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A Methodology of Quantifying Precipitation Exposure for Wet-Weather Collisions and Evaluating Effectiveness of Open-Grade Asphalt Concrete as a Countermeasure

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ABSTRACT

Weather-related crashes represent a significant concern in roadway safety. Wet collisions often resulted in injuries or fatalities, at a ratio higher than collisions that occur in dry roadway conditions. Therefore, it is of strong interest to identify and manage the locations where collisions are prone to happen under wet pavement surface or adverse weather conditions. This paper introduces a method to estimate precipitation exposure of roadway segments by linking weather station data to collision database. Subsequently, the corresponding crash rate for a subject location is calculated based on the concept of conditional probability. The method is then applied to quantify and compare the wet collision rates of some study sites before and after pavement projects of installing Open Graded Asphalt Concrete (OGAC), a pavement countermeasure commonly adopted for wet collision reduction. The findings demonstrated that OGAC offered the reduction of wet collisions at a large fraction of the study sites.

INTRODUCTION

Adverse weather conditions and wet pavement surface often present significant roadway hazards leading to crashes. Wet collisions often result in injuries or fatalities, at a ratio higher than collisions that occur in dry roadway conditions. A considerable body of literature has explored such issues [1-7]. Precipitation or rain has compounding effects on driving conditions. It may result in decreased visibility, which in turn causes drivers to respond untimely to situations on the roadways. In addition, the surface provides a reduced friction between vehicle tires and pavement surface, which further lessens the ability of drivers to maintain and control the vehicles in a responsive manner.

To mitigate the problems of wet-weather collisions, drainage or surface improvements are often installed as safety countermeasures. It is of great importance, from the perspective of roadway operating and maintenance agencies, to assess the exposure of wet collisions especially for those high-risk roadway segments and to determine the effectiveness of safety countermeasures. This paper describes the work conducted in a recent study in California to evaluate the performance of pavement improvements projects, with a selection of Open-Grade Asphalt Concrete (OGAC) installation. OGAC is known to allow water drainage relatively quickly and to reduce the splashing effects of water on roadway surface; therefore it is expected to improve driving conditions under wet-weather conditions [8, 9]. The focus of this paper is to introduce a method of estimating precipitation and wet surface exposure for a specific site, and then apply the methodology for a before-after evaluation of the safety performance of these OGAC installation sites.

In order to calculate the collision rates before and after a construction project, it is necessary to correctly estimate the exposure to precipitation and wet surface conditions. The duration of wet roadway condition and the amount of precipitation are two significant factors that affect the occurrence of wet-weather related collisions [10, 11]. Some studies have adopted an approximate method to estimate the time of wet pavement condition affecting crashes by using hourly precipitation data [12, 13]. However, the residual effect of wet surface after precipitation was not taken into account. To compensate for this residual effect, a methodology for estimating precipitation exposure with regional weather data was proposed and developed to allow better representation of traffic flow exposure to precipitation.

ESTIMATION OF WET COLLISION EXPOSURE

A collision rate is an index representing the risk of collisions within a roadway section by taking into account the exposure relevant to the related collisions. In general, this is formulated as a number of collisions divided by the length of road section and traffic volume, for a specified time period. The calculation of a wet collision rate is calculated similarly, but only accounting for the collisions occurring under wet conditions. Typically, the information about the wet condition of roadway surface is relying on the entry of such indicators on police reports.

To quantify the exposure of traffic flows to wet collisions for a roadway section, the crash rate should be calculated by dividing the number of wet collisions by the traffic volume passing through the subject roadway under wet surface conditions. In other words, instead of total number of traffic volume and collision within a certain section, only traffic volume passed and collisions occurred on the section of wet pavement are included in wet collision rate calculation defined by Equation 1.

$$\text{Wet collision rate} = \frac{\text{Number of wet collision}}{\text{Length of road section (mi)} \times \text{Traffic volume passed on wet pavement section (Veh.)}} \quad (1)$$

This wet collision rate is the average number of collision, given the occurrence of an event that a vehicle travels on a wet road surface. This expected value of conditional probability can be represented as Equation 2 below.

$$\text{Wet collision rate} \times \text{Length of road section (mi)} \cong E(B|A) = B \times P(B|A) \quad (2)$$

Where

A is the event that road surface is wet, and

B is the event that a car traveling on a certain road is involved in a collision.

