Comparison of Driver Behavior by Time of Day and Wet Pavement Conditions

Vinayak V. Dixit[1]; Vikash V. Gayah[2]; and Essam Radwan[3]

Abstract: This study uses the two-fluid model for traffic flow, to examine driver behavior during both wet and dry pavement conditions and various times of the day. It was found that parameters in the two-fluid model known to be strongly affected by driver behavior (particularly driver aggressiveness) were statistically different between wet pavement and dry pavement conditions. The results confirmed that drivers tend to behave more conservatively when the pavement was wet compared with dry. The parameters of the two-fluid model were found to be statistically different for the morning peak period from the midday and evening peak periods, the results of which indicated that drivers behave more aggressively during the morning peak. Although these findings have been observed in previous studies, they have not been quantified using traffic data. This study shows that the two-fluid model apart from being a measure of network performance may be able to unveil more about driver behavior. There is a strong possibility that the parameters of the model may be used by researchers as a surrogate measure of safety and could lead to a measure to evaluate aggressive driving. **DOI: 10.1061/(ASCE)TE.1943-5436.0000400.** © *2012 American Society of Civil Engineers.*

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Introduction

Urban traffic networks have been found to have lower average speeds during the evening peak period than during the morning peak period (Federal Test Procedure Review Project 1993). There are many possible explanations for this. Perhaps demand during the evening rush hour is more peaked than during the morning rush, causing higher densities and lower average flows in the morning. However, another possible explanation is that drivers may simply behave differently during the morning peak hours than evening peak hours.

A review of relevant literature found studies that support the conjecture proposed in the last statement. A study by Shinar and Compton (2004) found that drivers are more likely to commit aggressive acts during peak hours compared with nonpeak hours and weekends, even when controlling for the number of vehicles on the network. This finding is also consistent with findings by Kahneman et al. (2004), in which the authors found that morning commute was associated with increased negative feelings, such as anger, frustration, and depression. The increased likelihood of committing an aggressive act during peak period could be associated with the variable relationship between value of time and time of day; it is well known that drivers place a higher value on their time during peak periods than on the weekends and nonpeak periods (Tseng and Verhoef 2008). Several studies (Burris 2003; Peer et al. 2009) also suggest that the value of time premium placed during peak hour travel may be different during the morning and evening rush. This makes sense as drivers typically have much higher penalties associated with arriving late during the morning than during the evening (i.e., it is much more important for drivers to arrive to work in a timely fashion than to arrive home in a fashion after work).

These studies provide anecdotes of different driver behavior by evaluating measures such as number of aggressive acts, negative feelings, and value of time. The methods used to gather such data required a large amount of surveys and observations over a number of days. There is a need for a quantitative measure that can be used as a robust measure for traffic operations on urban networks and be able to capture differences in driver behavior. On the basis of recent studies by Dixit et al. (2011) and Park and Abdel-Aty (2011), the parameters of the two-fluid model developed by Prigorgine and Herman (1971) were shown to be directly correlated with crashes. Therefore, the two-fluid model may also be able to be used as a surrogate measure of safety on traffic corridors or networks.

The writers propose to use the two-fluid model to investigate changes in driver behavior for different time-of-day periods. The writers first show a clear relation between the two-fluid model parameters and driver behavior by examining the model parameters when drivers were known to drive more cautiously when the pavement is wet. The writers then compared the parameters during the a.m., middaym, and p.m. peak hours and found that drivers behave differently during the morning and evening peaks.

Two-Fluid Model and the Ergodic Assumption

The two-fluid model assumes that vehicular traffic flow in an urban network or street can be understood as consisting of stopped and running vehicles. The model describes the relationship between the vehicles' running speed (inverse of the time spent running per mile, 1 mile = 1.069 km) (v_r) and the fraction of running vehicles (f_r):

[1]Senior Lecturer, School of Civil and Environmental Engineering, Univ. of New South Wales, Sydney, 2052 (corresponding author). E-mail: v.dixit@unsw.edu.au

[2]Ph.D. Candidate, Univ. of California, Berkeley, 416G McLaughlin Hall, Berkeley, CA 94720. E-mail: vikash@berkeley.edu

[3]Professor, Civil, Environmental and Construction Engineering, Univ. of Central Florida, Orlando, FL 32816. E-mail: aeradwan@mail.ucf.edu

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$$v_r = v_m(f_r)^n \quad (1)$$

where v_r = running speed of the vehicles; f_r = fraction of running vehicles; and n = one of the two-fluid model parameters. When all vehicles are running (i.e., there are no stopped vehicles in the network, $f_r = 1$), the running speed (v_r) is equal to v_m. Therefore, v_m is defined as the average maximum speed, when no vehicles are stopped.

