American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)

ISSN (Print) 2313-4410, ISSN (Online) 2313-4402

http://asrjetsjournal.org/

Impact of Pavement Condition on Speed Change for Different Vehicle Classes

Ibrahim H. Hashim[a]*, Mohamed A. Younes[b], Saad A. El-hamrawy[c]

[a,b,c]*Civil Engineering Department, Faculty of Engineering, Menoufia University, Shebin El-Kom, Menoufia, Egypt*

[a]*Email: hashim1612@hotmail.com*, [b]*Email: m.adel1912@yahoo.com*, [c]*Email: s_hamrawy89@yahoo.com*

Abstract

Pavement surface conditions have an influence on traffic safety, operating speed, maneuverability, driver comfort and service volume. Although many researchers have studied the influence of different roadway characteristics on traffic stream characteristics and performance, little research has been conducted to investigate the impact of pavement conditions on traffic stream characteristics. This research therefore investigates the impact of pavement conditions on traffic speed, the most important traffic stream characteristic. Field data were collected across 13 sites from two-lane, two-way roads in Menoufia and Gharbya governorates, Egypt. Each site included two sections, distressed and un-distressed. Road geometry and pavement condition characteristics were collected manually while traffic surveys were carried out using automatic traffic recorders. The data analysis revealed that poor pavement conditions caused a large variation in vehicle speeds and consequently made the speed distribution deviate from the normal distribution. There was a significant difference between the mean speeds for different classes of vehicles. Inspection of the standard deviations of speed for distressed and un-distressed sections showed significant differences occurring mainly in distressed sections. The corollary of this is that greater uniformity of speed can be expected under pavement conditions which are good. Several regression models were developed for change in speed and pavement condition, across different classes of vehicles. For all models, the inverse Pavement Condition Index (1/PCI) was the best mathematical form for the independent variable. This means that as the PCI decreases, the change in speed increases. The developed models can calculate changes in speed over different levels of pavement distress and class of vehicle under investigation. Ultimately, they could assist traffic and pavement engineers to justify their decisions regarding maintenance strategies, to carry out safety and operational performance analysis, to study vehicle operating cost and to perform pavement life cycle assessment.

Keywords: Pavement distress; Speed change; Pavement Condition Index (PCI); Regression analysis, Egypt.

----

* Corresponding author.

1. Introduction

Road pavements facilitate the movement of traffic, contribute to surface drainage control and provide safe traffic operating conditions. Under given economic resources/restrictions, a road is built to the highest appropriate standard, to provide a high-quality pavement surface. However, as time passes, load repetitions and changing weather conditions impact on the condition of the pavement as seen by the appearance of different types of pavement distresses [1,2]. Such distresses influence driving behaviors including speed changes, maneuvers and route selection. This may increase the risk of traffic accidents [3,4] as well as lead to a decline in traffic capacity and operational performance [5]. Pavement distresses also have an impact on road functionality, vehicle operational costs (VOC) and environmental sustainability [6] in addition to potential legal issues, diversion of traffic to adjacent streets and longer emergency vehicle response time [1].

Accurate estimates and knowledge of road traffic flow characteristics are essential when planning, designing and operating transportation facilities [7], these traffic characteristics influenced by prevailing roadway, traffic and driver conditions [8]. Roadway conditions may comprise all the geometric parameters used to describe the roadway including type of facility, lane width, shoulder width, lateral clearance and horizontal and vertical alignments in addition to pavement conditions. The condition of the pavement can have a substantial impact on traffic flow characteristics, specifically speed characteristics. Speed characteristics are important for traffic performance evaluation, highway safety examinations, setting appropriate traffic control devices and speed limits and the development of simulation programs. Speed is also the parameter that reflects level of service.

It is argued that the effect of pavement condition on vehicle speed has not been given adequate attention as seen, for example, in The Highway Capacity Manual [8] which does not consider pavement conditions when estimating free flow speed and/or calculating of capacity and level of service. In response to this, the current research aims to identify the effect of level of pavement distress, in terms of the Pavement Condition Index (PCI), on traffic speed for different classes of vehicles. In doing so, an exploration is carried out on the relationship between pavement conditions and change of traffic speed on two-lane highways in Egypt.