In order to quantify this wet collision rate, the exposure to wet conditions based on traffic volume during wet-surface periods is needed. To provide accurate estimates of such numbers, the time period when the road surface is wet and traffic volume during that time period will be required. In this paper, a method is introduced to systematically acquire and calculate the time periods and traffic volume for the estimation of wet collision exposure. More details of the methodology are provided in the following section.

Once the time period of wet weather exposure is available, the wet collision rate in Equation 1 can be revised and expressed as Equation 3.

$$R_{wc_i} = \frac{C_{w_i}}{L_i \times (ADT_i \times \frac{1}{24}) \times H_{w_i}}, \quad i \in I \quad (3)$$

Where

- R_{wc_i} : Wet collision rate (col./mi/veh) on road section i ;
 C_{w_i} : Number of wet collision on road section i ;
 L_i : Length (mi) of road section i ;
 ADT_i : Average daily traffic volume (veh/day) on road section i ;
 H_{w_i} : Hour of wet condition on road section i ;
I: all road sections over the state.

In Equation 3, the hourly average traffic volume is estimated by dividing the average daily traffic by 24, since the precise hourly traffic data may not be available for a majority of roadways. However, this is not a limitation of the method, as more and more roadways are being equipped with traffic monitoring systems to provide real-time traffic volume with greater resolution and higher accuracy.

WET WEATHER EXPOSURE BASED ON PRECIPITATION DATA

With regard to the wet weather and wet surface conditions, the method suggested in this paper is based on the following hypotheses:

- (1) The time period when the road surface was potentially wet could be derived from the hourly precipitation data of a nearby weather station, and
- (2) There is a lingering or residual effect of the precipitation, which caused the road surface to remain wet for a sustained period even if rain fall had stopped.

The rainy hour for a specific site can be obtained from the hourly precipitation data of weather stations, such as those from the National Weather Service provided by National Oceanic and Atmospheric Administration, near the targeted road section. There may be more than one weather station in the vicinity of a chosen study site. Due to the dynamic nature of weather patterns and the possibility of micro-weather conditions, the best choice of a weather station may not be the one that is closest in distance to the study site.

For the current study, to choose a most reliable source of precipitation data, the following steps were taken:

- (1) Precipitation data were downloaded from weather stations,
- (2) Collision records of the same period were extracted from the California Traffic Accident Surveillance and Analysis System (TASAS), in which road surface condition and weather information are available.
- (3) The weather station with precipitation data that match the collision records with the highest percentage is considered the best-fit choice for further evaluation.

The procedure explained here will be illustrated in case studies presented in a section below. It should be noted that it is unavoidable that this process of estimation is not completely accurate due to complicating factors. For example, the collision records may not be completely accurate, and the timing of precipitation and roadway conditions are not necessarily synchronous. Nevertheless, this approach provides at least a well-grounded and systematic procedure of selecting a reliable method of acquiring precipitation data.

The period, during which roadway surfaces remain wet after rain falls, depends on precipitation amount, climate conditions, and roadway geometry. The residual effect of precipitation on roadway surface certainly varies from site to site and likely from time to time as well. Although a case-by-case analysis may more accurately represent the local variations of wet surface exposure, a more general approach is still desirable for the purpose of providing a system tool. To facilitate an overall system-wide assessment of wet surface exposure, a procedure was developed to estimate this time lag of precipitation residual effects. The residual effect of precipitation and the in-effect wet surface conditions can be examined by the distribution curve of precipitation hours versus the occurrence of wet collisions afterwards. Once the distribution curve is established, then a cut-off or maximum allowed time lag can be selected to account for the significant period of residual effects. Furthermore, statistical tests can be conducted to evaluate the time lag between wet collision and precipitation.

After precipitation stops for an extended period time, the occurrence of wet collisions is expected to decrease or disappear. At a certain time after raining, the association between the time since last precipitation and wet collisions becomes weak or non-existent. The maximum lag time is defined as the time period from last precipitation to a time when the aforementioned association is sufficiently weak or non-existent. In the case study of this paper, the maximum lag is estimated by examining the distribution curve representing the number of wet collision and time after last precipitation.