In general, the subscript r indicates that the variable is measured for vehicles that are running; and the subscript s indicates that the variable is measured for vehicles that are stopped; subscript m is used for the maximum speed or minimum travel time per mile.

Ardekani (1984), through field experiments, showed that it was possible to characterize urban networks using the two-fluid model. The study also used aerial photographs to validate the ergodic assumption of the two-fluid model. Which states that the ratio of running time per mile (T_r) to the travel time per mile (T) is equal to the ratio of the number of vehicles running to the total number of vehicles:

$$f_r = \left(\frac{T_r}{T}\right) \quad (2)$$

Using Eqs. (1) and (2), T_r, T, and T_m are reciprocals of v_r, v and v_m, respectively:

$$T_r = T_m^{1/n+1}\, T^{n/n+1} \quad (3)$$

Eq. (3) describes the relationship between the average travel time per mile (T) and the running time per mile (T_r). n and T_m are parameters of the two-fluid model and determine the sensitivity of the travel time per mile to the stopped time per mile. These parameters have been used in literature to describe the quality of traffic on the networks (Ardekani 1984). The travel time per mile is defined as the sum of the running time per mile and the stopped time per mile (T_S). Hence, Eq. (3) can also be written as

$$T_S = T - T_m^{1/n+1} T^{n/n+1} \quad (4)$$

Because stopped time per mile is a good measure of the level of congestion, it is sometimes useful to analyze the two-fluid model as a relationship between stopped time per mile and travel time per mile. Therefore, the two-fluid model identifies how the running time per mile changes for different levels of congestion (stopped time per mile), and the parameters of the model are independent of the level of congestion.

Two-Fluid Model and Network Performance

Earlier works (Vo et al. 2007; Ardekani 1984) have utilized the parameters (n, T_m) as indicative of the quality of service of the networks. Ardekani (1984) developed two-fluid models for urban traffic networks for various cities (Fig. 1) by collecting data using the chase-car methodology in which a driver was instructed to follow a randomly selected vehicle until it either parks or leaves the designated network. Based on the models, it was inferred that a city that had the highest y-intercept (i.e., T_m) and the steepest slope (i.e., n) was the worst performing network. As shown in Fig. 1, we can compare how the travel time per mile is different for a given stopped time per mile (congestion) in two different networks. The inference was based on the idea that a higher value of n suggests that the travel time increases at a faster rate as the stopped time increases, indicating that the network deteriorates rapidly during congestion. Also, the higher the value of T_m means lower free-flow speeds. Based on these data, Austin, Texas, can be considered to be the best performing network, whereas Matamoros, Mexico, was the worst performing network.

Recently, Vo et al. (2007) conducted a before-after (1994 versus 2003) study of the Arlington, Texas, network and observed that there has been no significant change in the performance of the

