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Enhancement of traffic management algorithms for UK motorways

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Abstract

The overall aim of this work is to review and improve traffic CM algorithm to delay the onset of flow breakdown. The results indicated that compared to other two classic models, the Underwood model was able to match the field data on the M25 motorway consistently and capture the speed-flow relationships successfully, in terms of larger R-squared coefficient (R^2) and smaller average values of root mean squared error (*RMSE*). In addition, it was found that Gaussian function can describe the relationship between flow values at the turning points of traffic speed and flow curve and the threshold of the CM algorithm. The fitted traffic speed and flow curve showed that the values at the turning points were significantly reduced under light and heavy rainfall. Thus, the threshold values of the CM algorithm should be optimized according to the determined Gaussian function in the present work.

Keywords: Weather; Traffic flow; Speed; Motorway; Speed-flow pattern.

1. Introduction

Macroscopic models of traffic are required to describe the relationship between traffic flow, speed, and flow density. Since 1935, Greenshields et al. (1935) has proposed a simple linear relationship between flow and speed. In the last few decades, the speed-flow relationship has advanced to the level of exponential and logarithmic functions, for example, the North-western model, Van Aerde model, and Underwood model (Drake et al.1967; Van, 1995; Underwood, 1961). The different models are suitable for different data sets. As a result, it is necessary to find the best model to fit the traffic speed and flow relationship on England's motorways.

According to the Highway Capacity Manual, the definition of capacity is "the maximum hourly rate at which persons or vehicles can be reasonably expected to traverse a point or a uniform section of a lane or roadway during a

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given time period under prevailing roadway traffic and control conditions" (Reilly, 2000). The capacity of the road is often assumed to be constant. Therefore, the threshold from the Congestion management (CM) algorithm are fixed values. However, variations in weather conditions and road conditions lead to the significant difference. Generally, visibility and road conditions are considered the main factors that affect driving conditions which can impact both the traffic flow and speed. Fog and precipitation can reduce visibility, while water, snow, and ice may reduce the friction between the ground and vehicle, leading to a speed reduction. Hence it is necessary to understand how the weather affects traffic conditions and enhance better traffic CM algorithm.

Rainfall is the most common adverse weather in the UK, and the traffic condition becomes worse on rainy days compared with normal conditions. Although previous studies have studied the impacts of weather conditions on the speed and flow, there is limited research on how they affect the UK motorways combined with the threshold values of the CM algorithm. The purpose of the paper is to analyze how the weather conditions impact the free-flow speed for UK motorways and consider whether it is necessary to enhance the threshold of the CM algorithm under the adverse weather conditions.

2. Literature review

Speed-flow models reflect the correlation between traffic speed, flow, and density. The Greenshields model was the most representative of the generalized polynomial models, which was first acquired by field data fitting Greenshields et al. (1935). The Underwood model (Underwood, 1961) was a representation of the generalized exponential models, which presents a satisfactory performance in low-density conditions. Moreover, many models such as Newell model (Newell, 1961), Kerner and Konhauser model (Kerner and Konhauser, 1994), and the Logistic 3PL model (Wang et al. 2015) have been proposed based on the Underwood model. Traffic patterns and driving behaviors may vary considerably from country to country, so it is necessary to select a fitted model which has the best performance to fit the traffic speed and flow relationship on England's motorways.