DATA SOURCES

In order to quantify the wet collision rate, three categories of data sources are needed: freeway traffic collision, traffic volume and hourly precipitation data. These data are acquired from the following sources:

- 1) Freeway Collision Data: TASAS (Traffic Accident Surveillance and Analysis System)
- 2) Traffic Volume Data: Caltrans Data Branch website, <http://traffic-counts.dot.ca.gov/>
- 3) Weather Station Information and Hourly Precipitation Data: NOAA (National Oceanic and Atmospheric Administration) website, <http://www.ncdc.noaa.gov/>

In California, state highway collisions reported by police officers and stored into the TASAS database. TASAS database contains a number of variables documenting the conditions of the collisions. From this data, the wet collisions from a number of study sites are extracted. The collision data of study sites over a 12-year period from 1994 to 2005 were used for before and after study.

In quantifying the wet collision rate, it will be ideal to use real time traffic volume, but this type of information is not necessarily available for all locations. Some of the study sites are located in rural areas, and there is no traffic monitoring system in place to provide hourly traffic data. Instead of using real-time traffic volume, the Average Annual Daily Traffic (AADT) provided by Caltrans Data Branch is used. Since this data is updated annually, the wet collision rate of study sites is calculated year by year accordingly.

NOAA provides the weather data at a number of weather stations across the country. The data from NOAA is acquired and processed according to the process defined in a previous section. As a first step, the precipitation data from 1994 to 2005 of all weather stations located within 20

miles from study sites are downloaded. Subsequently, one weather station was identified to provide the best-matching precipitation data for each individual study site.

Study Sites

In recent years, Caltrans has installed OGAC as a safety countermeasure against wet collisions in a number of locations. Thirteen study sites, which have sufficiently long before and after periods of data representation, are selected for this case study. The segment length and construction duration of these sites are given in Table 1. The shortest length of study site is 0.21 mile, and the longest one is 18 mile, and the average length of 13 sites is 3.13 miles. Attributes such as geometry, location, weather, and segment length were quite diverse among the study sites.

TABLE 1 Study Site with OGAC Pavement Installation

Site Number	Length (mile)	Started Date of Construction	Finished Date of Construction
Site 1	0.21	1997-10-29	1998-07-17
Site 2	0.5	1997-08-28	1998-07-17
Site 3	0.5	1997-08-28	1998-07-17
Site 4	0.4	1997-08-28	1998-07-17
Site 5	3.7	2001-07-31	2002-10-29
Site 6	0.5	1995-03-28	1999-12-16
Site 7	0.8	1999-01-04	1999-06-24
Site 8	0.5	2001-06-29	2002-09-17
Site 9	0.3	2001-06-29	2002-09-17
Site 10	18	2001-06-29	2002-09-17
Site 11	3.9	2000-11-13	2002-12-16
Site 12	8	2000-09-26	2001-09-11
Site 13	3.4	2001-06-29	2002-09-17

Weather Station Selection

As described above, a procedure for identifying the best-matching weather station for a study site has been proposed for this study. First, the list of weather stations located within 20 miles from study sites with hourly precipitation data from 1994 to 2005 is achieved from NOAA. Next, the time of collision occurred on study sites and weather information at that moment is extracted from TASAS. Subsequently, the weather condition variables of TASAS collision records are compared with the hourly precipitation information at the time of collisions. If a non-zero hourly precipitation record corresponds with a wet-weather record in TASAS, then it is considered a potential matched sample.

The suitability of one weather station to be used for one study site is evaluated by the percentage of matching samples between TASAS and precipitation data. There are two probable matching pairs. One is that a non-zero hourly precipitation data matches with a collision that was reported to have a “rainy” weather condition. The other is that a zero-precipitation data point corresponds

to a collision record with “dry” weather condition. The preferred weather station having the most suitable precipitation data for a study site is the one with higher matching percentage in both categories. Table 2 shows the number of weather stations within twenty miles from all study sites and the matching percentage of the best-matching percentage among these weather stations for each site. Once the preferred weather station is chosen, its precipitation data will be used for later analysis.

TABLE 2 Accuracy of Weather Station Information

Site Number	Number of Weather Stations within 20 miles	Matching Percentage of Weather Station	
		Rainy Hour	Not-rainy Hour
Site 1	6	60%	100%
Site 2	7	60%	94.7%
Site 3	8	58.3%	100%
Site 4	8	25%	100%
Site 5	4	65.2%	98.2%
Site 6	6	85.7%	90.6%
Site 7	15	89.5%	98.7%
Site 8	10	87.5%	100%
Site 9	12	77.8%	91.3%
Site 10	1	75%	98.4%
Site 11	8	70.6%	95.2%
Site 12	9	89.3%	98.4%
Site 13	9	75%	93%

ESTIMATION OF PRECIPITATION HOUR AND RESIDUAL TIME LAG

Following the procedure explained above, the 13 study sites were matched with the preferred weather station providing the best-matching precipitation data. In this section, the distribution of precipitation versus all wet-condition conditions in collision database is investigated to estimate the maximum time lag for estimating the residual effects of precipitation on roadway surface conditions. Note that in each collision record, there is one variable indicting weather condition as “rainy” or “dry.” There is another variable identifying the pavement surface to be “dry” or “wet.” A wet collision refers to a collision where pavement is wet, but it does not necessarily means that the weather condition is still rainy.