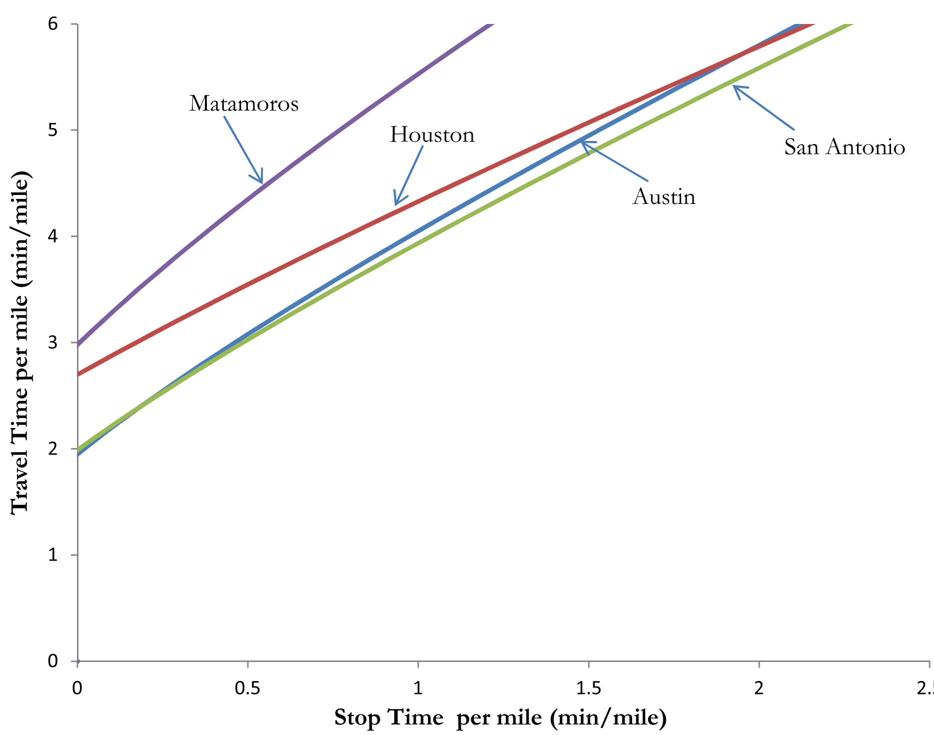

Fig. 1. Two-fluid model for various cities (Data from Herman and Ardekani 1984) (1 mile = 1.069 km)

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network despite large numbers of projects to improve the network. Similar analyses were performed for the Dallas and Fort-worth networks in Texas. The two-fluid model lends itself well to evaluate quality of traffic of an urban network, because it is able to capture how the travel time per mile changes with a unit increase in stopped time per mile (i.e., how the network behaves as it becomes congested).

Two-Fluid Model and Driver Behavior

The parameters in the two-fluid model have also been found to be affected by driver behavior on a network. This was first discovered by Herman et al. (1988), who studied the effects of extreme driver behaviors on the two-fluid model. This study found that a test car driver instructed to drive aggressively established a significantly different two-fluid trend than one instructed to drive conservatively in the same network at the same time. The aggressive drivers were found to have a consistently lower T_m than normal drivers, and normal drivers have a consistently lower T_m than conservative drivers. It was also found that all three trends converged for higher congestion levels. This is shown in Fig. 2. This makes sense because, as a network becomes more congested, drivers have fewer opportunities to improve their speeds through aggressive acts.

Two-Fluid Model and Safety

Additionally, a recent study by Dixit et al. (2011) also showed that the parameters in the two-fluid model that are affected by driver behavior were strongly correlated with crashes on signalized arterial corridors and suggested the use of the two-fluid model as a surrogate for traffic safety. Park and Abdel-Aty (2011) extended this work to develop a proactive network screening tool that estimates the crash rate using a stochastic cusp catastrophe model with the two-fluid model's parameters as inputs.

Thus, the two-fluid model is not only able to characterize the dynamics of travel time per mile as it relates to stopped time per mile, but also capture the effects of driving behavior and safety. The ability of the two-fluid model to holistically evaluate urban traffic makes it an attractive method to study differences

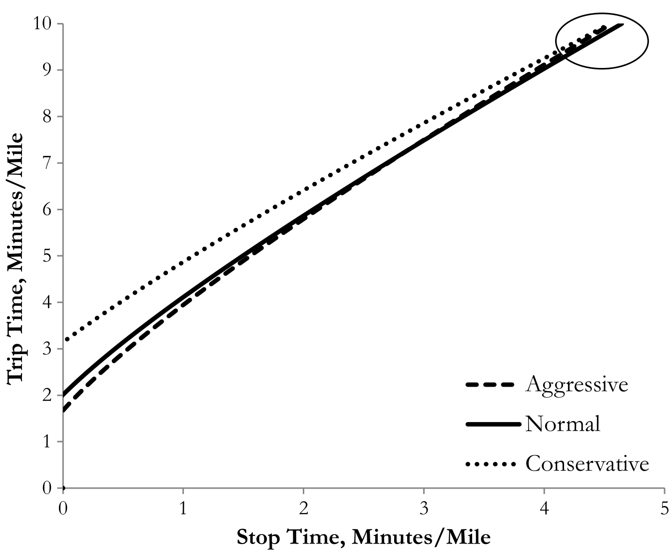

Fig. 2. Two-fluid trends for aggressive, normal, and conservative drivers in the Austin CBD (Data from Herman et al. 1988) (1 mile = 1.069 km)

in performance during wet and dry conditions, and at different times of the day.

