Multilevel Assessment of the Impact of Rain on Drivers' Behavior

Standardized Methodology and Empirical Analysis

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For all road managers, inclement weather events are a source of uncertainty that can affect traffic operations and safety. Regarding safety, various studies reveal significant effects of adverse weather conditions on the frequency and severity of crashes. Regarding mobility, because of a lack of data, there are few comprehensive studies, although the quantification of the effects of adverse weather on traffic represents the first step toward the development of weather-responsive traffic management strategies. This study deals with the analysis of the impact of rain on drivers' behavior and traffic operations. First, a generic methodology for assessing the effect of weather on traffic is proposed through a multilevel approach: from individual traffic data, the rain impact is assessed at a microscopic level (time headways, spacing). Next, the same data were used to extend the study to a mesoscopic and a macroscopic level. The mesoscopic level deals with the effects of rain on platoons, and the macroscopic level resides in the analysis of the impact of rain on the fundamental diagram enabling weather-responsive macroscopic traffic simulation. Second, following this approach, an empirical study is carried out from individual data collected on a French interurban motorway. Weather data were provided by a weather station located near the test site. The results exhibit a significant impact of rain on drivers' behavior and traffic operations, which increases with the intensity of rainfall.

Putting proactive real-time traffic management strategies into practice implies the consideration of all sources of uncertainty impacting the traffic operations. Regarding road safety, rain is one important meteorological factor leading to death and injuries. According to FHWA, 75% of weather-related vehicle crashes occur on wet pavement and 47% happen during rainfall (*1*). Thus, inclement weather conditions affect drivers' safety by degrading the state of the pavement, the visibility, and the performances. A recent review (*2*) concludes that rain can increase the crash rate by 71% and the injury rate by 49%. Moreover, Eisenberg underlined a substantial lagged effect of precipitation across days (*3*): the effect of rain on traffic crash rates is higher if many days have passed since the last precipitation. Regarding traffic management, the meteorological factor is of paramount importance for road managers, not only in terms of safety but also in terms of mobility. Further to the seminal studies of Jones et al. (*4*) and Hall and Barrow (*5*), analyses about the effects of adverse weather on traffic indicators have seen an expansion over the last years. For example, Rakha et al. (*6*) report a maximum reduction in the range of 6% to 9% in free-flow speed and 8% to 14% in speed-at-capacity if the rain intensity is 1.6 cm/h. In a previous study (*7*), we noticed an average decrease of 15.5% of the capacity during rainy conditions and a drop of 9% in free-flow speed. This trend was confirmed by Cools et al. (*8*) and Unrau and Andrey (*9*). In spite of these results, the impact of rain on traffic still needs to be addressed: there is no consensus on the main findings. The main reasons for that are twofold: (i) a lack of standardized methodology dealing with the quantification of the rain effects and (ii) a lack of comprehensive data, which often prevents separating the study according to the intensity of rainfall.

The originality of the proposed study resides in a multilevel approach: from individual data provided by double loop sensors, a microscopic analysis is carried out, enabling observation of individual drivers' behavior under adverse weather conditions. Next, the same data could lead to a mesoscopic study, that is, an observation of the rain influence in terms of platoons. Finally, the study can be extended to a macroscopic point of view with the assessment of the rain impact on the fundamental diagram through the use of traffic models. Indeed, the changes in the relationships between speed, flow, and density must capture the weather effects. Such results could lead to a parameterization of the fundamental diagram according to the intensity of rain. In this paper, a systematic methodology is proposed. Next, this methodology is implemented through an empirical analysis on a French interurban motorway. The promising results could enable integration of the new findings about the rain effects into a decision support system, allowing road managers to deal online with both traffic and weather data. Following the example of the road weather program of the FHWA, this study is the first part of a more global project launched recently in Europe (*Weather-Responsive Tools for Real-Time Monitoring, Surveillance, and Control of Road Networks Under Adverse Weather Conditions*), under the sponsorship of the European Cooperation in the Field of Scientific and Technical Research program, aiming at developing weather-responsive traffic management strategies (*10*).

METHODOLOGY

Figure 1 describes a systematic methodology that enables an analysis of the rain impact on traffic by tackling the problem at three different levels: micro-, meso-, and macroscopic. Such an approach requires the use of individual traffic data collected by loop detectors. The following information is recorded for each vehicle: date, hour,