The maximum time lag represents the time period of residual effects from precipitation to have maintained the wetness on the road surface until the association with wet collisions has become weak or non-existent. To estimate the maximum lag, the time record of a wet collision from

TASAS is compared with the time of precipitation from weather stations. The time difference between the collision time and the last hourly precipitation data point is calculated for each incident. Figure 1 shows the number of wet collisions of all study sites from 1994 to 2005 versus the time gap between the collision time (in hours) and the last precipitation data sample. It can be seen that the distribution of wet collisions decrease rapidly in the first few hours of last precipitation intervals. For the purpose of discussions, the maximum time lag is chosen to be 6 hours.

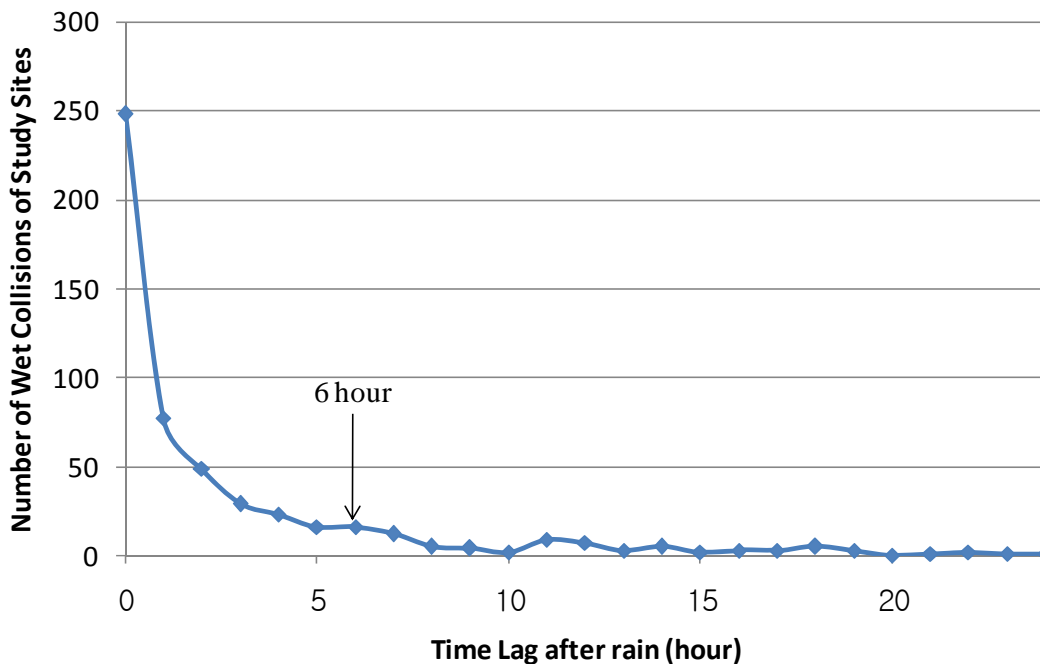


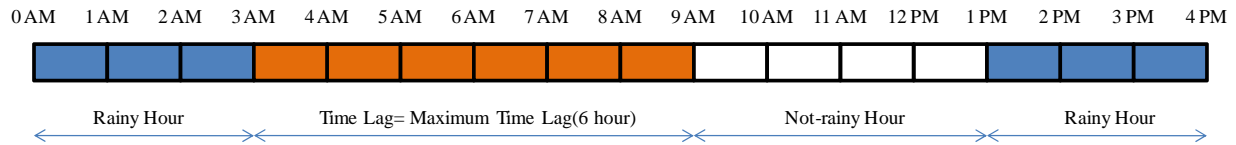
FIGURE 1 Number of Wet Collisions of Study Sites versus Time Lag from Last Precipitation

The maximum time lag will be used for estimating the traffic flow exposed to potential wet pavement conditions. The maximum lag is used in the following manners:

- (1) If no precipitation occurred within six hours, the time lag is defined to be six hours.
- (2) If precipitation occurs again within six hours, then the definition of maximum time lag is reset for the next precipitation interval.