The rest of this paper is organized as follows. The first section gives details on the network that was used for this study and calibrates the two-fluid model aggregating data over several times of day and pavement wetness conditions as is typically done in network analyses. The next section segregates the data into various pavement wetness populations to show a change in the two-fluid model parameters attributable to driver aggressiveness, whereas the following section segregates the data into various time-of-day populations. The final section provides concluding remarks and implications for future use of the two-fluid model as a network performance analysis tool and safety.

Data Collection

For this study, data were collected from the downtown Orlando, Florida, traffic network; the boundary of this network is shown in Fig. 3. The portion of the Orlando downtown network considered in this study was an approximately 1.7×1.7 mile network with approximately 120 signalized intersections, with an average cycle length of approximately 100 s.

Data were collected on two typical weekdays, Tuesday, February 19, 2008, and Thursday, February 21, 2008, for three distinct time periods: a.m. peak (7:30–9:00 a.m.), midday (11:45 a.m.–1:15 p.m.), and afternoon peak (5:00–6:30 p.m.), using the chase-car methodology. A 1-mile travel segment was considered as a trip. Travel time, running time, and stop time data were collected for multiple 1-mile trips. In the chase-car method adopted in this study, the driver follows a randomly selected vehicle until it leaves the network, parks, or the chase requires unsafe and/or illegal maneuvers, after which the next vehicle is selected for following. While transitioning from one vehicle to the next, the vehicle is driven normally with respect to surrounding traffic. The two-fluid model was estimated, based on the travel times that were recorded per mile by the chase car. Through this method it is expected that the data collected would be representative of the behavior of drivers in the network. An observer accompanies the driver on the data collection trips and records the odometer readings and the absolute travel time and stopped time corresponding to the start and end of each trip. During the three time periods on the two days, 2 vehicles collected trip-related data. This chase-car methodology was also used in two-fluid model studies conducted by Ardekani (1984), Jones and Farhat (2004), and Vo et al. (2007). Because there were two vehicles collecting data by randomly following cars throughout the network, it was assumed that the trip data collected sufficiently represented the average behavior of the road network users, because it samples trips in the network based on routes taken by an average driver.

As noted by Prigorgine and Herman (1971) and Ardekani (1984), the two-fluid model is defined for urban arterial networks. Therefore, the data collection did not include freeways. Table 1 presents a summary of the number of observations collected for each day and time period. Each observation shown in Table 1 represents a 1-mile trip. The data from Tuesday, February 19, 2008, and Thursday, February 21, 2008, were pooled together for the a.m. and evening peaks. Therefore, there was a total of 44 trips for the a.m. peak and 41 trips for the afternoon peak. Because there was rain during the midday period of Thursday, February 21, 2008, the data from the 2 days could not be pooled. But there were still 29 trips available for the dry midday on February 19, 2008, and 15 trips for a wet midday on February 21, 2008. The road surface had dried by the evening, and the data