2. Previous Work

2.1. Effect of pavement condition on speed and capacity

Relatively little research has been carried out investigating the relationship between roadway surface conditions and traffic stream characteristics. One of the earliest studies was conducted by M.A. Karan and his colleagues [9] who built a model representing average vehicle speed and pavement condition for two-lane highways, in terms of a riding comfort index (RCI), volume-capacity (v/c) ratio and speed limit, based on observations in 72 locations in Ontario, Canada. The main pavement condition factor was defined as roughness, M.A. Karan and his colleagues [9] concluding that speed was significantly affected by pavement condition (level of roughness) and that neglecting this may result in major errors in the economic evaluation of alternative pavement design strategies.

I.A. Haj-Ismail [1] examined the effect of roadway surface conditions on traffic speed during both day and night finding that an inverse relationship existed between traffic speed and level of pavement distress represented by Pavement Condition Index (PCI) values. As the level of pavement distress decreases, the mean speed of traffic increases. The comparison between day and night speed of traffic under the same level of pavement distress, revealed no statistical differences in speed.

S. Chandra [10] studied the effect of road roughness on speed and capacity on two-lane roads in India. His study indicated that free flow vehicle speed decreases as the roughness of the road surface increases. The effect of roughness is more apparent on the speed of passenger cars than on heavy vehicles. S. Chandra [10] also found that the capacity of a two-lane road decreases by 300 PCU/h when road roughness increases by 1,000 mm/km.

J. Ben-Edigbe and N. Ferguson [5] investigated the impact of pavement distress on the traffic capacity of uninterrupted road link sections, taking observations at eight sites in Nigeria. A capacity estimation method, based on extrapolation from a fundamental diagram representing the relationship between traffic flow and density, was used. Sections of roads suffering from both distress and no distress, were used to estimate capacity on the road link, significant differences found between the two.

More recently, B. Yu and Q. Lu [11] developed an empirical model to study roughness on vehicle speed. Explanatory variables included in addition to roughness, were volume–capacity (v/c) ratio, pavement type (flexible/rigid), number of lanes and speed limit. The preliminary analysis indicated that pavement type and speed limit were not significant factors influencing average vehicle speed. The developed regression model indicated that the average vehicle speed decreased 0.0083 mph with every 1 inch/mile increase in roughness. As acknowledged by the authors, the model did not consider vehicle type as an independent variable, something which may reduce the reliability of the model, this remaining a topic for further research.

T. Wang and his colleagues [12] was conducted a research to investigate the impact of changes in pavement roughness on free flow speed on freeways in California. The independent variables included lane number, total number of lanes, day of the week, region, gasoline price and pavement roughness, as measured by the international roughness index (IRI). The results indicated that making a rough segment of pavement smoother through application of a maintenance or rehabilitation treatment, will not result in significantly faster vehicle operating speeds. That said, the authors admitted that their model was not entirely successful as a key limitation of their study was the lack of data addressing different classes of vehicles.

K.A. Ghazlan and his colleagues [13] carried out a study to investigate the effect of pavement conditions on multi-lane highways free-flow speed (FFS) in Jordan. They developed several regression models to estimate FFS for inner lanes, outer lanes and the total section. In addition to pavement condition, other explanatory variables included speed limit, standard deviation of speeds, right lateral clearance and access point density. Based on the results of this study, the authors recommended the inclusion of pavement condition in FFS prediction equations.

2.2. Pavement conditions and other characteristics

In addition to the studies presented above, several have been conducted to examine the impact of pavement condition on other related factors such as traffic accidents and fuel consumption.

According to H.R. Al-Masaeid [3], pavement condition, expressed in terms of the International Roughness Index (IRI) or Present Serviceability Rating (PSR), has a significant influence on single- and multiple-vehicle accident rates. The results presented in his study revealed that an increase in IRI levels, or decrease in PSR levels, would reduce single-vehicle accident rates. In contrast, an increase in IRI level would increase multiple-vehicle accident rate.