Figure 2 shows two examples estimating the lag time. In the case of (a) in figure 2, the time lag is determined as the maximum lag, while in the case of (b), the lag is determined as four hours.

(a) Time lag same as the maximum lag



(b) Time lag less than the maximum lag

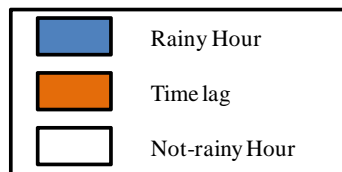
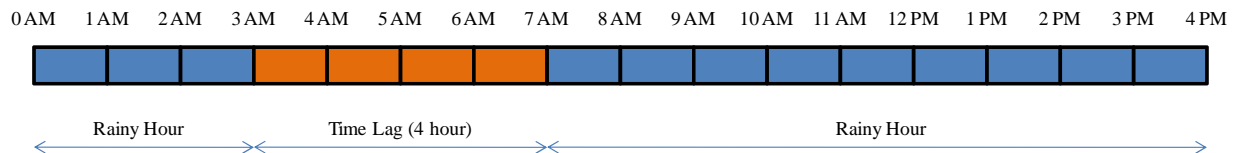


FIGURE 2 Two Examples Measuring Lag Time

BEFORE AND AFTER COLLISION ANALYSIS OF OGAC STUDY SITES

In this section, the processed data according to the procedure described in the pervious section is applied to the study sites to compare the exposure and safety performance of the study sites where OGAC was installed. OGAC is a pavement type with more voids percentage to make a better drainage capacity than the regular pavement materials. It is expected to drain water on road surface more effectively and potentially to reduce the probability of wet collision occurrence. The list of study sites has been given in a section above.

Wet Collision Rate Quantification

As an illustration of the suggested methodology, a before-after comparison is made by using the yearly collision rates. Equation 3 is revised into Equation 4 below so that the wet collision rate is represented by an average of annual wet collision rates using AADT.

$$\bar{R}_{wc_i} = \frac{\sum R_{wc_i,t}}{T} = \frac{1}{L_i} \sum \frac{C_{w_i,t}}{(ADT_{i,t} \times \frac{1}{24}) \times H_{w_i,t}}, \quad i \in I \tag{4}$$

Where

- \bar{R}_{wc_i} : Average wet collision rate (col./mi/veh) on road section i;
- $R_{wc_i,t}$: Wet collision rate (col./mi/veh) in year t on road section i;
- T: Total number of years;
- L_i : Length (mi) of road section i;

$C_{w_{i,t}}$: Number of wet collision in year t on road section i;

$ADT_{i,t}$: AADT (veh/day) in year t on road section i;

$H_{w_{i,t}}$: Total hours of wet condition in year t on road section i, sum of rainy hour and lag;

I: study sites.

For the before-after study, the annual collision rates are averaged separately before and after the installation of OGAC, and then compared. Thus, total number of years (T) in the equation of wet collision rate before the installation of OGAC is the duration from 1994 to the starting year of installation, and for the after period is the duration from the completing year of installation to 2005. Note that there are other methods to evaluate the safety performance, especially if the yearly values fluctuate considerably. If desired, other safety indexes can always be adopted to supplement the final assessment.

Table 3 and Figure 3 show the result of wet collision rates calculated above, and compare their values before and after OGAC installation. Among thirteen study sites, after the OGAC was repaved, the wet collision rates of nine sites decreased, and those of four sites increased.

TABLE 3 Wet Collision Rate Before and After OGAC Installation

Site Number	Wet Collision Rate (Col./mi/MVT)		Ratio of Wet Collision Rate (y/x)
	Before Construction (x)	After Construction (y)	
Site 1	49.22	14.28	0.29
Site 2	5.54	10.96	1.98
Site 3	8.26	55.51	6.72
Site 4	16.93	32.29	1.91
Site 5	1.70	1.07	0.63
Site 6	5.52	1.52	0.27
Site 7	2.38	2.38	1.00
Site 8	7.61	5.68	0.75
Site 9	17.48	5.26	0.30
Site 10	0.22	0.37	1.65
Site 11	2.03	0.46	0.22
Site 12	1.34	0.50	0.37
Site 13	1.91	0.25	0.13

Among the four sites with increased collision rates, the absolute values of wet collision rates at Site 10 are comparatively small in comparison with other sites. On the other hand, Site 2, 3 and 4 show relatively large increase. It will be worthy to investigate these sites more in depth and explores the probable factors that have caused the relatively high rates and the increase in

collision rates in the after-installation period.