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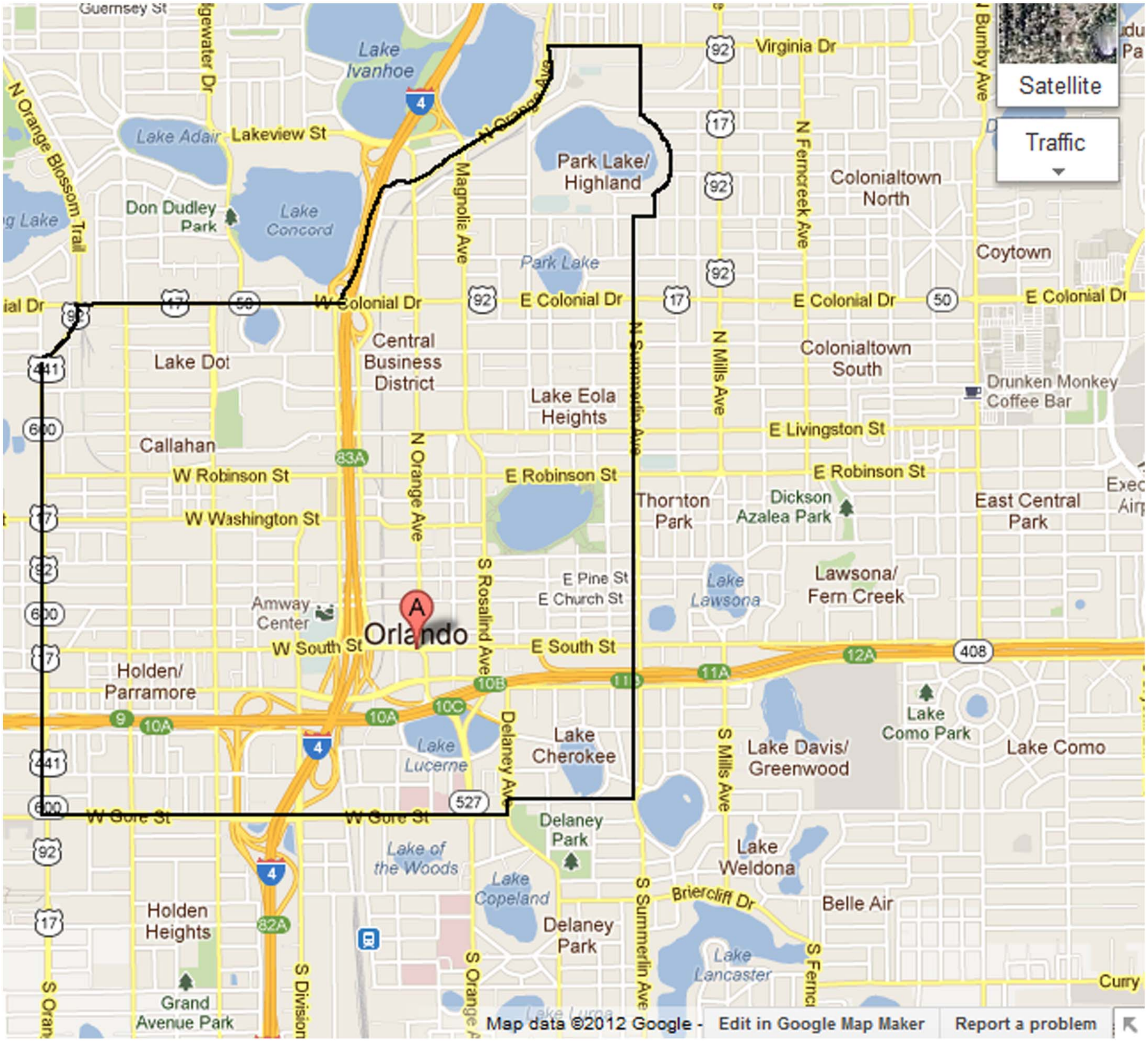

Fig. 3. Orlando downtown network analysis area (Map data © 2012 Google)

collected during the p.m. peak on February 21, 2008, were under dry conditions. Because there were two vehicles collecting data by randomly following cars throughout the network, it was assumed as in previous studies that the trip data collected sufficiently represented the network.

Estimation Method

The two-fluid model parameters were estimated using the travel time per mile and running time per mile information collected for the downtown network. Taking a logarithm of both sides of Eq. (3) yields

Table 1. Number of Trip Observations Made Based on Time of Day

Day	Time period	Number of observations (trips)	Range of stop time per mile minimum-maximum (min)	Range of travel time per mile minimum-maximum (min)
Tuesday, February 19, 2008	A.m. peak	28	0.45–3.92	2.49–7.88
	Midday (dry)	29	0.33–8.94	3.01–12.44
	Evening peak	34	0.17–6.68	2.26–9.74
Thursday, February 21, 2008	A.m. peak	16	0.43–5.03	3.09–8.97
	Midday (wet)	15	0.44–5.33	3.04–9.62
	Evening peak	17	0.09–10.21	2.15–15.02