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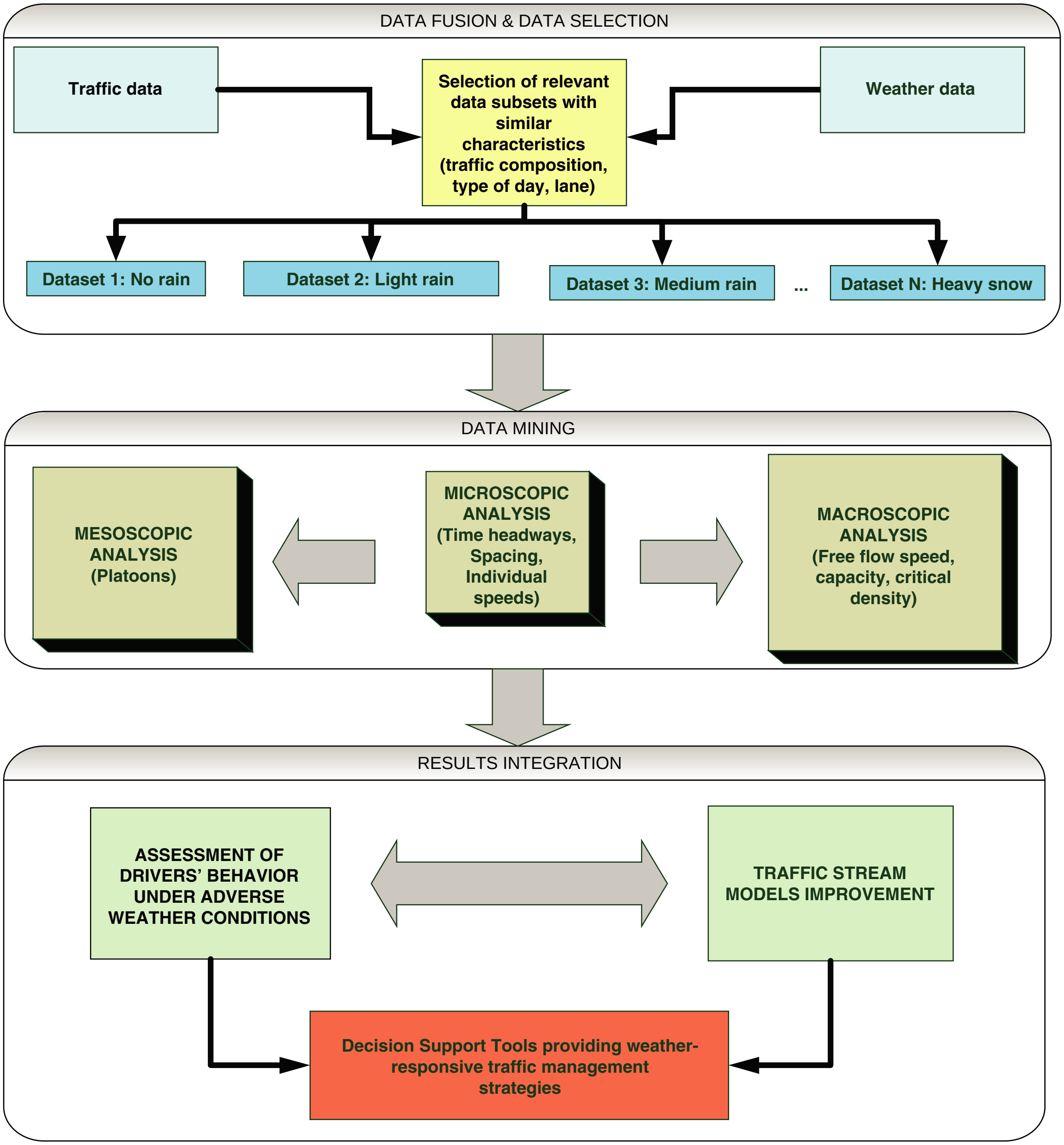


FIGURE 1 Standardized methodology for analysis of adverse weather impact.

minute, second of vehicle crossing, number of axles, length, type of lane (slow, median, or rapid lane), vehicle category, time headway, spacing, and speed.

After description of the methodology through Figure 1, some critical issues will be explored.

DATA SELECTION AND STRATEGY FOR CONTROLLING EXOGENOUS FACTORS

An empirical analysis of the effects of rain on traffic operations requires a rigorous approach that enables the isolation of weather effects and the similarity of exogenous factors. Along this principle, the following requirements need to be carefully examined:

- Data set has to be formed by paired samples with both traffic and weather data. Weather data must be collected near the test site to really reflect the weather conditions experienced in the considered section.
- Other meteorological factors, such as wind and light, must be known and similar for all data sets.
- Other traffic-related factors have to be kept constant or at least similar. Among such factors, one can mention traffic composition (in terms of percent of cars or heavy goods vehicles), day category and time of day, type of lane, etc.

In this way, by following this standardized methodology and crossing weather and traffic data, relevant data subsets can be built. Hence, only weather parameters must change and others are kept controlled.

MULTILEVEL ANALYSIS

To conduct the analysis, data subsets have to be sorted according to the rainfall intensity. The study can be carried out at three complementary levels:

- Microscopic level. Vehicles are considered individually and the goal is to assess the changes in drivers' behavior under adverse weather conditions. The distributions of spacing, speeds, and time headways are compared and modeled.
- Macroscopic level. There are two ways to achieve a macroscopic study. One possible method resides in a transformation of the individual data into 6-min (for instance) aggregated traffic data by the computation of flows (veh/h) and space mean speeds. Density (veh/km) can next be obtained through the ratio between flow and space mean speed (km/h). Second, it could be considered that macroscopic and microscopic levels are directly linked by the relationships between time headways and flow and time headways and spacing. Indeed, the flow rate can be defined as the inverse of the mean headway and the density as the inverse of the mean spacing. Whatever the way of transformation is, the main task from these aggregated data consists in analyzing the impact of rain intensity on the macroscopic traffic characteristics like free-flow speed, capacity, critical density, etc. Besides this one-dimensional analysis, the impact of rain can be achieved using the fundamental diagram models (e.g., Greenshields, Pipes, Van Aerde).
- Mesoscopic level. At this level, the assessment of rain effects is analyzed through platooning phenomena. More precisely, the goal is to provide insight on how rain or other weather influences platoon formation. In this case, too, platoon data can be directly derived from the individual data.

By combining the traffic stream model improvement enabling by the macroscopic approach and the assessment of the changes in drivers' behavior thanks to those analyses, such an approach paves the way for providing road operators with decision support tools taking into account the weather conditions.