H. Zeng and his colleagues [4] carried out a study to evaluate the safety of pavement conditions on rural, two-lane, undivided highways in Virginia. Using the Empirical Bayes method, it was found that while good pavements reduce accident injuries and fatalities by 26 percent in comparison to deficient pavements, they do not have a statistically significant impact on overall accident frequency. H. Zeng and his colleagues [4] concluded that improving the condition of pavements can offer significant safety benefits in terms of reducing the severity of accidents.

Regarding fuel consumption studies, S.I. Sandberg [14] reported that the surface texture of the pavement has a significant effect on rolling resistance and therefore on fuel consumption. He reported that at a speed of 55 mph or 90 km/h, an increase in the International Roughness Index (IRI) and texture depth by a factor of 10, will result in an increase in rolling resistance (RR) by 48 and 72 percent, respectively, corresponding to a 5 and 7 percent increase in fuel consumption.

I. Zaabar and K. Chatti [15] also reported that roughness has a statistically significant effect on rolling resistance forces and consequently on fuel consumption.
II. They found that an increase in IRI by 2 m/km will translate to a 2% increase in fuel consumption. I. Zaabar and K. Chatti [15] then went on to study the effect of texture on fuel consumption. Their detailed analysis showed that the effect of texture is statistically significant at 35 mph (56 km/h) for all vehicle classes but is not significant at higher speeds. An increase of the texture depth by a factor of 6, will increase fuel consumption by 1.6 % for articulated trucks and by 0.2 % for passenger cars.

While this review of the literature shows that work has been carried out studying the impact of pavement conditions on traffic stream characteristics, it appears that no research has been done so far, specifically in Egypt, to examine the relationship between different traffic characteristics and pavement surface conditions. Studying the relationship between level of pavement distress and traffic speed characteristics with a specific emphasis on changes in speed in different classes of vehicles, is therefore the main aim of this research.

3. Data Collection

3.1. Site selection and characteristics

Rural, two-lane, two-way highways present a particular challenge to highway engineers as they constitute the majority of highway networks [16].

Because of this, the focus of this research is on intercity, rural, two-lane roads (speed limit 60km/h) in Egypt, traffic and pavement data gathered from thirteen sites inside Menoufia and Gharbya Governorates, Egypt. All sites are classified as Class II highways, according to the HCM classification [8], serving shorter trips and different trip purposes.

These sites were determined by the following criteria:

- The study sites are representative of the characteristics of rural two-lane roads.
- All sites are divided into two sections; distressed and un-distressed.
- Both sections at each site have the same geometric characteristics (i.e. pavement width and shoulder width).
- The un-distressed sections were without any apparent defects/distresses (i.e. in an excellent condition).
- The sites are far from the impact of intersections, driveways and horizontal curves and located on sections with level terrain to avoid the effect of longitudinal gradients.

3.2. Pavement condition data

The process of data collection to ascertain the condition of pavements includes visual inspection of defects, measurement of these defects and finally calculation of the Pavement Condition Index (PCI). This was performed according to ASTM D6433-07 [17].

During the inspection task for each road, the inspector walked over each distressed section, measured each distress type and severity and recorded this data on an asphalt-surfaced pavement inspection sheet.

This sheet reports pavement distress (number, name and measurement unit), as well as the amount and severity of each distress.

After recording the inspection data into the above-mentioned sheets, a surface distress evaluation was calculated based on a numerical rating from 0 (failed) to 100 (excellent) pavement condition, called PCI (See Figure 1, for PCI and rating scale).

The PCI provides an indication of pavement failure, maintenance and repair requirements.

This calculation was performed using Micro PAVER software [18].

The major pavement distresses found during the inspections were longitudinal and alligator cracking, edge cracking, shoulder drop off, potholes, bleeding, polished aggregates, patching and rutting. Figure 2 shows examples of the un-distressed and distressed pavement sections which were examined.

