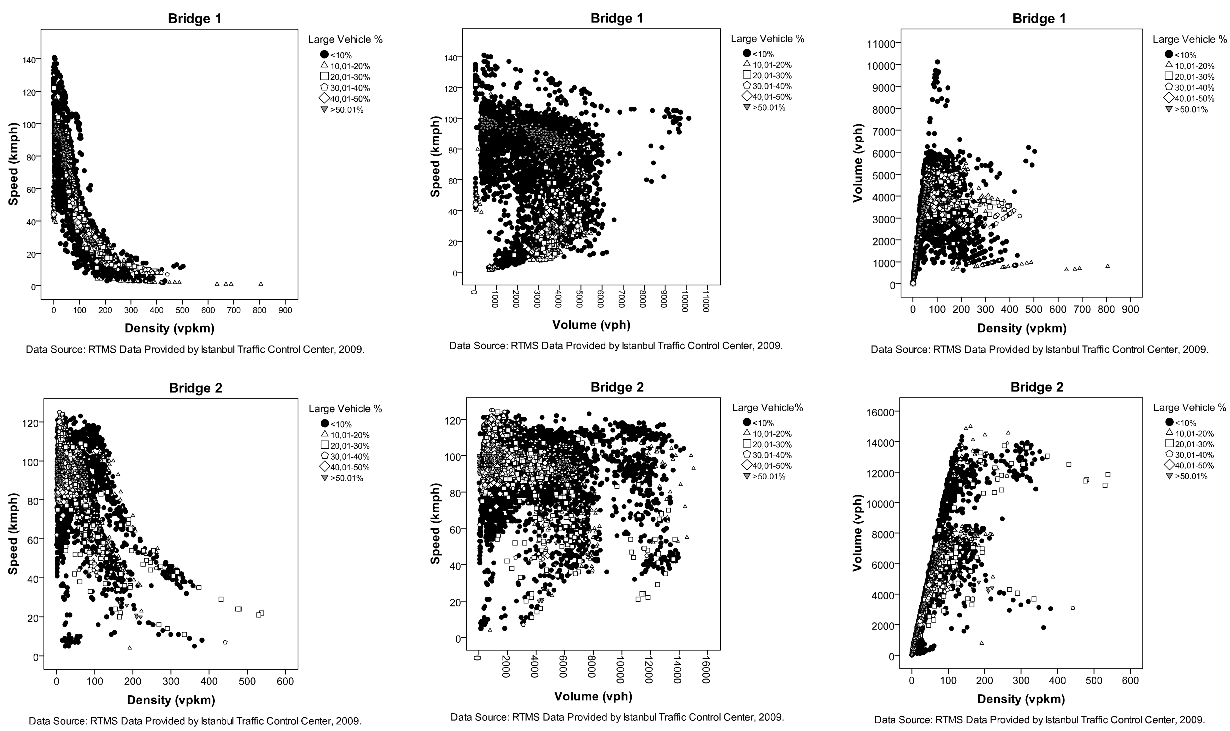

Figure 4. Speed-density-volume relationships for various rates of large vehicles for the two study routes.

Table 6. Speed-density-volume data statistics by LV% for clear weather conditions on both bridge routes