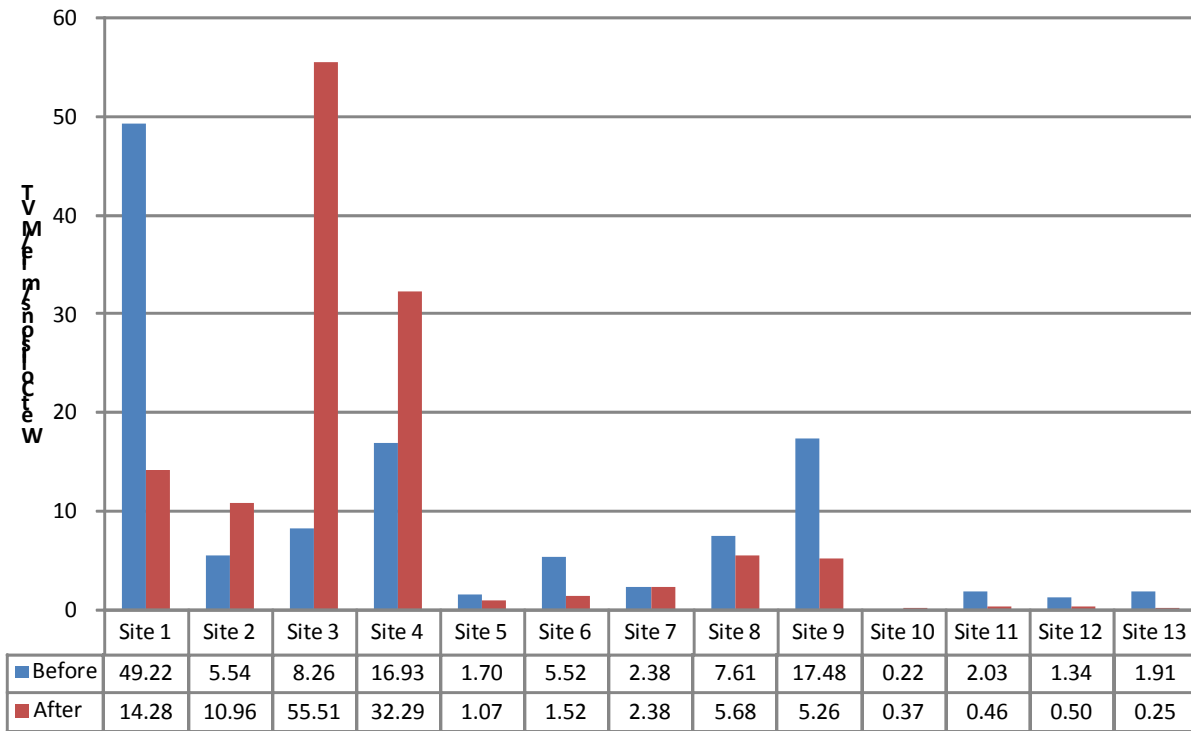


FIGURE 3 Wet Collision Rate Before and After OGAC Installation

Comparison with Dry Collision Rate

In order to compare the overall safety performance, it is also important to compare collision rates in all conditions, wet or dry. In this section the dry collision rate is also calculated to allow before-after analysis. The definition of dry collisions in this case is the surface conditions of the collision record in TASAS records are indicated as “dry.” Dry collision rate is defined by Equation 5:

$$\bar{R}_{dc_i} = \frac{\sum T R_{dc_i,t}}{T} = \frac{1}{L_i} \frac{\sum C_{d_i,t}}{T (ADT_{i,t} \times \frac{1}{24}) \times H_{d_i,t}}, \quad i \in I \tag{5}$$

Where

\bar{R}_{dc_i} : Averaged dry collision rate (col./mi/veh) on road section i;

$R_{dc_i,t}$: Dry collision rate (col./mi/veh) in year t on road section i;

T: Total number of years;

L_i : Length (mi) of road section i;

$C_{d_i,t}$: Number of dry collision in year t on road section i;

$ADT_{i,t}$: AADT (veh/day) in year t on road section i;

$H_{d_{i,t}}$: Total hours of dry condition in year t on road section i, days without the rainy hour and lag;

I: study sites.

