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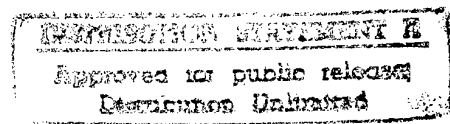
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title
**Effects of rain on daily traffic volume
and on driving behaviour**

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In dit rapport wordt verslag gedaan van een studie die is uitgevoerd in het kader van het V&W doelfinancieringsproject Weg- en weerscondities. Het doel van deze studie was om de effecten van regen op dagverkeersvolume en op rijgedrag te bepalen.

De analyses zijn uitgevoerd met behulp van in een ander project verzamelde data. Gebleken is dat regen geen effect heeft op het verkeersvolume over hele dagen: blijkbaar heeft regen geen modaliteitsverschuiving naar wegverkeer tot gevolg. Het rijgedrag in regen bleek voorzichtiger te zijn dan in droog weer. De gemiddelde snelheid en het aandeel korte volgtijden waren lager in regen. Ook in Time-To-Collision werd een verschuiving naar veiliger gedrag vastgesteld. Aangezien uit verschillende veiligheidsstudies een verhoogde ongevals kans tijdens regen is gebleken, zijn deze aanpassingen van het rijgedrag blijkbaar onvoldoende om een constant veiligheidsniveau te handhaven.

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SUMMARY

As a part of the project Road and Weather conditions, a study was carried out with the aim to investigate the effects of rain on total daily traffic volume, and on driving behaviour. With respect to the daily traffic volume, no effect of rain was found. Apparently, rain does not cause a major modality shift towards road traffic. Driving behaviour in rain was found to be more cautious than in dry weather. The mean speed and the percentage of short time headways (< 1 s) were reduced in rain. Also the percentages of Time-To-Collisions < 5 and < 10 s were reduced in rain. However, since several safety studies reveal a higher accident rate in rain, this adaptation of driving behaviour to rain is apparently insufficient to maintain the same level of safety.

Effecten van regen op verkeersvolume en op rijgedrag

J.H. Hogema

SAMENVATTING

Als onderdeel van het project Weg- en weerscondities is een studie uitgevoerd met als doel de effecten van regen op dagvolume en op rijgedrag te onderzoeken. Voor wat betreft het volume over hele dagen werd geen effect van regen gevonden. Blijkbaar heeft regen geen modaliteitsverschuiving naar wegverkeer tot gevolg. Het rijgedrag in regen bleek voorzichtiger te zijn dan in droog weer. De gemiddelde snelheid en het aandeel korte volgtijden (< 1 s) waren lager in regen. Ook de percentages Time-To-Collision < 5 s en < 10 s namen af in regen. Aangezien uit verschillende veiligheidsstudies een verhoogde ongevals-kans tijdens regen is gebleken, is deze aanpassing van het rijgedrag kennelijk onvoldoende om een constant veiligheidsniveau te handhaven.

1 INTRODUCTION

As a part of the project Road and Weather conditions, conducted together with the TNO Road-Vehicles Research Institute and sponsored by the Dutch Ministry of Transport, Public Works, and Water Management, an explorative study was carried out on the effects of rain on driving behaviour.

On days with heavy rain, one could expect the following effects:

- Travellers may be more inclined to use a car instead of modes of transport with less protection against rain. This would lead to an increase of traffic volume on days with rain compared to dry days.
- Drivers may change their driving behaviour (free-driving speed, car-following behaviour) because of the reduced visibility or friction potential as caused by rain.

The aim of this study was to investigate and quantify both these effects. In the study, data were used that had been collected in a previous project (Hogema, Van der Horst & Bakker, 1994).

2 METHOD

2.1 Data registration

The data used in this study were collected during the evaluation study of a fog signalling system on the A16 motorway near the city of Breda, the Netherlands (Hogema et al., 1994). The A16 is a motorway with two separated carriageways which have two lanes each. The speed limit is 100 km/h. The usual traffic volume on the A16 can be characterized as fairly high but usually below capacity. There is a relatively high proportion of trucks: 20–30%, whereas the average percentage for Dutch motorways was 14.2% (RWS-AVV, 1993).