DESCRIPTIVES									ANOVA				
	LV%	N	Mean value	Mean Change	Std. Dev.	Std. Error	Maximum value	Maximum Change	Comparison	df	Mean Square	F	Sig.*
Speed (kmph)	<10%	5306	79.70	na	25.851	.355	141	na	Between Groups	5	1785.559	2.580	0.024
	10.01-20%	493	79.76	0%	28.708	1.293	130	-8%					
	20.01-30%	246	77.07	-3%	30.624	1.953	124	-12%					
	30.01-40%	135	85.49	7%	31.038	2.671	125	-11%	Within Groups	6380	692.046		
	40.01-50%	46	81.04	2%	28.375	4.184	120	-15%					
	>50.01%	160	83.84	5%	20.912	1.653	106	-25%					
	Total	6386	79.84	na	26.323	.329	141	na	Total	6385			
Volume Per Lane (vphpl)	<10%	5194	1022.10	na	697.160	9.673	3584	na	Between Groups	5	13503655.22	28.756	0.000
	10.01-20%	481	1186.15	16%	670.301	30.563	3752	5%					
	20.01-30%	241	850.24	-17%	652.150	42.009	3263	-9%					
	30.01-40%	135	566.16	-45%	536.818	46.202	2936	-18%	Within Groups	6252	469592.534		
	40.01-50%	47	444.34	-57%	388.435	56.659	1458	-59%					
	>50.01%	160	850.89	-17%	553.062	43.723	2021	-44%					
	Total	6258	1009.54	na	692.826	8.758	3752	na	Total	6257			
Density (vpkm)	<10%	5306	56.94	na	57.643	.791	503	na	Between Groups	5	57179.987	14.987	0.000
	10.01-20%	493	77.11	35%	76.896	3.463	471	-6%					
	20.01-30%	246	72.51	27%	93.209	5.943	538	7%					
	30.01-40%	135	53.70	-6%	94.793	8.159	418	-17%	Within Groups	6380	3815.304		
	40.01-50%	46	37.98	-33%	56.918	8.392	206	-59%					
	>50.01%	160	44.45	-22%	45.346	3.585	209	-59%					
	Total	6386	58.58	na	62.105	.777	538	na	Total	6385			

*: All flow parameters (V-K-Q) are significantly different at various LV ratios at the 0.05 level (all $p<0.05$).

Table 7. Speed-density-volume data statistics by LV% for rainy weather conditions on both bridge routes

DESCRIPTIVES									ANOVA				
	LV%	N	Mean value	Mean Change	Std. Dev.	Std. Error	Maximum value	Maximum Change	Comparison	df	Mean Square	F	Sig.*
Speed (kmph)	<10%	406	75.07	na	26.870	1.334	132	na	Between Groups	5	2966.084	3.849	0.002
	10.01-20%	70	72.90	-3%	26.028	3.111	111	-16%					
	20.01-30%	52	59.79	-20%	30.624	4.247	108	-18%					
	30.01-40%	15	63.73	-15%	36.033	9.304	102	-23%	Within Groups	587	770.536		
	40.01-50%	9	63.00	-16%	35.627	11.876	98	-26%					
	>50.01%	41	65.93	-12%	30.409	4.749	100	-24%					
	Total	593	72.37	na	28.091	1.154	132	na	Total	592			
Volume Per Lane (vphpl)	<10%	404	1161.48	na	680.327	33.848	3437	na	Between Groups	5	2246170.344	5.319	0.000
	10.01-20%	69	1322.49	14%	510.040	61.402	3344	-3%					
	20.01-30%	52	1386.86	19%	721.486	100.052	3141	-9%					
	30.01-40%	15	743.52	-36%	548.563	141.638	1618	-53%	Within Groups	584	422275.188		
	40.01-50%	9	682.34	-41%	614.409	204.803	1615	-53%					
	>50.01%	41	933.63	-20%	464.012	72.466	1758	-49%					
	Total	590	1166.40	na	661.633	27.239	3437	na	Total	5231			
Density (vpkm)	<10%	406	71.01	na	66.989	3.325	426	na	Between Groups	5	33406.447	6.283	0.000
	10.01-20%	70	85.68	21%	63.766	7.621	299	-30%					
	20.01-30%	52	130.24	83%	116.752	16.191	530	24%					
	30.01-40%	15	85.21	20%	90.604	23.394	250	-41%	Within Groups	587	5317.297		
	40.01-50%	9	73.58	4%	79.778	26.593	193	-55%					
	>50.01%	41	74.80	5%	63.687	9.946	220	-48%					
	Total	593	78.60	na	74.529	3.061	530	na	Total	592			

*: All flow parameters (V-K-Q) are significantly different at various LV ratios at the 0.05 level (all $p<0.05$).