Some findings of past research have demonstrated the significant effect of precipitation intensities on traffic flow and speed. However, almost all the findings implied that a general decrease happens in flow and speed as intensities rise. Manual (2000) contained information on speed and capacity reductions caused by light and heavy rain or snow. The handbook suggested that capacity decreases of 0−15%, while 2−14% and 5−17% reductions happen in speed, respectively, owing to light and heavy rains. Similarly, it recommended 5−10% and 25−30% capacity reductions, as well as 3−10% and 20−35% reductions in speed in light and heavy snow conditions. Chin et al. (2004) investigated the effects of several weather conditions (rain, snow, and ice) and discovered that rain had the greatest effect on road capacity reduction, followed by snow and ice, and rural freeways had more effect than urban freeways. Additionally, the heavier the rainfall, the greater impact on capacity and speed would be. Agarwal et al. (2005) analyzed the impacts of weather conditions on traffic flow and capacity characteristics of urban freeways and indicated that heavy rains and heavy snow had capacity reductions of 10−17% and 19−27% and speed reductions of 4−7% and 11−15%, respectively. Chung et al. (2006) found that rain decreased capacity ranging from 4−7% in light rain to a maximum of 14% during heavy rain. Free flow speed is also affected by rain because drivers have to adapt to the slippery road and poorer visibility driving conditions thus increasing headways. Reductions in free-flow speed between 4.5% in light rain to 8.2% in heavy rain were observed. Maze et al. (2006) found that heavy rain caused 14−15% reductions in highway capacities, while heavy snow reduced 25−30%. Reductions in speed were 5 to 10 km/h and 38 to 50 km/h for heavy rain and snow respectively, and 2 to 3 km/h when it was light. Hranac et al. (2006) found that light snow resulted in larger reductions in traffic free-flow speed and capacity when compared to light rain. Light rain (less than 0.25 inch/h) and light snow (less than 0.25 inch/h) resulted in reductions in free-flow speed and capacity at 2−3.6% and 10−11% as well as 5−16% and 12−20%, respectively. However, there are not significant differences when the rain and snow are heavy. Akin et al. (2011) studied the historical data (weather conditions and surface conditions) of two main highway corridors and found that rainfall resulted in a reduction of 8−12% in free-flow speed and 7−8% in capacity. Jensen (2014) implied that precipitation had an obvious negative effect on speed when the road was not under congestion. Furthermore, the capacity of the highway seems to be lower during inclement weather and they have evidenced that travel time increased as well, at least under the free-flow condition. Heavy precipitation reduced speed and capacity by around 5−8%, but snow reduced capacity substantially. Heshami et al. (2019) studied the basic diagram parameters on various weather conditions of the highway in Canada and found that snow had a greater negative impact on the traffic condition, reducing speed and flow by 10.9% and 14%, respectively. Zhang et al. (2019) studied the expressway in Beijing and found that the reduction of speed was 3−5.3% and 6.6% under light and heavy rain and 7.3−11.0% and 17.1% reduction in the capacity, respectively. Besides, some researchers focused on three aspects to analyze the impacts, including free-flow speed, the speed at capacity, and capacity volume. Rakha et al. (2008) quantified the impacts of rainfall on the highway in several areas in the United States and found that rainfall led to a 6−9% and 8−14% reduction in free-flow speed and speed at capacity and a 10−11% decrease in capacity. Lam et al. (2013) found that the rainfall had a substantial impact on the traffic conditions in Hong Kong.

3. Methodology

3.1. Fitting speed-flow model

Various models have been developed based on real-world data from different countries. Traffic patterns and driving behaviors may vary considerably from country to country, so it is desirable to find the best model to fit the traffic speed and flow relationship on the congested motorways in England.

To find the best model to fit the traffic speed and flow relationship, this study chose three classic models to fit the traffic speed-flow relationship on the M25 motorway. In the present work, R-squared coefficient (R2) and root mean squared error (RMSE) was introduced as the basis for model evaluation, as shown in Equations (1) and (2).

$$R^2 = \frac{\sum (f_o(v) - f_p(v))^2}{\sum (f_o(v) - f_m(v))^2} \tag{1}$$

$$RMSE = \frac{1}{n}\sqrt{n\sum_{i=1}^{n}(f_p(v) - f_o(v))^2} \tag{2}$$

where n is the number of observations, $f_o(v)$ is donated as the actual data, $f_p(v)$ is the prediction data and $f_m(v)$ refers to the average value of actual data. The closer R^2 value is to 1, the better the model performance is. By contrast, the closer the *RMSE* value is to 0, the better the model performance is.

3.2. Speed–flow relationship under different weather conditions

Previous studies have proved that weather conditions affect both the driving conditions and the travel demand, which inevitably influence the relationship between speed and flow. Fig. 1 shows the traffic speed and flow of the randomly chosen two days where one day is sunny and the other is heavy rain all day. It was found that traffic speed and flow on the M25 motorway were affected by the heavy rain. As a result, the traffic speed-flow relationship would be different in the case of sunny and heavy rain. To capture this relationship in different weather conditions, this work used the selected model to fit the traffic speed-flow in different weather conditions (i.e. with and without rain) according to the effects of adverse weather on traffic speed and flow reported in previous studies.

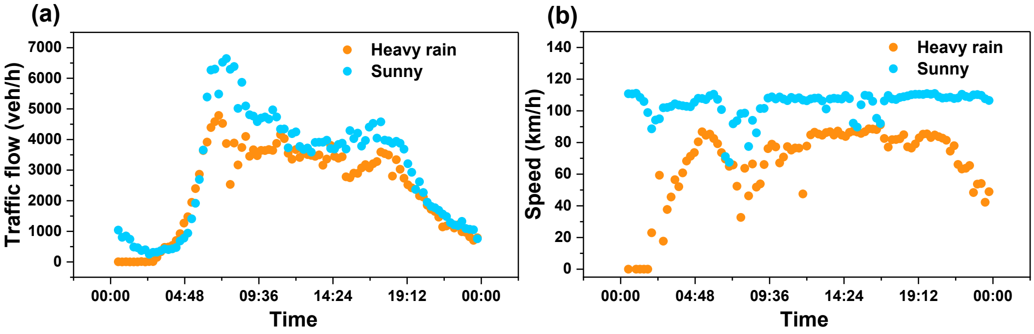

Fig. 1. (a) Effect of heavy rain on traffic flow; (b) Effect of heavy rain on speed.