For the period from November 1991 until March 1994, data from the following sources were collected.

Traffic measurements

During the entire evaluation period, traffic measurements were obtained on a continuous basis by means of inductive loop detectors. There were five traffic measurement locations on the A16 motorway, and two more on the A59 motorway. On every location an inductive loop detector pair was present in each of the lanes. This detector measured the following variables of all passing vehicles:

- lane number,
- time of day (0.1 s),
- speed (km/h) and
- length (0.1 m).

Since these data were registered on an individual vehicle level, it was possible to derive additional variables that describe car-following behaviour:

- headway (s),
- Time-To-Collision TTC (s).

Meteorological data

General meteorological data were available on a one-hour basis from the nearest meteorological station (Gilze-Rijen). Variables such as temperature, air humidity, wind speed and direction, precipitation (kind and quantity) were registered.

Visibility measurements

The visibility sensors which are a part of the fog-signalling system were also used in the evaluation to determine the visibility conditions near the loop detectors. These so-called Present Weather Sensors measured an extinction coefficient, which was transformed into a visibility range (m) using the standard equation for the meteorological visual range (visibility range equals 3.0 divided by the extinction coefficient, see for instance White & Jeffery, 1980). Measurements were available for the entire evaluation period for each minute during which the visibility at one or more sensors was less than 1000 m.

VMS data

Messages shown on the Variable Message Signs were logged as well. Initially, only the fog-warning system generated messages, but after November 1992, an Automatic Incident Detection (AID) system became operational as well on the same motorway section. When very slow traffic was detected, the AID displayed '50' and '70' speed limits on the matrix signs upstream of the incident.

Other data

The local road administrator ("Dienstkring Autosnelwegen Breda" from the Ministry of Transport, Public Works, and Water Management) logged any special event about the traffic on the A16 and the A59. Entries were given for situations such as accidents, lane closures, road maintenance, large-scale police surveillance, and so on.

2.2 Analysis

General

Since the traffic volume on the A16 is generally higher than on the A59 motorway, one of the A16 loop measurement points was used in the analysis (Zevenbergschen Hoek, distance marker 55.9). This location has no nearby on- or off-ramps.

Periods were excluded from the analysis if one or more of the following requirements were fulfilled:

- the visibility range was smaller than 1000 m (either in the KNMI data from Gilze-Rijen or on the A16 visibility sensors that were representative for the visibility range near the loop detectors)
- there were unusual weather conditions other than rain (temperature $< 0^{\circ}\text{C}$, wind force 7 Beaufort or higher)
- unusual road or traffic conditions occurred (accidents, road maintenance, etc.).

Additionally, in the part of the study dealing with effects of rain on driving behaviour, periods during which messages were shown on the VMSs (either from the fog-warning system or from the AID system) were excluded.

Daily volume

In the first part of the analysis, the effect of rain on the daily traffic volume were investigated. Rainy days were selected using a criterion that consisted of minimum number of hours with at least moderate rain, within a specified time frame. For example, the criterion could be that between 6 and 19 o'clock, there had to be at least 5 hours with at least moderate rain. Several such criteria were used in the analysis. Based on Van Engelen (1995), the hourly rain data were categorized as shown in Table I.

Table I Categorisation of rain intensity.

rain quantity Q (mm per hour)	rain category
$0.1 \leq Q \leq 1$	light
$1 < Q \leq 5$	moderate
$Q > 5$	heavy

For each rainy day, a control day without rain was determined. The control day had to meet the general criteria listed above, and additionally it had to be completely dry. Candidate control days were one week before or after the day with rain. If neither of these were suitable as a control day, 2 or 3 weeks before or after the rainy day were alternative candidates.

For each selected day, the daily volume (sum over both carriageways) was determined from the loop detector data. The conditions with and without rain were compared statistically in a t-test.