EMPIRICAL ANALYSIS ON A FRENCH INTERURBAN MOTORWAY

Following the proposed methodology, an empirical analysis was carried out on a two-line interurban freeway section located on 118 National Road (RN-118) near Paris (Figure 2). Traffic data were provided by the West Paris Regional Laboratory, and collected from 2005 to 2007 from nine double-trap loop sensors.

The speed limit in this section is 110 km/h (68.3 mph). Only the southbound direction toward Paris is considered in the present analysis. Data were selected from three out of nine sensors located on a homogeneous section (same topography). For each considered period, data were selected from one out of these three sensors according to the availability in the database. Hourly weather data were provided by a weather station located near the section (less than 3 km). In a standard way and according to the meteorological experts, four classes of rain intensity were defined:

- No rain: no rainfall (i.e., 0 mm/h),
- Light rain: rainfall up to 2 mm/h (i.e., 0.08 in./h),
- Medium rain: rainfall from 2 mm/h to 3 mm/h (i.e., 0.08–0.11 in./h), and
- Heavy rain: rainfall up to 3 mm/h (i.e., 0.11 in./h).

However, in the data set used, it was not possible to obtain data within the "heavy rain" class, so only the three first classes were considered. According to these three levels of rainfall intensity, three traffic data subsets were built. The previous methodology for data selection was applied:

- Same day category (regular weekday) and same time periods (morning and evening peaks hours) for each data set,
- Similar other meteorological factors (wind, temperature), and
- Similar traffic composition (Table 1) and significant amount of vehicles (more than 10,000 vehicles per lane in each data set).

The differences in the number of vehicles are just linked to the fact that more similar days were available for dry and medium rain conditions and those days were aggregated. That means that the number of vehicles would have been almost equivalent if we hadn't added these periods. This condition enables a rigorous comparison among the three data sets.

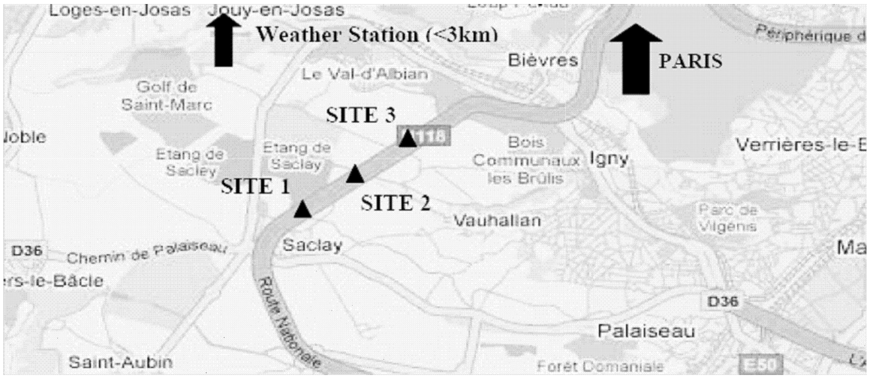


FIGURE 2 Test site location.

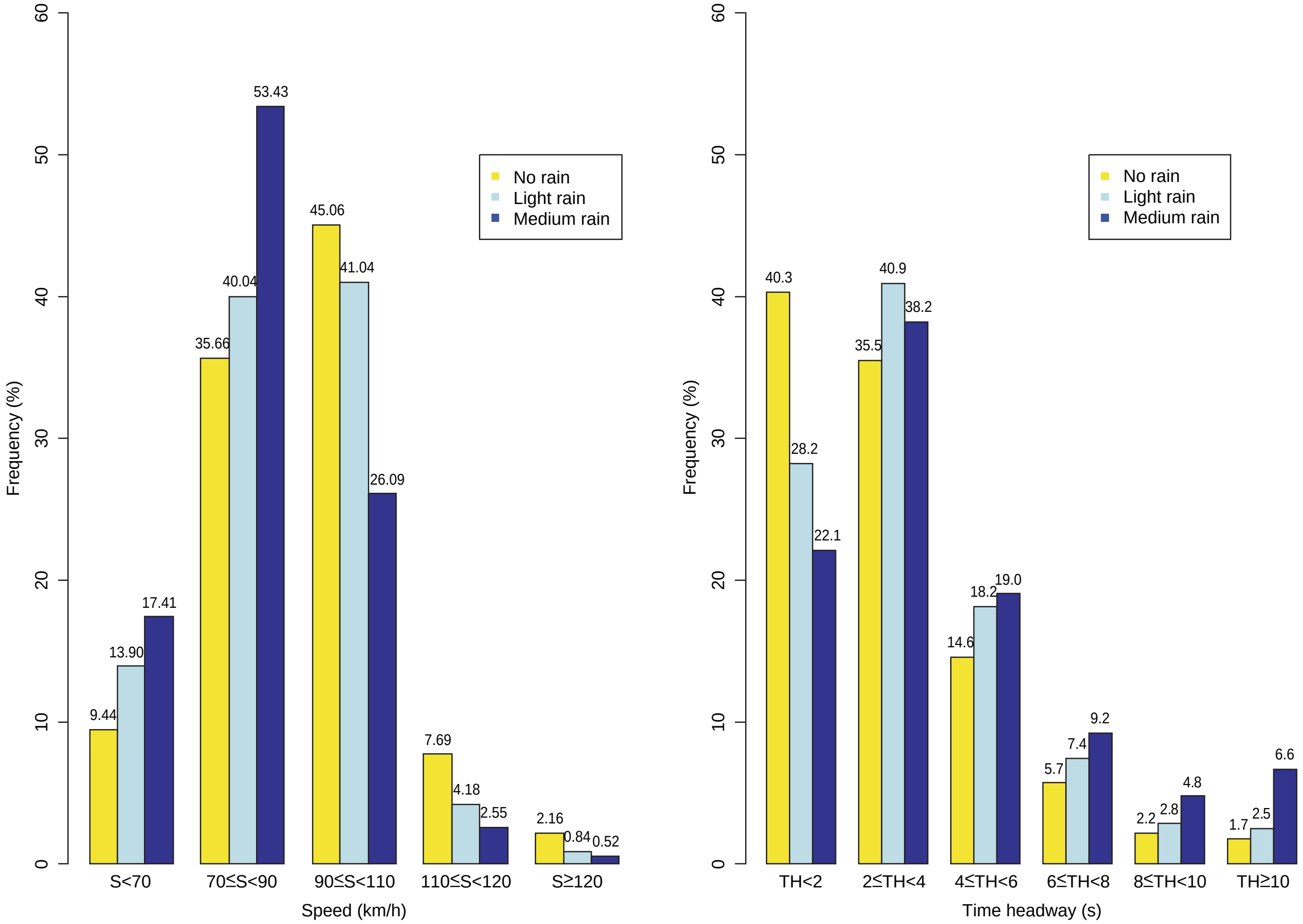
TABLE 1 Traffic Composition of Three Data Sets