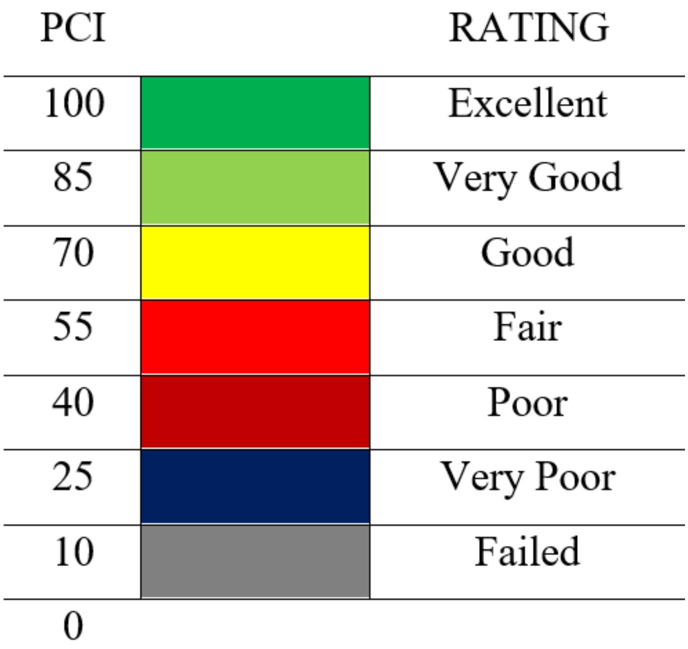


Figure 1: Pavement condition index and rating scale [17]

Un-distressed section **Distressed section**

Figure 2: Examples of un-distressed and distressed sections of pavements

3.3. Traffic data

This survey involved positioning two roadside automatic traffic recorders in situ at the selected sites, at both distressed and un-distressed sections for 6 to 8 hours. Collection of traffic data was carried out on working days during daylight hours and clear weather conditions to eliminate extraneous effects.

The roadside automatic data recorder is a dual air sensor data logging unit. Figure 3 illustrates the configuration positions of the two recorders, the minimun distance (X) not less than 160m [5,19] to ensure that vehicles reach the desired speed before the distressed section.

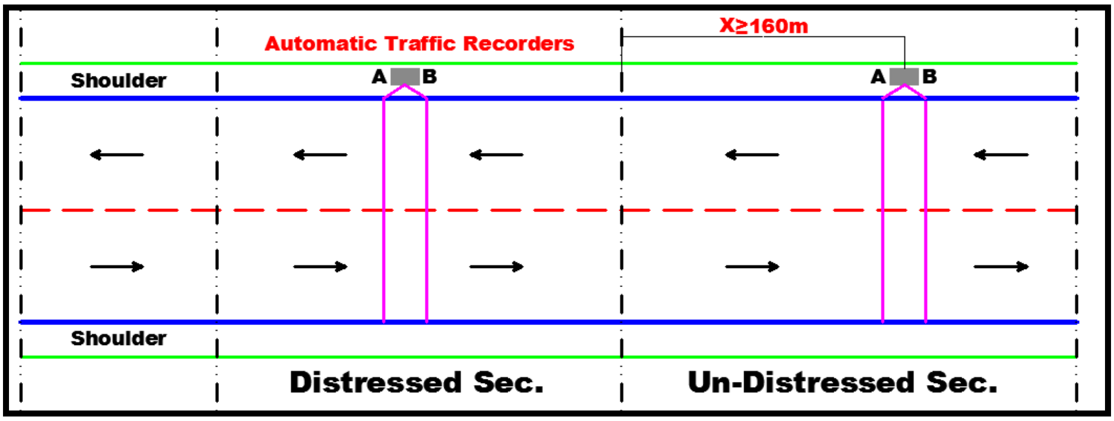


Figure 3: Positions of automatic traffic recorders

Site characteristics, data collection duration, vehicular counts, percentage of heavy vehicles and values of PCI at distressed sections are provided in Table 1.

Table 1: Site characteristics, duration of data collection, vehicular count, percentage of heavy vehicles and PCI Values

Site no.	**Road width, (m)**	**Average shoulder width from both sides, (m)**	**Duration of data collection (hours)**	**Traffic counts during data collection period (vehicles)**	**Percentage of heavy vehicles (%)**	**PCI**
A1	7.5	1.5	7.0	3308	3.69	86
A2	9.5	1.5	8.0	3264	5.94	43
A3	6.6	1.5	6.0	3319	4.61	51
A4	7.5	2.0	6.0	2086	4.22	88
A5	8.4	1.25	6.0	1717	3.61	72
A6	6.25	1.5	7.0	1939	4.28	63
A7	6.5	1.5	6.0	3031	3.7	70
A8	7.0	1.5	6.0	4375	8.07	58
A9	7.4	1.4	7.0	2471	4.05	25
A10	6.5	1.5	7.0	2926	4.41	53
A11	6.0	1.5	7.0	3570	3.84	50
A12	6.0	1.5	6.0	1558	1.6	24
A13	6.5	2.5	7.0	3244	3.64	29