3.3. Enhancement of CM algorithm

The overall aim of this work is to improve the traffic management algorithm which is used for congestion management, as part of the operation of intelligent transport systems on motorways in the UK. The CM algorithm seeks to delay the onset of flow breakdown (when traffic flow exceeds road capacity). However, a traditional CM algorithm do not consider the influence of weather factors. As a result, it is desirable to optimise the current algorithm under the adverse weather conditions. First of all, the traffic flow values at the turning point of traffic speed and flow curve were determined at various sites on the M25 motorway. Secondly, these values were used to build the possible relationship with the flow threshold of the CM algorithm provided by National Highways. Finally, the new recommended threshold of the CM algorithm was derived in the case of adverse weather.

4. Results and Discussion

4.1. Data collection

The data was provided by National Highways MIDAS (Motorway Incident Detection and Automatic Signalling) system, which collects data from detectors located 400-500 metres apart on each lane (Midas standard). Traffic speed and flow of the M25 motorway were calculated with fifteen-minute observation intervals. Because the goal of this research is to examine the overall speed-flow correlation on the congested motorway network, all data, including the morning and evening rush hours for the whole year from July 2018 to June 2019, were analysed on the M25 motorway. In order to provide a more complete picture of the correlations between the variables, the data was not filtered by weekday.

4.2. Selecting the speed-flow model

According to previous studies, three classic models including the Green-shield model, North-western model, and Underwood model were selected in the present work to fit field data from 120 congested sites on the M25 motorway. Fig. 2 illustrates an example of the above models for fitting to field data from the M25 motorway (M25/4229A). It can be observed that compared to the other two models, the Underwood model could match the field data of the M25 motorway well under both free-flow and congested-flow situations. This means that the Underwood model presents a better performance when compared to the other two models. To quantify the performance of various classic models, the coefficient of R^2 and *RMSE* were introduced. Table 1 summarizes the R^2 and RMSE results of the data-fitting for 8 randomly selected sites on the M25 motorway.

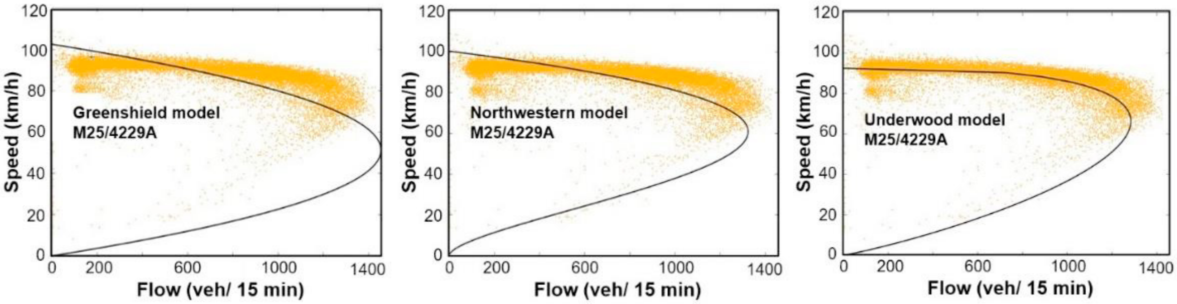

Fig. 2. Performance of different models fitting to field data on the M25 motorway.

It can be seen from Table 1 that the R^2 values for the Underwood model were apparently larger than those for the Greenshied and Northwest models, which indicates that Underwood model matched the field data on the M25 motorway consistently and captured the speed-flow correlation successfully. Moreover, the Underwood model had smaller *RMSE* values at various sites on the M25 motorway relative to the other models. The *RMSE* results also proved the best performance for the Underwood model among three classic models. The results above indicate that among three classic models, the Underwood model is more suitable to capture the relationship between traffic speed and flow on the M25 motorway. As a result, the Underwood model was used to fit field data on the M25 motorway in the current work.

Table 1. Results of data fitting using different models.