	Data Set				
	Slow Lane		Fast Lane		
Weather Condition	Number of Vehicles	% Cars	Number of Vehicles	% Cars	Total Number of Vehicles
No rain	36,078	87.7	30,193	92.9	66,271
Light rain	27,744	90.0	25,126	96.5	52,870
Medium rain	11,236	89.2	11,406	95.5	22,642

Microscopic Analysis

As mentioned before, the main goal of the microscopic analysis is to assess changes in drivers' behavior under rainy conditions. It is recognized that drivers try to adapt their behavior by reducing their speed on wet road surfaces. Figure 3 shows a clear decrease for the slow lane of the frequencies of speeds >110 km/h under rainy conditions whereas the frequency of speeds between 70 and 90 km/h is higher under light and medium rain conditions (e.g., 53% under medium rain conditions versus 35% under dry conditions). This speed drop will be reflected on two critical microscopic indicators: time headway and spacing. Figure 3 also presents the time headway distribution for the slow lane. Because the sample sizes of the three data sets are not equivalent, time headway variable (TH) has been discretized and analyzed according to the frequency of six different categories.

Figure 3 confirms the trend underlined in a previous study (*11*). There is a drop of the short TH under rainy conditions. The higher the intensity of rain is, the higher the drop is. In terms of frequency and regarding the short TH on the slow lane, a drop of 12.1% of the TH < 2 s is observed under rainy conditions (light rain). In medium rain conditions, a sharper decrease of more than 18% is observed. This drop is reported on a rise of the TH between 2 and 10 s.



(a)

(b)

FIGURE 3 Speed and time headways distributions in slow lane.

Alternatively, the effect of rain on TH distribution can be assessed by use of a density histogram. Figure 4 shows in parallel the histogram of the TH under dry versus medium rain conditions.

First, the upper part of Figure 4 shows graphically a significant difference between the two empirical TH distributions under dry and medium rain conditions. Second, those distributions were modeled to better compare the three situations on the basis of an analytical model. Lognormal distribution was selected as a candidate for such fit. In many situations, lognormal is seen as an attractor distribution for the product of independent random variables.

The lower part of Figure 4 represents the three corresponding density functions independently. The lognormal distribution has the probability density function

$$f(x,\ \mu,\ \sigma)=\frac{1}{x\sigma\sqrt{2\pi}}\exp\left(-\frac{(\ln x-\mu)^2}{2\sigma^2}\right)$$

where μ and σ are, respectively, the mean and the standard deviation of the logarithm of the variable x.

The observation of the density functions appears as a convenient way to confirm the results foreseen with the frequency plots. The density of the TH < 3 s is higher under dry conditions whereas the density of TH becomes higher for the two data sets with rain from TH of about 3 to 10 s. The higher the intensity of rain is, the lower the density of short TH is. The last graphic describes the empirical cumulative distribution function of the three data sets. It shows that the TH < 10 s covers the whole distribution for the "dry weather" data set whereas the two other empirical distribution functions tend slower toward 1. It is expected that this time headways increase goes together with a spacing increase. Drivers feel less secure under adverse weather conditions, reduce their speed, and increase their spacing (Figure 5).

Figure 5 clearly exhibits that the frequency of short spacing decreases during inclement weather conditions. Indeed, a drop of about 5% of the spacing less than 50 m is noticed. During medium rain conditions, a drop of 10% is observed. Drivers adapt their spacing to meet safe driving manoeuvres: the frequency of spacing greater than 70 m is 42.2% under dry weather conditions versus 47% and 52.6% under light and medium rain conditions, respectively.