Driving behaviour

In the second part of the analysis, the effects of rain on driving behaviour was investigated. First, periods with rain on the A16 were selected. This had to be done based on measurements from the KNMI station Gilze-Rijen. The meteorological data measurement interval was rather long (one hour intervals), and additionally, the distance of the meteo station to the A16 was approximately 12 km. In order to be sufficiently sure that there was rain on the A16, the following procedure was used.

- From the meteo database, all periods were selected which had at least 5 hours of at least moderate rain in a row.
- Of all selected periods, the first two hours and the last two hours were removed.

Next, for each rain period a control period with the same time-of-day was selected in the same way as for the daily volume analysis.

The selected periods were split up into 5-minute intervals. For each of these intervals, the following quantities were determined for each lane separately:

- the mean speed (km/h)
- the traffic volume (vehicles per lane per hour)
- the percentage of vehicles with a time headway < 1, 3, and 5 s, respectively
- the percentage of vehicles with a Time-To-Collision (TTC) < 5 and 10 s, respectively.

Results were subjected to analyses of variance (ANOVAs). For this purpose, the traffic volume was categorized using an interval width of 250 vehs/hour/lane, as in Hogema et al. (1994). Unless mentioned otherwise, factors used in these ANOVAs were weather (dry *vs* rain), lane (fast lane *vs* slow lane, i.e. left and right lane, respectively), volume category, and carriageway (northbound *vs* southbound). For the factor volume category, as many levels were used as possible without introducing empty cells in the ANOVA design.

3 RESULTS

3.1 Effects on daily traffic volume

Because of the explorative character of this study, several criteria for selecting rain days were used. In the left-hand part of Table II, the criteria are shown. The hours given in the first two columns indicate the moment at which the rain quantity measurement was registered, i.e. the end of the measurement interval. For example, in the first row, the criterion for rainy days was that during the entire day, there had to be at least 6 hours with at least moderate rain intensity. Other criteria only regarded rain in a specific time frame. For instance, in the 5th row, days were only selected as rain if there was sufficient rain between 7 and 9 o'clock in the morning. The rationale for this criterion is that if travellers are more willing to travel by car on rainy days, this effect will be most pronounced when it rains during the morning hours when most commuters make their choice for the mode of transport for that day.

The right-hand part of Table II shows the results for each criterion: the total number of days selected, and the mean daily volume (vehicles per 4 lanes per 24 hours) for dry and for rainy days. The results were analyzed statistically by means of t-tests; the resulting p-levels are shown in the last column of Table II. The results show that there were no significant differences in the daily traffic volume between rainy and dry days, regardless of the selection criterion.

Table II Selection criteria and the resulting mean daily intensity (sum over 24 hours over all 4 lanes) on dry and rainy days.

selection criterion				results			
time frame		minimum hours of rain	minimum rain intensity	nr. of days (dry+rain)	mean daily volume		p-level
from	until				dry	rain	
1	24	6	moderate	20	64968	63127	0.73
1	24	5	moderate	34	62475	61887	0.89
6	19	5	moderate	16	66872	64737	0.75
6	19	4	moderate	28	62784	61372	0.77
7	9	2	moderate	12	68283	65155	0.57
1	24	12	light	64	62769	61559	0.62

3.2 Effects on driving behaviour

The analysis procedure as described in § 2.2 resulted in the selection of 1976 five-minute periods (988 dry and 988 rain periods).

To study the sub-division of traffic over lanes, the percentage of carriageway traffic that was driving in the fast and in the slow lane was determined for each period. The percentage of traffic in the slow lane was analyzed by means of an ANOVA using the factors weather, carriageway volume category, and carriageway. The carriageway volume category width was selected at 500 vehicles per carriageway per hour. There was a main effect of weather [$F(1,957)=13$, $p<0.001$] showing that in dry conditions the percentage of traffic in the slow lane (59.5%) was somewhat higher than in rain conditions (56.8%). There also was an effect of volume category [$F(6,957)=1072$, $p<0.001$] and an interaction between volume category and weather [$F(6,957)=4.6$, $p<0.001$], see Fig. 1. In the lowest traffic volume condition, almost all traffic is in the slow lane, and the effect of rain is the largest. As traffic volume increases, the percentage of traffic in the slow lane decreases, ending at 40% in the traffic volume category of 3000 to 3500 per carriageway per hour. Judged from the shape of the graphs in Fig. 1, this percentage may decrease somewhat more at even higher traffic volumes.