Data sites	Greenshield		Northwestern		Underwood	
	R^2	*RMSE*	R^2	*RMSE*	R^2	*RMSE*
M25/4134A	0.12	248	0.16	214	0.82	8.65
M25/4229A	0.07	335	0.07	310	0.85	9.25
M25/4259A	0.15	208	0.07	200	0.73	7.54
M25/4423A	0.08	364	0.14	204	0.76	7.45
M25/4426A	0.10	359	0.16	194	0.78	6.95
M25/4792A	0.08	434	0.09	362	0.80	7.43
M25/4802A	0.06	324	0.22	268	0.81	7.45
M25/4811A	0.09	376	0.11	297	0.79	9.34

4.3. Optimization of traffic management algorithms under different weather conditions

Previous studies have demonstrated that weather conditions would affect the traffic speed and flow significantly, as summarised in Table 2. For instance, Reilly (2000) reported that light and heavy rains caused a reduction in traffic speed and flow of up to 17% and 15%, respectively. Agarwal et al., (2005) studied the effect of weather conditions on urban freeway traffic speed and flow and found that heavy rains presented flow reduction of 10−17% and speed decrease of 4−7%. Recently, Zhang et al., (2019) revealed that the reduction of free-flow speed was 3% and 7%, as well as the reduction of traffic flow were 7% and 17% under light rain and heavy rain, respectively. The average percentage reduction in traffic speed and flow was calculated due to the adverse weather effects based on the published literature, and calculated results are listed in Table 2. It can be seen that compared to normal weather, the average reduction of speed and traffic flow in light rain was 5% and 7%, respectively. The average reduction of speed and traffic flow in heavy rain was 7% and 11%, respectively. In the present study, it is assumed that the effect of light and heavy rain on traffic speed and flow on M25 motorway is the same as to the average values from the published literature. The chosen Underwood model was used to fit the traffic speed and flow under light rain and heavy rain conditions. An example of the obtained results is illustrated in Fig. 3. This site corresponded to the 4229A on the M25 motorway, where the traffic speeds and flows on the normal weather were calculated from real data, whilst the traffic speeds and flows under light and heavy rain conditions were obtained by using the Underwood model according to average values of the published literature on the reduction of the traffic speeds and flows by light and heavy rains.

Table 2. The reduction in traffic speeds and flows in the light and heavy rains.

References	Rain			
	Light rain		Heavy rain	
	speed	flow	speed	flow
Reilly (2000)	2–14%	~15%	5–17%	~15%
Agarwal et al. (2005)	/	/	4–7%	10–17%
Chung et al. (2006)	5%	4–7%	8%	~14%
Maze et al. (2006)	2–4%	2–7%	6%	14%
Hranac et al. (2006)	2–4%	10–11%	/	/
Jensen (2014)	/	/	5–8%	5–8%
Zhang et al. (2019)	3%	7%	7%	17%
Average	5%	7%	7%	11%

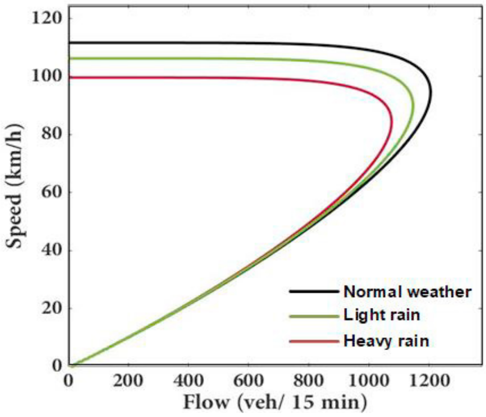

Fig. 3. Fitting traffic flow and speed under different weather conditions using the Underwood model.

National Highways uses MIDAS to automatically set signals on the motorway network to postpone the onset of flow breakdown according to the CM algorithm. CM signalling is dependent mainly upon traffic flow. The principle is that as traffic flows approach the road's capacity, flow threshold (FT2), 60 mph signals are displayed to road users to smooth the traffic flow, minimise lane changes and postpone the onset of flow breakdown. As traffic flows continue to increase, flow threshold (FT3) is triggered, and the signals change to 50 mph. Traffic signals of the CM algorithm come on according to the capacity of all lanes. Each lane has the same threshold at each site, and these threshold values were determined by National Highways at various sites on the M25 motorway. To build possible relationships between the flow value at the turning point of real traffic speed and flow curve and FT2 and FT3, the corresponding values of randomly chosen sites are summarised in Table 3. The Gaussian function was used to fit the above relationship, the fitted curves are expressed by Equations (3) and (4), and the corresponding results are shown in Fig. 4.