To summarize, one can conclude that rain has a clear impact on drivers' behavior. The impact of rain finds expression in significant decreases of short headways and spacing under rainy weather conditions. It has been confirmed that the higher the intensity of rainfall

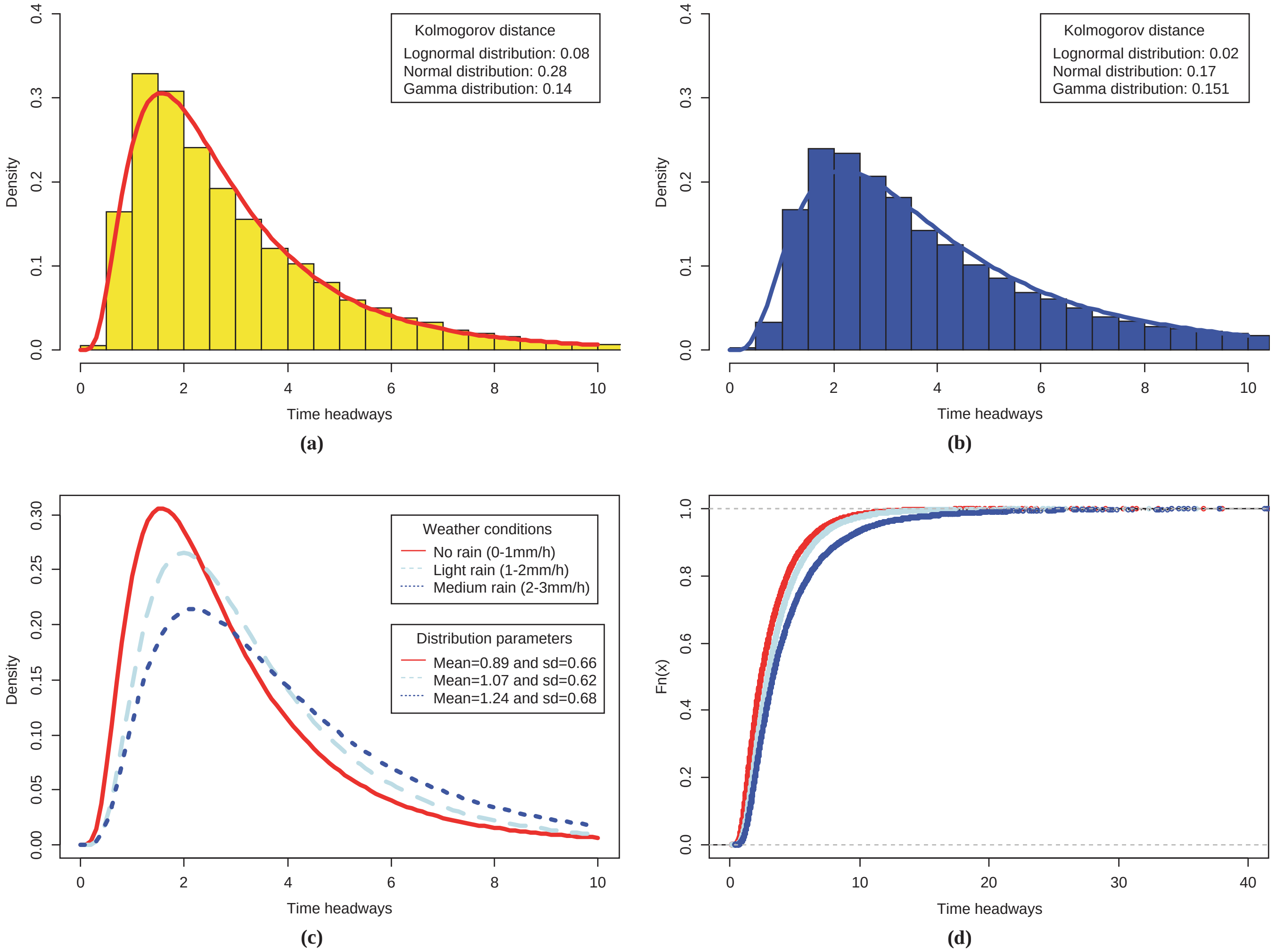


FIGURE 4 Time headway modeling, with lognormal distribution and empirical distribution: (*a*) dry weather conditions, (*b*) medium rain (2–3 mm/h), (*c*) density functions (lognormal distribution), and (*d*) empirical cumulative distribution functions.

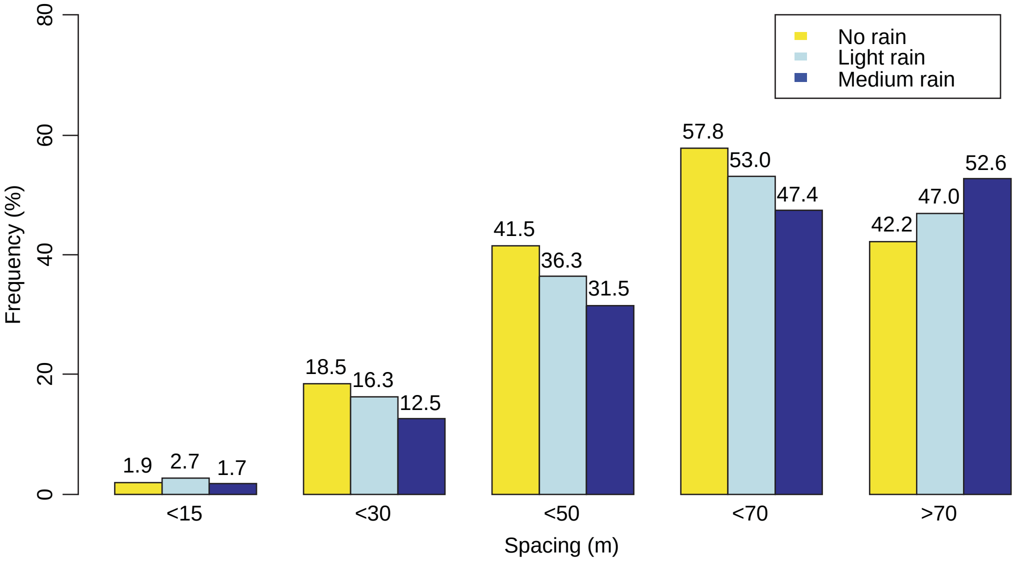


FIGURE 5 Frequency of five spacing categories on slow lane.

is, the higher the effects are. The TH distributions were modeled by lognormal distributions that appropriately fit the empirical distribution. This modeling enables a comprehensive and accurate comparison through the observation of the density functions for the three data sets. Moreover, these microscopic analysis results confirm a previous study carried out on a French highway (*11*). Thus, the larger number of data of this new study validates the first conclusions of our preliminary works.