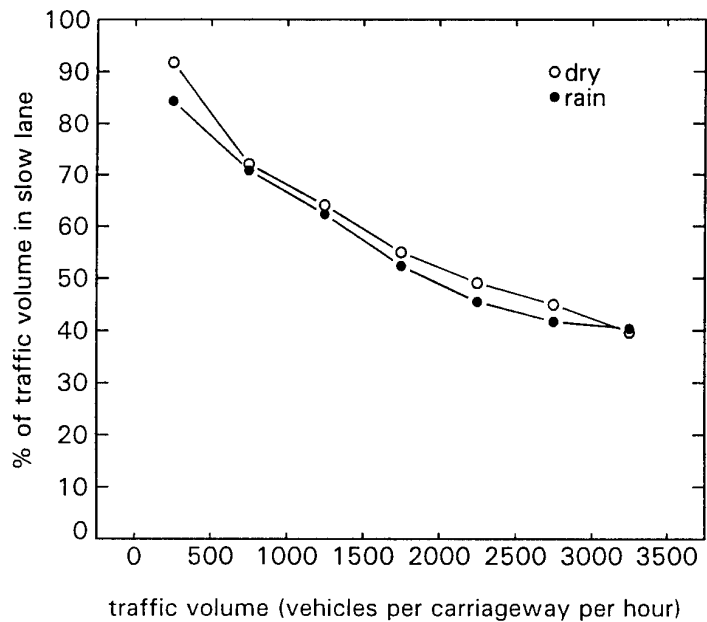


Fig. 1 Percentage of traffic in the slow (right) lane as a function of weather and carriageway traffic volume.

For the further ANOVAs, it was possible to use levels 1 until 6 for the factor lane volume category (i.e. up to 1500 vehicles per hour per lane) without introducing empty cells in the ANOVA design. The total number of periods actually used in the ANOVAs was 1807.

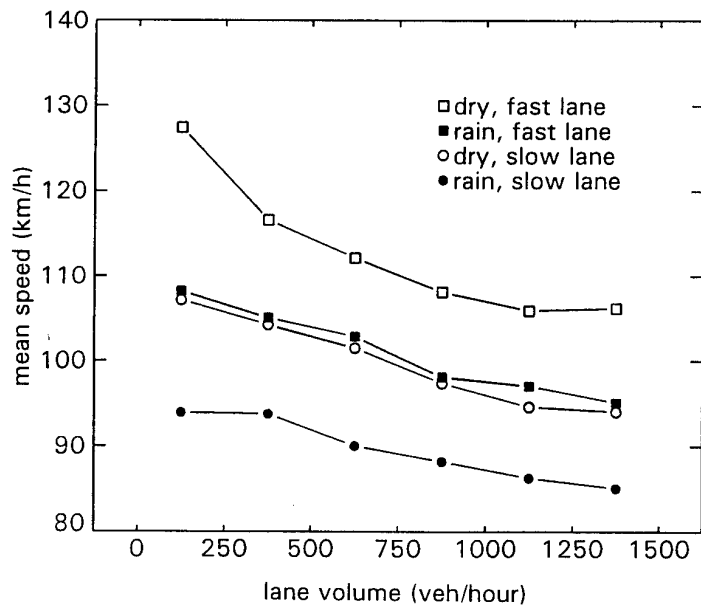


Fig. 2 Mean speed as a function of traffic volume, weather and lane.