Table 4 shows the result of comparison of dry and wet collision rates. It is noted that the absolute values of wet collision rates are greater than those of dry collision rates in all study sites regardless of before or after periods. The simple averages of the collision rates, which are significantly dictated by a few large numbers in the mix and therefore are not necessarily a good representation of the before-after comparison, also given at the bottom row of the table.

TABLE 4 Comparison of Wet and Dry Collision Rate

Site Number	Wet Collision Rate (Col./mi/MVT)		Dry Collision Rate (Col./mi/MVT)		Ratio of Collision Rate	
	Before Construction (x)	After Construction (y)	Before Construction (z)	After Construction (w)	Wet (y/x)	Dry (w/z)
Site 1	49.22	14.28	2.88	2.59	0.29	0.90
Site 2	5.54	10.96	2.99	3.10	1.98	1.04
Site 3	8.26	55.51	5.92	2.58	6.72	0.44
Site 4	16.93	32.29	6.89	3.77	1.91	0.55
Site 5	1.70	1.07	0.52	0.71	0.63	1.36
Site 6	5.52	1.52	1.08	1.14	0.27	1.06
Site 7	2.38	2.38	0.27	0.32	1.00	1.18
Site 8	7.61	5.68	2.93	3.19	0.75	1.09
Site 9	17.48	5.26	7.25	4.39	0.30	0.61
Site 10	0.22	0.37	0.20	0.25	1.65	1.28
Site 11	2.03	0.46	0.38	0.16	0.22	0.43
Site 12	1.34	0.50	0.77	0.57	0.37	0.74
Site 13	1.91	0.25	1.19	0.94	0.13	0.79
Average	9.24	10.04	2.56	1.82	1.25	0.88

Figure 4 shows of the comparison of before and after OGAC installation by the ratio of wet and dry collision rates. If the ratio of collision rates before and after OGAC installation is equal to one, it means there is no change in rates. The ratios of dry collision rates are much closer to one than those of wet collision rate. This implies that dry collision rates are less sensitive to OGAC installation. Considering that wet collision rates decreased in nine of 13 study sites and dry collision rates generally do not show negative impacts, OGAC appears as whole in these 13 study sites to have positive impacts as a countermeasure to reduce wet collisions.