Mesoscopic Analysis

From a microscopic study, a data analysis allows us to observe the vehicles in terms of platoons. The platooning state of the traffic is usually defined using a critical headway (CH) value, which is usual taken as 4 s (*12*). However, within weather effect assessment and evaluation, a common value of critical headway for all weather situations is not desirable. Indeed, as demonstrated in the previous section, drivers naturally adapt their behavior to the prevailing weather conditions by increasing their TH; then we advocate that the CH value has to be weather sensitive. That is why, through this study, the CH value was defined as the median of the TH with respect to the three classes. This choice enables us to be sure that considered vehicles in the platoon are indeed in interaction whatever the data set is. We concentrate on platoons with at least four vehicles. This arbitrary choice was motivated by the fact that we are mainly interested in vehicle interactions within large platoons. Table 2 summarizes the main characteristics of the platoons with respect to the slow lane and the fast lane facing different weather conditions.

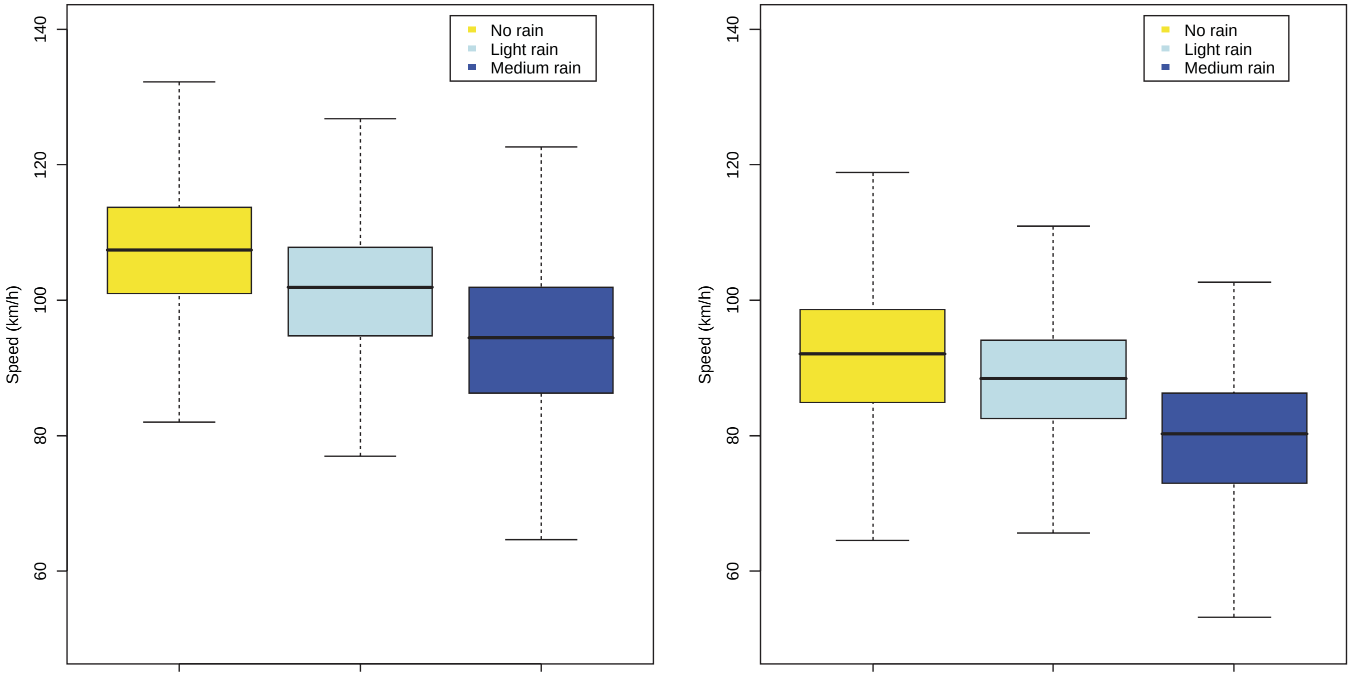
Table 2 reports a slight trend in favor of platoon formation under rainy conditions. Indeed, whatever the lane is, the proportion of vehicles in platoons with more than four vehicles tends to increase when rain occurs. For instance, there is an increase of 7.5% of the vehicles in platoons under medium rain conditions. Regarding the number of vehicles in a platoon, no conclusion can be drawn. There is no difference of the median number of vehicles, and the light increase in mean number could be directly linked to the fact that the proportion of vehicles in platoons becomes higher under adverse weather conditions. With respect to percentage in cars, there is no significant difference because the small variations in values may also be linked to the variations in the traffic composition.

In analysis of platoons using the speed distribution within each platoon, the box plot figure exhibits an overall decrease with rainfall intensity (Figure 6).