Based on the data presented in Table 1, the mean PCI value equals 54.8 with a maximum of 88, a minimum of 24, and a standard deviation of 21.1. This indicates that the PCI data used in this research can be considered as covering a relatively wide distribution of distressed sections.

4. Data Analysis

4.1. Normality test

The distribution of speed of individual vehicles must be specified in the form of a suitable mathematical model. Spot speed data on a highway generally follows a normal distribution when traffic conditions are more or less homogenous [20]. This part of analysis addresses this issue by examining the levels of similarity between the collected speed data with the normal distribution for both distressed and un-distressed sections of the road as follows:

- Free flow speed data with headway≥ 5 seconds were obtained for distressed and un-distressed sections at each site.
- The Kolmogorov–Smirnov one-sample test (1-sample K–S test) was used to ascertain whether the distributions of speed were representative of a normal distribution.
- The Kolmogorov–Smirnov one-sample test for normality is based on the maximum difference between the sample's cumulative distribution and the hypothesized cumulative distribution. This goodness-of-fit test examines whether observations could reasonably have come from the specified distribution or not (i.e. normal distribution in this case). If the "D" statistic, the most extreme absolute difference, is significant, then the hypothesis that the distribution is normal should be rejected.
- The test was applied for speed data at each section and pavement condition, the results presented in Table 2.

Table 2: 1-Sample K–S test results for different sections at different sites

Site No.	**Distressed Section**			**Un-distressed Section**	
	PCI (%)	D	Asymp. sig. (2-tailed)	D	Asymp. sig. (2-tailed)
A1	86	0.025	0.831	0 .036	0.089
A2	43	0.050	**0.001**	0.023	0.401
A3	51	0.036	0.059	0.034	0.093
A4	88	0.037	0.092	0.039	0.064
A5	72	0.027	0.465	0.039	0.098
A6	63	0.070	**0.000**	0.026	0.375
A7	70	0.039	**0.019**	0.027	0.208
A8	58	0.024	0.261	0.020	0.568
A9	25	0.094	**0.000**	0.025	0.359
A10	53	0.046	**0.002**	0.066	0.06
A11	50	0.060	**0.010**	0.021	0.581
A12	24	0.126	**0.000**	0.042	0.076
A13	29	0.120	**0.000**	0.043	0.054

Regarding sections of pavement which are un-distressed, the p-value (listed here as Asymp. sig. (2-tailed)), is greater than 0.05 ($p>0.05$) in all cases.

This confirms that the speed data are normally distributed.

In contrast, for distressed sections, the p-value is less than 0.05 ($p<0.05$) in the vast majority of the cases, especially the cases with lower PCI values.

This means that the speed data deviates from a normal distribution.

In other words, poor pavement condition has an impact on the behavior of vehicle speed. It causes a large variation in vehicle speed and consequently makes the speed distribution curve deviate from the normal distribution. Such speed variations may lead to driver error and accidents [16].

This finding draws attention to the impact of pavement conditions on road safety.

4.2. Analysis of speed behavior for different classes of vehicle

ANOVA was used to compare the speed behavior of vehicles belonging to different classes as this test examines the difference between the means of three or more groups. Vehicle speeds were classified according to four vehicle classes, namely:

- All vehicles (ALL).
- Cars (CAR): Passenger cars only.
- Light Good Vehicles (LGV): Light commercial vehicle types including mini-trucks, light pick-up trucks and mini buses.
- Heavy Good Vehicles (HGV): Heavy vehicle types containing single unit trucks, trailer trucks, farm-equipment vehicles and construction-equipment vehicles.

Comparisons were performed between the mean speeds of pairs of vehicle classes for each direction of travel (AB or BA), at each point of the two sections (distressed and un-distressed) at each of the 13 sites.