$$FT2 = 1532\exp(-(\frac{F_T - 1869}{1113})^2) \tag{3}$$

$$FT3 = 1674\exp(-(\frac{F_T - 1977}{1330})^2) \tag{4}$$

where F_T refers to the flow value at the turning point of traffic speed and flow curve. From Fig. 4, the R^2 values between the flow values at the turning point and FT2 as well as between the flow values at the turning point and FT3 are 0.94 and 0.87, respectively. It means that the equations (3) and (4) can catch the correlations between the flow values at the turning point and FT2/FT3 successfully. As shown in Fig. 3, the traffic flow value at the turning point of traffic speed and flow curve has changed under the light and heavy rain conditions. As a result, the corresponding FT2 and FT3 of the CM algorithm should be adjusted accordingly in the case of the light and heavy rainfall.

Fig. 5 illustrates an example at the M25/4229A. It can be seen from Fig. 5 that traffic flow values at the turning points of traffic speed and flow curves under light and heavy rainfall were smaller than that under normal weather. The corresponding FT2 and FT3 values were determined based on the equations (3) and (4), and the results are shown in the Fig. 5. In other words, the threshold values of traffic flows (FT2 and FT3) should be advanced in the case of light and heavy rainfall (see Fig. 5). In the current work, just M25 motorway in the UK was explored, so more motorways are required to consider the effect of weather on the CM algorithm.

Table 3. The flow value at the turning point of traffic speed and flow curve, FT2 and FT3.

Data sites	Flow value at turning point (veh/15 min)	FT2 (veh/15 min)	FT3 (veh/15 min)
M25/4134A	1386	1320	1530
M25/4229A	1201	1065	1245
M25/4259A	862	705	825
M25/4423A	1359	1110	1170
M25/4426A	1579	1425	1485
M25/4792A	1644	1575	1665
M25/4802A	1418	1305	1350
M25/4811A	1849	1485	1635

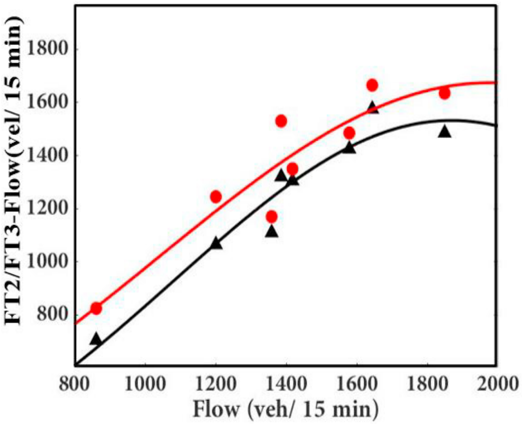

Fig. 4. Relationship between FT2/FT3 threshold and flow values at the turning point.

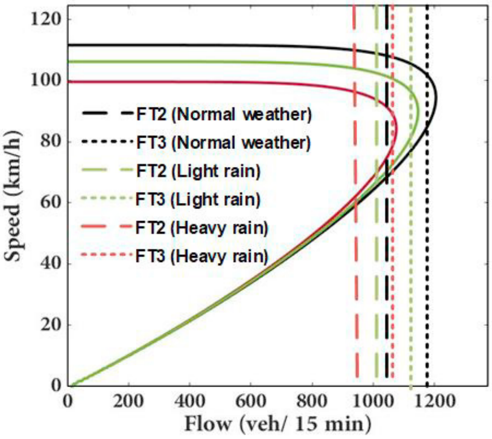

Fig. 5. FT2/FT3 threshold values suggested for light and heavy rains.

5. Conclusion

In this study, classic models were used to capture the speed-flow correlation using real-world traffic flow and speed data from the M25 motorway in the UK. The results suggested that the Underwood model can match the field data on the M25 motorway consistently and captured the speed-flow correlation successfully. Specifically, compared to other models, the underwood model had larger R^2 value and smaller *RMSE* values. In addition, the variation of speed and traffic in light rain and heavy rain was determined according to the published literature. The obtained results showed that the average reduction of speed and traffic flow in light rain is 5% and 7 %, respectively. The average reduction of speed and traffic flow in heavy rain is 7% and 11%, respectively. It was found that Gaussian function can describe the relationship between flow values at the turning points of traffic speed and flow curve and the threshold of the CM algorithm. The Underwood model with better performance was used to fit the traffic speed and flow curve based on the average reduction values of traffic speed and flow in the case of light and heavy rainfall. The fitted traffic speed and flow curve revealed that the values at the turning points were significantly reduced under light and heavy rainfall. Thus, the threshold values of CM algorithm should be optimised according to the determined Gaussian function in the present work.

Acknowledgements

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