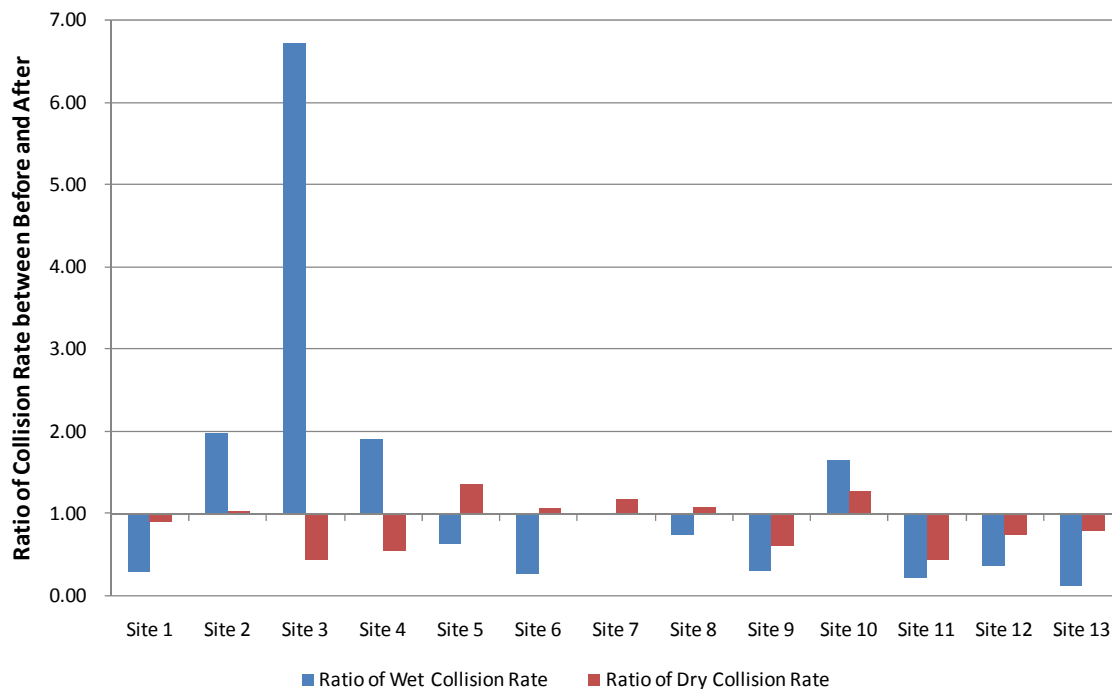


FIGURE 4 Ratio Comparison between Wet and Dry Collision Rate

SUMMARY AND CONCLUSION

This paper provides a description of a recent study aimed at evaluating the safety performance of roadway segments under wet-weather conditions. A methodology was developed to quantify the precipitation exposure for wet-weather collision based on the concept of hourly precipitation data and a residual time lag. The method is applied to calculate the wet collision rate of 13 study sites in California to evaluate the safety performance before and after the pavement projects of installing OGAC.

The proposed approach takes into account the precipitation exposure and associated traffic flow volume, which allows a better assessment of wet collisions. Based on the findings from the before-after analysis, it was found that wet-weather related collision rates were reduced at nine out of thirteen study sites after the OGAC installation project. In addition, dry-surface collision rates were also calculated for the study sites, which were found to be less sensitive to OGAC installation.

While several issues have been explored in the current study to investigate the potential effects

of OGAC treatment at the study sites, the analysis can be further improved and refined in many ways. For example, it will be worthwhile pursuing a comparative analysis by using neighboring segments near the study sites as control groups to minimize the effects of variations in roadway configurations or environmental changes over the years. Moreover, verification of OGAC effectiveness as a safety countermeasure can be further confirmed by adopting statistical tests of significance in the analysis. In addition, due to the diversity of site characteristics, it will be necessary to explore further the geometric and traffic attributes of individual locations to explore the causal effects of specific collision phenomena. These remain topics of future studies.

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REFERENCES

1. Fridstrom, L., J. Ifver, S. Ingebrigtsen, R. Kumala and L. Krogsgard Thomsen, Measuring the contribution of randomness, exposure, weather, and daylight to the variation in road accident counts. *Accident Analysis and Prevention*, Vol. 27, 1995, pp. 1-20.
2. Shankar, V., F. Mannering and W. Barfield, Effect of roadway geometrics and environmental factors on rural freeway accident frequencies. *Accident Analysis and Prevention*, Vol. 27, No. 3, 1995, pp. 542-555.
3. Levine, N., K.E. Kim and L.H. Nitz, Spatial analysis of Honolulu motor vehicle crashes. I. Spatial Patterns. *Accident Analysis and Prevention*, Vol. 27, No. 5, 1995, pp. 663-674.
4. Levine, N., K.E. Kim and L.H. Nitz, Daily fluctuations in Honolulu motor vehicle accidents. *Accident Analysis and Prevention*, Vol. 27 No. 6, 1995, pp. 785-796.
5. Edwards, J.B., The relationship between road accident severity and recorded weather. *J. Safety Research*. Vol. 29, No. 4, 1998, pp. 249-262.
6. Keay, K. and I. Sommonds, The association of rainfall and other weather variables with road traffic volume in Melbourne. *Aust. Accident Analysis and Prevention*. Vol. 37, 2005, pp. 109-124.
7. Keay, K. and I. Sommonds, Road accident and rainfall in a large Australian city. *Accident Analysis and Prevention*. Vol. 38, 2006, pp. 445-454.
8. Allen, J.G. and R.I. Peters, Performance of Open-graded Asphaltic Concrete Friction Courses in Arizona. *Transportation Research Record*, Vol. 821, 1981, pp. 1-4.
9. Frick, K., *Evaluation of New Patching Material for Open-Graded Asphalt Concrete (OGAC) Wearing Courses*. University of California Pavement Research Center, 2005.
10. Brijs, T., D. Karlis and G. Wets, Studying the effect of weather conditions on daily crash counts using a discrete time-series model. *Accident Analysis and Prevention*. Vol. 40, 2008, pp. 1180-1190.

11. Eisenberg, D., The mixed effects of precipitation on traffic crashes. *Accident Analysis and Prevention*. Vol. 36, 2004, pp. 637-647.
12. Caliendo, C., M. Guida and A. Parisi, A crash-prediction model for multilane roads. *Accident Analysis and Prevention*. Vol. 39, No. 4, 2007, pp. 657-670.
13. Brodsky, H. and A. S. Hakkert, Risk of a road accident in rainy weather. *Accident Analysis and Prevention*. Vol. 20, No. 2, 1988, pp. 161-176.