This resulted in 52 comparisons between each pair of vehicle classes.

The results at one of the study sites (A9) can be seen in Table 3 which shows that the p-values between groups, for AB and BA, for distressed and un-distressed sections, are less than 0.05 meaning that there is a significant difference between the mean speeds for different classes of vehicles.

Table 3 also shows the p-values for multiple comparisons at the same site where it is seen that p-values are less than 0.05 for 18 comparisons out of 24.

This means that a significant difference in speed was found between all possible comparisons of vehicle classes in 75% of cases. Similar examinations were carried out for all other sites.

Table 3: Example of ANOVA results at Site A9

Site	Section	Direction	p-value	Multiple Comparisons (p-values)				
					ALL	CAR	LGV	HGV
A9	Distressed	AB	0.002	ALL	-	0.939	0.915	.001
				CAR		-	0.991	0.001
				LGV			-	0.002
				HGV				-
		BA	0.000	ALL	-	0.373	0.032	0.001
				CAR		-	0.002	0.000
				LGV			-	0.093
				HGV				-
	Un-distressed	AB	0.000	ALL	-	0.002	0.001	0.000
				CAR		-	0.000	0.000
				LGV			-	0.000
				HGV				-
		BA	0.000	ALL	-	0.003	0.003	0.024
				CAR		-	0.000	0.452
				LGV			-	0.000
				HGV				-

The results of the 52 comparisons between each two classes of vehicle were summarized and presented in Table 4. This table presents the number and percentage of significant differences in mean speeds between different vehicle classes, showing that mean speed differences between classes of vehicles are significant in the majority of cases. These results confirm the need to classify vehicles in almost all cases when developing models.

Table 4: Number and percentage of significance differences in mean speeds between different classes of vehicles

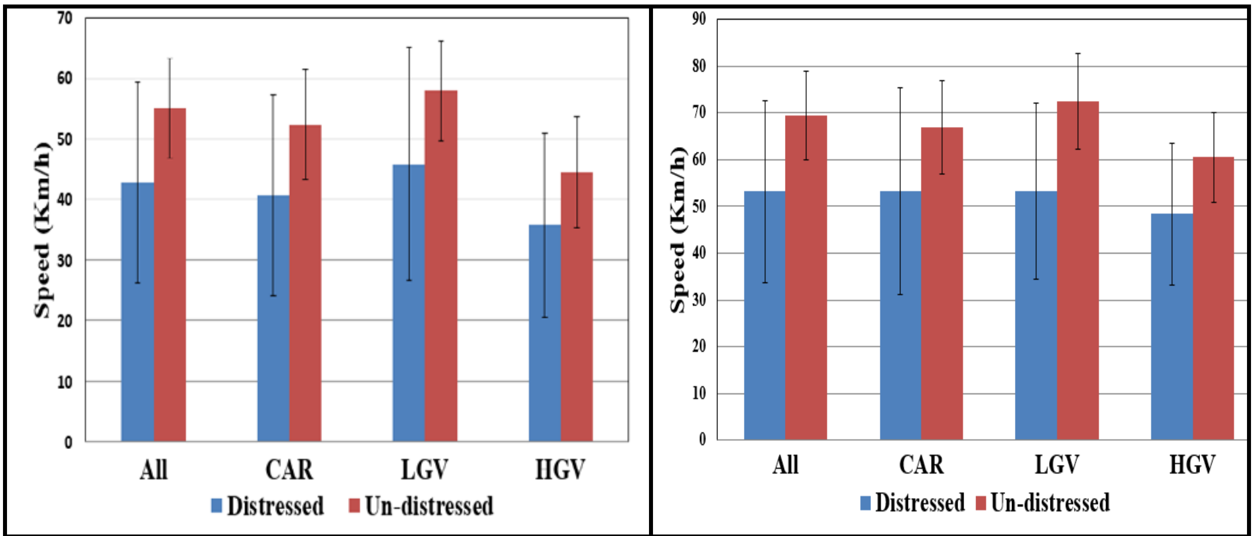
	ALL	CAR	LGV	HGV
ALL	-	25(48%)	42(81%)	41(79%)
CAR		-	45(86%)	30(58%)
LGV			-	46(88%)
HGV				-