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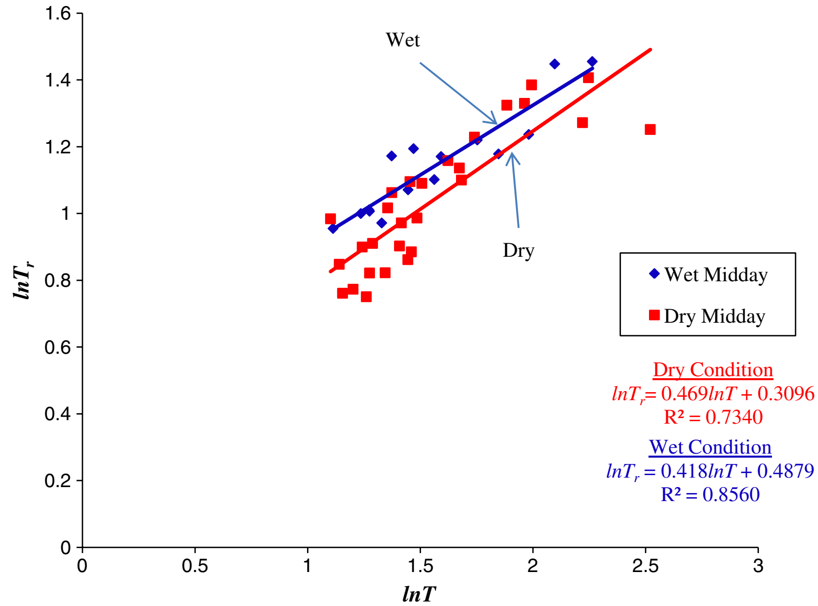

Fig. 4. Two-fluid model data for wet and dry pavement during the midday peak

$$\ln T_r = \frac{1}{n+1}\ln T_m + \frac{n}{n+1}\ln T \tag{5}$$

This can be rewritten as

$$\ln T_r = B\ln T + A \tag{6}$$

The coefficients A and B are estimated using linear regression between $\ln T_r$ and $\ln T$ and the two-fluid model parameters n and T_m are estimated using Eqs. (5) and (6) as:

$$n = \frac{B}{1-B} \tag{7}$$

$$T_m = e^{A/1-B} \tag{8}$$

For example, Fig. 4 shows the data for the dry and wet pavement sections, along with the coefficients A and B estimated from linear regression.

Effect of Pavement Wetness

On February 21, rains occurred during the midday period, resulting in extremely wet pavement conditions during this time. One would expect that drivers would drive conservatively during this period because it was very clearly not as safe. That was confirmed by reports from the observer in the chase car, which stated that drivers were behaving extremely cautiously during this time period. Therefore, the writers first compare the two-fluid model parameters using the data from the midday period for both February 19, which had dry conditions, with data collected on February 21, which had wet conditions, to see what parameters are different when drivers behave more cautiously. The parameters of the two-fluid model were estimated based on the method described in the section titled "Estimation Method."

Fig. 4 and Table 2 show that $A_{\text{wet}} > A_{\text{dry}}$ and $B_{\text{wet}} < B_{\text{dry}}$. An unequal variance two-sample t-test was conducted between these coefficients, and the difference in the value of A was found to be statistically significant to a 90% confidence level (Table 3). The values of the two-fluid model parameters T_m and n obtained from the linear regression are also displayed in Table 2.

Because B is a monotonic function of n, statistical differences in B would imply that n would be different for two samples. But because A is a function of both T_m and n it would be harder to infer whether differences in A were attributable to T_m or n. In the case of wet versus dry conditions, no statistical difference was observed for the two Bs; this implies that the n for the wet and dry conditions were not statistically different. But because A was found to be statistically different, whereas the n was not statistically different, it could be concluded that T_m for the two were statistically different.