For instance, a drop of about 20% of the median speed is observed from dry to medium rain conditions in the fast lane. Figure 6 also

TABLE 2 Basic Statistics of Platoons' Compositions

		Data Set							
		Slow Lane				Fast Lane			
Weather Condition	Critical Headway (s)	% Platooning Vehicle (≥4 veh)	Mean Number of Veh. in a Platoon	Median Number of Veh. in a Platoon	% Cars in a Platoon	% Vehicles in Platoon (≥4 veh)	Mean Number of Veh. in a Platoon	Median Number of Veh. in a Platoon	% Cars in a Platoon
No rain	3.00	53.0	6.41	5	89.6	75.3	8.67	7	93.4
Light rain	3.60	57.3	6.32	5	91.6	76.2	9.19	7	96.7
Medium rain	4.45	60.5	7.07	6	89.6	82.03	11.34	8	95.5



(a)

(b)

FIGURE 6 Box plots of platoons' speed distributions.

highlights a clear difference between the left lane and the slow lane results. This offers a justification that a consistent study on the impact of weather must be conducted by considering lanes separately although many databases are built by merging the data from the different lanes in order to save communication and storage costs.

Macroscopic Analysis

From individual data, the main traffic stream variables can be computed, namely, space–mean speed, density, and flow. Indeed, for any aggregation period, the flow rate q and the density k can be computed directly from the TH and spacing (spacing noted s) values as follows:

$$q = \frac{n}{\sum_i \mathrm{TH}_i}$$

and

$$k = \frac{n}{\sum_i s_i}$$

where n is the number of vehicles passing the point during the period of aggregation (e.g., 6 min).

This macroscopic analysis aims at assessing the changes of the macroscopic traffic characteristics and the quality of traffic conditions under various weather conditions. The most convenient way to achieve this goal is through the use of the classical fundamental diagram describing relationships among speed, flow, and density. The fundamental diagram is the basis of macroscopic traffic simulation and a valuable tool for traffic management. To develop weather-responsive traffic management strategies, the bottom line is thus to assess the effects of weather on the fundamental diagram. More precisely, the weather effects on free-flow speed, capacity, and critical density are assessed. With regard to the traffic modeling, there is plenty of literature, and many single- and multiregime models were proposed. Nowadays, single-regime models such as the Greenshields model (*13*) are still used because of the simplicity of calibration. Regarding the multiregime models, one difficulty resides in the determination of the frontier point between the different regimes. For instance, it is often necessary to implement a procedure to determine what the best separation between the two regimes is. However, those models better produce the complexity of the traffic stream behaviors than the one-regime model. Analyzing the impact of inclement weather requires an efficient and flexible model with enough degrees of freedom in the modeling to better catch the changes with respect to the rain intensity. For these reasons, the Van Aerde model (*14*) was selected. The attractiveness of the Van Aerde model resides in a combination between Greenshields and Pipes car-following models. By comparison with the Pipes model, the critical point is an additional degree of freedom allowing the speed-at-capacity to be different from the free speed. The calibration of the model requires four parameters—$\{c_1, c_2, c_3, m\}$—function of the free-flow speed s_{FF}, the speed-at-capacity S_{Q_x}, the capacity Q_x, and the jam density K_J:

$$k = \frac{1}{c_1 + c_3 u + \frac{c_2}{s_{\mathrm{FF}} - u}} \qquad m = \frac{2S_{Q_x} - s_{\mathrm{FF}}}{\left(s_{\mathrm{FF}} - S_{Q_x}\right)^2}$$

$$c_2 = \frac{1}{K_J\left(m + \frac{1}{\mathrm{FS}}\right)} \qquad c_1 = mc_2$$

and

$$c_3 = \frac{-c_1 + \dfrac{\mathrm{CS}}{Q} - \dfrac{c_2}{\mathrm{FS} - \mathrm{CS}}}{\mathrm{CS}}$$

where

k = traffic stream density (veh/km),
u = traffic stream space-mean speed (km/h),
c_1 = fixed distance headway constant (km),
c_2 = variable headway constant (km^2/h), and
c_3 = variable distance headway constant (h) (*14*).