4.3. Descriptive statistics of speed percentiles

The two most important speed percentiles are the 50th and the 85th percentiles. The 50th percentile speed (median speed) represents the speed where half the observed vehicles lie below and half above. The 85th percentile speed (operating speed) is the speed (or below this speed) at which 85% of the observed vehicles are traveling. The two percentiles for each site for distressed and un-distressed sections, for each vehicle class and for all vehicles as one category, were calculated regardless of direction of travel. To do this, the observed speeds in both directions were merged to a single database. Table 5 presents the summary statistics of the speed percentile values while Figure 4 illustrates graphically the mean values and SD's for the 50th and 85th speed percentiles for both pavement conditions for each class of vehicle.

Table 5: Summary statistics of speed percentiles (V_{50th} & V_{85th}) based on traffic at distressed and un-distressed sections regardless of direction

Variable		Distressed section				Un-distressed section			
		Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
PCI (%)		54.8	21.1	24.0	88.0	-	-	-	-
V_{50} Km/h	All	42.88	17.76	13.30	66.20	55.07	8.27	44.60	70.90
	CAR	40.68	16.56	13.70	62.30	52.28	9.07	40.70	69.80
	LGV	45.88	19.35	13.00	69.10	57.91	8.22	46.80	73.10
	HGV	35.79	15.17	10.80	58.30	44.45	9.15	24.80	60.10
V_{85} Km/h	All	56.67	21.52	18.10	82.10	69.42	9.55	54.70	86.40
	CAR	53.23	19.45	17.90	79.60	66.86	10.03	52.20	85.30
	LGV	58.90	22.18	18.40	86.00	72.42	10.33	56.50	87.80
	HGV	48.35	18.79	14.80	70.60	60.48	9.67	42.50	74.20



a. Means and standard deviations calculated for the 50th speed percentiles for distressed and un-distressed sections over each class of vehicle.

b. Means and standard deviations calculated for the 85th speed percentiles for distressed and un-distressed sections over each class of vehicle.

Figure 4: Means and standard deviations for 50th and 85th speed percentiles

Several results are of note on looking at the information presented in Table 5 and Figure 4.

- PCI values vary widely across distressed sites with a maximum value of 88 and a minimum of 24. The means and standard deviations of all values are 54.8 and 21.1 indicating the diversity of the characteristics of surveyed sites.

- Examination of the mean, maximum, and minimum speed values for distressed and un-disserted sections showed that speeds are always higher in the case of un-distressed sections, regardless of class of vehicle and speed percentile. This indicates that the pavement condition has a pronounced influence on vehicle speed and consequently on traffic operational performance.
- Regardless of pavement condition, LGV's usually have the maximum speeds followed by CAR then HGV. This reflects the generally acknowledged aggressive driving attitudes and behaviors of the drivers of this vehicle class (LGV) in Egypt.
- Examination of the standard deviation values for distressed and un-distressed sections showed that significant differences occurred mainly in the distressed sections. The corollary of this is that greater uniformity of speeds can be expected on good pavement conditions.
- The standard deviation values, as well as the difference between maximum and minimum speeds in distressed sections for different vehicle classes and speed percentiles, are generally higher than those of un-distressed sections.
- These results add to those of other studies indicating that as these values increase, the frequency of accidents also increases, due to speed differential. In other words, higher variations in speed interrupt the homogeneity of drivers' speed and may lead to driver error and accidents [16].
- Accidents are less likely to occur when drivers are travelling at more consistent speed [21,22]. These findings confirm that the condition of the pavement surface has a considerable role to play in traffic safety.
- However, it must be noted that accident data to investigate the association between pavement condition and accident rates, were not available for this study.

5. Development of Speed Change Models

One of the primary objectives of this research is to develop several models that predict and estimate the relationship between speed change and pavement condition. For this reason, the analysis used spot speed data to determine the observed median speed (50^{th} percentile) and operating speed (85^{th} percentile) for un-distressed and distressed sections of road. Change in speed was calculated between both types of pavement at each site. The speed data was that collected under free flow conditions in order to avoid the effect of traffic volume and to minimize the effect of other variables. The dependent variable in this model is the expected change in speed and the independent variable is the pavement condition expressed in terms of PCI.