It was observed that the two-fluid model was able to capture drivers' lower free-flow speed preference when pavement conditions are wet [$v_m = 25.94$ mi/h (41.75 km/h)] than when they are dry [$v_m = 33.50$ mi/h (53.91 km/h)]. Although the results are expected and agree with earlier findings (Kyte et al. 2000; Prevedouros and Kongsil 2003; Agarwal et al. 2005) of reduction in free-flow speeds during wet conditions, there is no study that compares the dynamics of how the travel time changes as the stopped time per mile (congestion) changes under wet and dry conditions. The two-fluid model is not only able to characterize the dynamics of travel time per mile as it relates to stopped time

Table 2. Two-Fluid Model Parameters for Wet and Dry Pavement during the Midday Peak

Pavement conditions	A Mean (standard error)	B Mean (standard error)	T_m (min/mile) [min/km]	n	R^2	v_m[a] (miles/h) [km/h]
Dry	0.31 (0.09)	0.47 (0.06)	1.79 [1.11]	0.88	0.73	33.50 [53.91]
Wet	0.49 (0.09)	0.42 (0.05)	2.31 [1.44]	0.71	0.86	25.94 [41.75]

[a] v_m is the average maximum speed when no vehicles are stopped.

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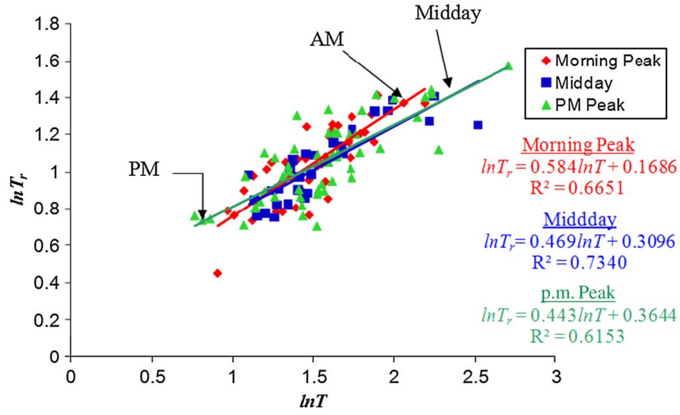

Fig. 5. Two-fluid model for different times of day for Orlando

per mile, but also to capture driving behavior. Thus, although it is not surprising to find that individuals drive conservatively on wet pavements, it is important to recognize that the two-fluid model is able to capture this phenomenon.

Effect of Time of Day

The two-fluid models for the three times of day populations (a.m. peak, midday peak, afternoon peak) are presented in Fig. 5. The method described in the "Estimation Method" section was used to estimate the parameters A and B from each population according. A summary of these data are presented in Table 4. Data during wet pavement conditions were excluded from the midday period analysis to ensure that the results were not biased by inclement weather.

As shown in Fig. 5 and Table 4, $A_{\text{a.m.}} < A_{\text{Midday}} < A_{\text{p.m.}}$ and $B_{\text{a.m.}} > B_{\text{Midday}} > B_{\text{p.m.}}$. An unequal variance two-sample t-test was undertaken between the estimated coefficients for the different time-of-day populations (Table 3). As shown, the difference in the coefficients for the midday and evening peak periods were not statistically different. However, the difference in the B between the a.m. peak period and the other two time periods is statistically different to a 90% confidence level.

The evening peak and midday peak were found to have similar two-fluid model trends with no statistical differences for coefficients B and A. Therefore, it could be inferred that T_m and n are statistically not different between the midday and evening peak. While comparing the a.m. and midday peak, a statistically significant difference was found for B, indicating the n was statistically larger for the a.m. peak than the midday peak. Because A is inversely related to n, and the A for the a.m. and midday peak were not found to be significant, it implies that differences in T_m counteracts the difference in n, therefore it can be concluded that T_m is statistically smaller during the a.m. peak than the midday peak. In the case of a comparison of morning and evening peak, it was observed that B for the a.m. peak was statistically larger compared with the evening peak, indicating that n was statistically larger for the a.m. peak than the p.m. peak. A was found to be statistically smaller for the a.m. peak compared with the p.m. peak, which indicates that T_m for the a.m. peak was smaller than that for the p.m. peak.

There are several reasons why these parameters may change as shown in various studies: signal density, average speed limit, average number of lanes per street, fraction of one-way streets, fraction with actuated signals, average block lengths, and average cycle length (Ayadh 1986; Ardekani et al. 1992; Bhat 1994). Of these, only the cycle length and fraction of actuated signals could change within the course of a day. However, during these three time periods, the average cycle length was relatively constant, and the number of actuated signals did not change (as confirmed by traffic engineers from the city of Orlando). The only changes were the phasing of the signals, and this was just done to reverse the directional priority provided to traffic during the a.m. and p.m. peaks. Thus, the difference in the coefficients could be attributed to changes in driver behavior during these time periods.