An ANOVA was carried out on the mean speed, using the factors weather, lane, lane volume category, and carriageway. There was a main effect of weather [$F(1,1759)=655$, $p<0.001$] showing that the mean speed in rain was 11 km/h lower than in dry conditions. The mean speed decreased as a function of volume level [$F(5,1759)=211$, $p<0.001$], and in the fast lane, speeds were higher than in the slow lane [$F(1,1759)=812$, $p<0.001$]. These effects are shown in Fig. 2. There also was an interaction between volume category and weather [$F(5,1759)=17$, $p<0.001$] and between volume category, lane, and weather [$F(5,1759)=3.1$, $p<0.01$]. The decrease of speed due to rain was larger in the lowest traffic volume category, especially in the fast lane.

An ANOVA was carried out on the percentage of time headways < 5 s using the factors weather, lane, volume category, and carriageway. ANOVAs with the same factors were carried out on the percentage of headways < 3 s and 1 s, respectively. Fig. 3 shows the results of these ANOVAs.

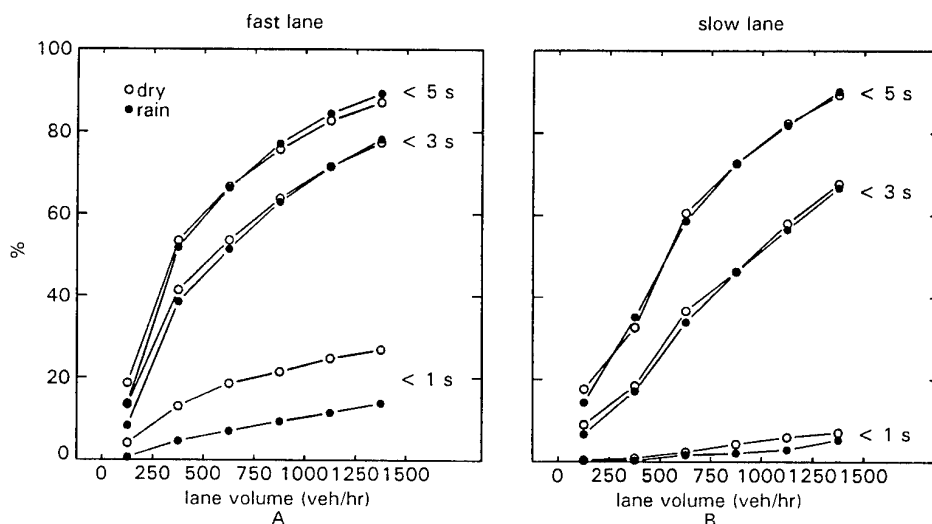


Fig. 3 Mean percentage of time headways < 1, 3 and 5 s, respectively, as a function of weather and traffic volume. A fast lane; B slow lane.

The ANOVAs yielded the following results.

- For the percentage of headways < 1 s, there was a main effect of weather [$F(1,1759)=412$, $p<0.001$], showing that this percentage was smaller in rain conditions (5.0%) than in dry conditions (10.8%). The headway < 3 s analysis showed a similar (but smaller) effect [$F(1,1759)=8.2$, $p<0.01$]: the percentages were 44.8 and 46.4, respectively. For the < 5 s analysis, there was no main effect of weather [$p>0.6$].
- In all three ANOVAs, there was an effect of volume category [all $F(5,1759) > 211$, all $p<0.001$]: the percentages increased with traffic volume.
- The percentages of headways < 1 s, 3 s and 5 s were all larger in the fast lane than in the slow lane [main effects, all $F(1,1759) > 57$, all $p<0.001$].
- For the percentage of headways < 1 s, there was an interaction [$F(1,1759)=238$, $p<0.001$]: the reduction due to rain was larger in the fast lane than in the slow lane. A

planned comparison showed that in both lanes the reduction was significant [both $p < 0.01$].

- For the percentage of headways < 5 s, there was an interaction between flow category and weather [$F(5,1759)=3.6$, $p < 0.01$]. In the flow category of 0–250 veh/hour/lane, the percentage of headways < 5 s was smaller in rainy than in dry conditions, whereas in all the other flow categories, there was no effect of weather.