The analysis shows that although the presence of large vehicles reduced the average speed as well as the FFS significantly on both bridge routes for rainy weather conditions, on clear days the presence of large vehicles has very minor reduction effect (only 3% reduction for 10-20% LV) on average speeds but significant reduction on FF speeds (8 to 25% reductions). On rainy days the effect of large vehicles (LV) on either average or FF speed is significant for all LV% ratios compared to 10% LV (reductions in average speed varied between 3 to 20% and 16 to 26% for FF speed). Furthermore, over 30% large vehicle ratios reduced the average flow rate significantly on both bridge routes (20 to 57% reductions in average flow rate). Also density reductions were higher on clear days for over 30% LVs (6 to 22% reductions) than those on rainy days.

Using data from both bridges, a linear regression model was fitted to relate the speed to large and small vehicle volumes, density and weather parameters such as weather temperature and surface temperature as follows:

$$Log_{10}(V) = 0.486 + 0.087 * Log_{10}(LV) + 0.769 * Log_{10}(SV) - 0.925 * Log_{10}(K) + 0.026 * Log_{10}(WT) + 0.026 * Log_{10}(ST) \quad (1)$$

where

V: Speed in kmph,
LV: Large vehicle volume in vph,
SV: Small vehicle volume in vph,
K: Density in vpkm,
WT: Weather temperature in degrees of celcius,
ST: Surface temperature in degrees of celcius,

The model yielded an R^2= 0.895 (adjusted; F=16008.150, p=0.000<0.01) and all the independent variables are statistically significant at 0.01 level (all p<0.01).

4. Discussion with Respect to HCM 2000 Considerations

In their work, Prevedouros and Kongsil (2003) discussed that in the HCM 2000 “base conditions assume good weather, good pavement conditions, users familiar with the facility, and no impediments to traffic flow”. Similarly, the HCM 2000 specifies that “the base conditions under which the full capacity of a basic freeway segment is achieved are good weather, good visibility, and no incidents or accidents” (HCM. 2000). In Chapter 22 - Freeway Facilities, there is a brief accounting for the effect of inclement weather in the form of speed-flow curves for different weather conditions. The HCM 2000 suggests that free-flow speed (FFS) is reduced by 10 km/h in light rain. and by 19 km/h in heavy rain. The capacity reduction in wet and rainy conditions is not specified. The Exhibit 22-7 in HCM 2000 roughly approximates averages from several studies in terms of speed reduction under free flow conditions. In this study, capacity reduction due to rainy conditions accounted for 7 to 8% for the two study highway sections and observed speed reductions due to rain ranged from 8-12% (or 7-8 km/h).

5. Conclusion and Recommendations

The following conclusions were reached by the results of the sudy:

1. The relationships among flow parameters (V-K-Q) as observed from the analysis of empirical data at the study sites are in general agreement with the ones documented in the literature.
2. Inclement weather appeared to have an impact on speeds and flow rates on both roadway sections studied. Rain reduced the average vehicular speed by 8 to 12% and light snow resulted in 65 to 66% traffic volume reduction. Rainy conditions also led to a 7-8% capacity reduction.
3. The impact of light snow, fog or haze on average speed as well as FFS on both bridge sections was minimal.
4. Wet surface conditions resulted in a reduction of average speeds by 6 to 7%.
5. The correlation between traffic flow parameters and weather temperature and surface tempereature was found to be statistically significant at 0.05 level.

Further analysis is recommended to validate the results from this work using data from other sites and/or other years of analysis. This is expected to increase the confidence on the value of the analysis and potential use of the findings to predict weather impacts on speed-flow relationships at locations outside the city of Istanbul. Moreover, as the new

2010 HCM manual becomes available in 2011. HCM considerations of weather impacts on capacicy should be revisited.

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