It was observed that drivers prefer speeds that are faster during the a.m. peak period [$v_m = 40.04$ mi/h (64.44 km/h)] than during the evening peak period [$v_m = 31.20$ mi/h (50.21 km/h)]. Also, comparing the a.m. and p.m. peaks it was found that the a.m. peak period has a lower value of T_m and higher value of n. Based on the results of Herman et al. (1988), these values are consistent with more aggressive driver behavior. The writers conjecture that this is attributable to the higher value of time that drivers place during travel during the morning and during the evening. This makes sense because there is a clear objective and penalty for travel during the a.m. peak (arriving to work on time, avoiding being late for work). Thus, drivers tend to drive more aggressively to reach their workplace on time during the a.m. than they tend to drive to reach home after work.

Discussion

Aggressive or conservative driving is a result of driver's perception of risk and attitude to risk of a crash, while trying to get to the destination as quickly as possible. The perceptions of risk are a function of road geometry, signal systems, signage, speed limits, and the road environment in general. These factors have been found to affect the two-fluid model in past studies (Ayadh 1986; Ardekani et al. 1992; Bhat 1994). As part of this study, wet and dry pavement was found to affect driver behavior. One possible explanation for this is that drivers perceive a higher likelihood of crashing on wet pavements, which results in them driving more conservatively, therefore apart from the geometric and signal factors identified

Table 3. Statistical Difference between the Coefficients of the Two-Fluid Model Using t-Test

Comparison	Difference in A (P-value)	Difference in B (P-value)
Dry versus wet	−0.18 (0.08)	0.05 (0.25)
A.m. and evening peak	−0.19 (0.06)	0.11 (0.04)
A.m. peak and midday	−0.14 (0.14)	0.14 (0.09)
Evening peak and midday	0.05 (0.25)	−0.03 (0.27)

Table 4. Two-Fluid Model Parameters Segregated by Time of Day

Time of Day	A mean (standard error)	B mean (standard error)	T_m (min/mile) [min/km]	n	R^2	v_m (miles/h) [km/h]
A.m. peak	0.17 (0.10)	0.58 (0.06)	1.50 [0.93]	1.40	0.66	40.04 [64.44]
Midday	0.31 (0.09)	0.47 (0.06)	1.79 [1.11]	0.88	0.73	33.50 [53.91]
Evening peak	0.36 (0.08)	0.44 (0.05)	1.92 [1.19]	0.79	0.62	31.20 [50.21]

in earlier studies, pavement conditions impact driver behavior. Although this result (that drivers may be more cautions when the driving surface is wet) is not surprising, it is interesting to find that the two-fluid model showed a clear statistical different during wet pavement conditions.

In addition, based on the results of the two-fluid model, driver behavior was found to be different during the a.m. peak, compared with the midday and p.m. peak. Although this has been found through surveys regarding negative feelings, value of time, and aggressive acts (Burris 2003; Shinar and Compton 2004; Kahneman et al. 2004; Tseng and Verhoef 2008; Peer et al. 2009), the two-fluid model was able to capture behavioral variations, such as aggressive and conservative driving.

These observations in conjunction with earlier findings by Dixit et al. (2011) and Park and Abdel-Aty (2011) that indicate that the parameters of the two-fluid model can be used as surrogate measures of safety provide a possibility for use of the two-fluid model to measure the aggressiveness and safety. Although free-flow speed versus speed limit or speed variance provides simple and good measures for aggressiveness, they are unable to track aggressive driving over a range of congestion (stopped time per mile). By using the two-fluid parameters as a surrogate could help in determining whether certain calming measures undertaken have helped improve safety without having to wait for sufficient crash data to be accumulated. However, this potential needs to be investigated further, with data for two-fluid models collected from multiple roadways from around the country.

The ability of the two-fluid model to evaluate aggressive driving behavior may possibly be extended to capture the effect of weather, road conditions, and various road infrastructures on the two-fluid model. This understanding can then be used to develop policy and engineering solutions for promoting safe driving. For instance, recognizing that drivers drive more aggressively during the morning could be discouraged through higher level of enforcement during the morning or development of engineering solutions to reduce aggressiveness, such as deploying speed reader signs.

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