Next, ANOVAs were carried out on the percentage of $TTC < 5$ and < 10 s, respectively, using the factors weather, lane, volume category, and carriageway. For the percentage of $TTCs < 5$ s, a main effect of weather [$F(1,1759)=53$, $p < 0.001$] occurred: the mean percentage was smaller in conditions with rain (0.14%) than in dry conditions (0.47%). A similar effect was found for the percentage of $TTCs < 10$ s [$F(1,1759)=113$, $p < 0.001$]: 2.8% for dry, and 1.2% for rain periods.

4 DISCUSSION AND CONCLUSIONS

The data used in this study were originally collected to evaluate the effects of a fog-warning system on driving behaviour. The same set of data was now used to study the effects of rain. A limitation of this data set was that the rain measurements were only available from a measurement point which was located at considerable distance (approximately 12 km) from the traffic measurement point, with a relatively long measurement time interval (1 hour). Therefore, the analysis of driving behaviour had to be restricted to a dichotomous comparison between dry and rain conditions. It was not possible to use a more refined scaling for the variable rain intensity. Neither could the effects of reduced visibility and of reduced friction potential as caused by rain be distinguished. Finally, the current data set could not be analysed using atmospheric conditions (raining/dry) and road surface conditions (wet/dry) as separate factors. More refined analyses would be possible by using sensors close to the traffic measurement location with a much shorter measurement time interval (for instance 1 minute, as the A16 visibility sensors). A further refinement that would be possible based on the currently available data is to include vehicle category (cars/trucks) and light condition (day/night) as factors in the analysis.

In the first part of this study, effects of rain on the daily traffic volume were investigated. Several selection criteria were used, but for none of them an increase of the daily traffic volume was found. Apparently, rain does not cause a major modality shift towards car use.

In terms of driving behaviour, the results showed that drivers reduce their speed in rain. With respect to time headways, the results showed that the proportion of traffic with a headway < 1 s decreases in rain, and that this proportion is larger in the fast lane than in the slow lane. These effects are in correspondence with those reported by Van der Vlist (1996). The percentage of headways < 3 s was reduced in rain as well, but this effect was smaller. The time headway distributions are strongly influenced by traffic volume. Therefore, when these indicators are used as a dependent variable, traffic volume should be either held constant over other conditions, or (as in this study) explicitly included as an

independent variable. Finally, the proportions of $TTC < 5$ s and < 10 s were both reduced in rain.

The literature shows that traffic unsafety is increased during rain. Andrey and Olley (1990) give a survey of eight studies on the effect of weather on accident rates. The average increases in accident rates found range from 20% to 130%. Fokkema (1987) gives another overview of literature on the relationship between rain and traffic safety. In rain, the accident risk increased by a factor from 1.5 to 5.1. Apparently, the adaptation of driving behaviour is insufficient to maintain the same level of safety. Additionally, this shows that variables such as speed, headway and TTC are not suitable as absolute safety indicators when comparing driving behaviour in dry vs rainy weather.

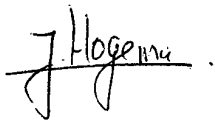
The highest traffic volume category included in the analyses ranged up to 1500 vehicles per hour per lane. This is still well below the road capacity, which is in the order of magnitude of 2200 veh/hour/lane (Van der Horst, 1993). Therefore, the results of the current study do not lead to conclusions about the effect of rain on road capacity. In fact, during a major part of the measurement period, an Automatic Incident Detection was operational (see § 2.1). If congestion occurred, the AID would show speed limits on the matrix signs, so then behaviour was not only influenced by the weather, but also by the AID. Therefore, the currently available data base is only partially usable to study effects of weather on traffic around congestion. However, there is evidence from the literature that capacity is reduced in rain. Jones, Goolsby and Brewer (1970) reported a reduction of freeway capacity between 81 and 86 percent of the dry weather capacity. Also Hall and Barrow (1988) and Van der Vlist (1996) reported a reduction in capacity.

To summarize the findings of this study, there is no indication that rain causes an increase of road traffic volume. Drivers do adjust their behaviour to rain, but apparently not sufficiently to maintain the same level of safety.

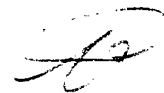
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