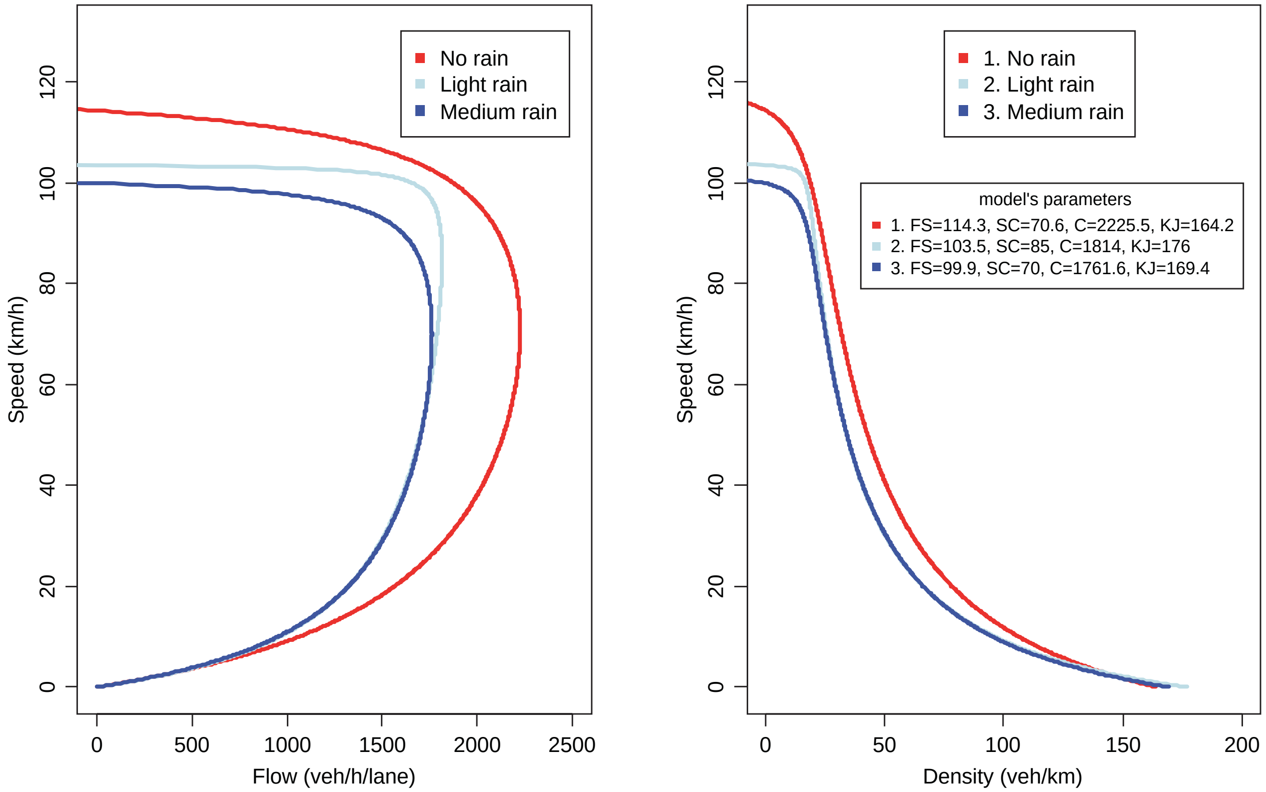
The calibration was carried out with the SPD_CAL software, a heuristic tool developed by Rakha and Van Aerde (*15*). This calibration procedure is based on a nonlinear least squares approach in three dimensions. It proceeds by iteratively varying the values of the free-speed, speed-at-capacity, and jam density using a hill climbing optimization technique and selects the parameters that minimize the sum of squared orthogonal errors.

The Van Aerde model was calibrated according to the described procedure with the three weather configurations (Figure 7). As a result, the impact of rain on the fundamental diagram is clear. First, as previous studies mentioned (*6, 7*), it must be noticed that the jam density is not affected by weather-related events, here rainfall. This is consistent with physical considerations since the maximum number of vehicles to be accommodated by a roadway section is not weather sensitive. With respect to the other key traffic parameters, a drop in the free-flow speed is observed. This drop is of about 8% under light rain conditions and of about 12.6% under medium rain conditions. The capacity's decrease, which is linked to the reduction of the free-flow speed and the time headway drop previously observed at a microscopic level, is also noticeable. The roadway capacity decreases by 18.5% under light rain conditions and by 21% under medium rain conditions. Regarding the critical density, there is a drop of about 26% under light rain conditions and 40% under medium rain conditions.

The presented macroscopic analysis highlights a significant distortion in the fundamental diagram facing meteorological changes and particularly rain intensities. From this analysis, it comes out that the influence of rain on the fundamental diagram appears as a key aspect to be taken into account in real-time traffic management strategies. Indeed, the accommodation of weather impact through capacity, speed, and critical density could lead the road operators to react according to the meteorological changes. The ultimate goal is then to provide a weather-responsive decision support system for traffic managers and road operators. To achieve this goal, comprehensive databases with all weather events are required to integrate the impacts of all types of precipitation into the current traffic management tools.

CONCLUSION AND PROSPECTS

In this paper, a multilevel assessment of the effects of rain on drivers' behavior has been carried out. A systematic methodology has been proposed, aiming at analyzing traffic and weather data. The key aspect resides in a third-level process, starting from a microscopic point of view to mesoscopic and macroscopic ones. Thanks to the empirical



(a) **(b)**

FIGURE 7 Calibration of Van Aerde model.

analysis illustrating our approach, some important findings can be highlighted with respect to these three levels of analysis:

1. From a microscopic standpoint, drivers reduce their speeds under adverse weather conditions and increase their headways and spacing. A drop of 18% of the time headways less than 2 s on the slow lane was observed as well as a decrease of 20% of the spacing less than 50 m. A lognormal distribution fit of the TH distribution was carried out, which highlights the differences according to the weather conditions.
2. There is a platooning phenomenon under adverse weather conditions (+ 7.5% of platoons > 4 vehicles on the slow lane) and platoons speeds are reduced (–20% between dry and medium rain conditions).
3. Finally, the rain impacts the main macroscopic traffic characteristics. The fundamental diagram is affected and capacity decreases from 18.5% to 21% according to the intensity of rain as well as free-flow speed decreases from 8% to 12.6%. As mentioned before, rain has no impact on the jam density.

This study has to be completed as it does not cover all other weather events (e.g., heavy rain was not recorded during the collection period). Nevertheless, it offers the basis to integrate the rain effects into online traffic management strategies. More generally, there is a need to cross worldwide results in order to obtain a consensus about adverse weather effects. Such knowledge sharing would also make it possible to take into account the regional aspects and cultural behavior in the conclusions.

Future research will illustrate the benefits of the integration of rain effects into online traffic simulation and management tools. This work was introduced by Billot et al. (*7*) and Sau et al. (*16*) through the use of particle filters (*17*) for constructing an observer-based traffic state estimation. This traffic state estimation is of paramount importance for real-time monitoring and control of road network. Moreover, the research dealing with the impact of rain on another critical traffic indicator—travel times—needs to be further investigated. Such studies would enable the road managers to adapt online their travel time estimation and inform the drivers through variable message sign and on-board information and guidance unit (*18*).

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