Three different approaches according to direction of flow (1. change of speed from distressed to un-distressed, 2. change of speed from un-distressed to distressed, and 3.

speed data merged into one single database, regardless of direction, for distressed and un-distressed sections) were examined to model the relationship between change in speed and pavement condition. The results of the three approaches revealed similar trends. It should be noted that, the models for the second approach were presented in this research paper. The reason for this is that the speed changes/reductions from un-distressed to distressed sections are a critical safety issue as they are associated with vehicle deceleration.

The analysis considered many mathematical forms of the independent variable including linear, inverse, square, square root and Logarithmic.

Tables 6 includes definitions of the variables for speed change models, Table 7 showing the summary statistics for speed change characteristics and related PCI values.

The best models found for different types of vehicles are presented in Table 8, the details of the regression analysis for these models in Table 9. The results of the best models are also presented graphically in Figures 5 and 6.

Table 6: Definitions of variables for speed change models

ΔV_{50A}	Change in 50th percentile speed for all type of vehicles (km/h)
ΔV_{50C}	Change in 50th percentile speed for cars (km/h)
ΔV_{50L}	Change in 50th percentile speed for LGV (km/h)
ΔV_{50H}	Change in 50th percentile speed for HGV (km/h)
ΔV_{85A}	Change in 85th percentile speed for all type of vehicles (km/h)
ΔV_{85C}	Change in 85th percentile speed for CAR (km/h)
ΔV_{85L}	Change in 85th percentile speed for LGV (km/h)
ΔV_{85H}	Change in 85th percentile speed for HGV (km/h)
PCI	Pavement condition index (distressed section), (%)

Table 7: Summary statistics for speed change characteristics and PCI values at study sites

Variable	Mean	SD	Minimum	Maximum
ΔV_{50A}	12.7	15.1	0.4	49.3
ΔV_{50C}	11.2	12.9	0.0	46.1
ΔV_{50L}	13.5	16.2	0.4	52.5
ΔV_{50H}	9.0	10.4	0.7	41.8
ΔV_{85A}	14.1	16.8	1.1	58.3
ΔV_{85C}	14.5	15.2	1.1	55.5
ΔV_{85L}	15.7	16.9	0.8	60.4
ΔV_{85H}	12.2	13.4	2.2	53.6
PCI	54.8	21.1	24.0	88.0

Table 8: Best models for different classes of vehicles

Vehicle Class	Change in V_{50th} Speed	Change in V_{85th} Speed
All vehicles	$\Delta V_{50A} = \frac{1275.372}{PCI} - 14.997$	$\Delta V_{85A} = \frac{1385.406}{PCI} - 15.985$
CAR	$\Delta V_{50C} = \frac{979.823}{PCI} - 10.028$	$\Delta V_{85C} = \frac{1231.997}{PCI} - 12.248$
LGV	$\Delta V_{50L} = \frac{1396.015}{PCI} - 16.792$	$\Delta V_{85L} = \frac{1413.189}{PCI} - 14.927$
HGV	$\Delta V_{50H} = \frac{683.296}{PCI} - 5.838$	$\Delta V_{85H} = \frac{941.354}{PCI} - 8.201$

Table 9: Regression analysis for each model

Dependent Variable	Independent Variable	Coefficients	Std. Error	t	Sig.	R^2	Significance of F statistic
ΔV_{50A}	Constant	-14.997	5.014	-2.99	0.012	0.770	<0.001
	(1\PCI)	1275.372	209.911	6.08	<0.001		
ΔV_{50C}	Constant	-10.028	5.457	-1.84	0.093	0.626	<0.001
	(1\PCI)	979.823	228.479	4.29	0.001		
ΔV_{50L}	Constant	-16.792	4.988	-3.37	0.006	0.802	<0.001
	(1\PCI)	1396.015	208.821	6.69	<0.001		
ΔV_{50H}	Constant	-5.838	5.304	-1.10	0.295	0.463	0.011
	(1\PCI)	683.296	222.063	3.08	0.011		
ΔV_{85A}	Constant	-15.985	5.967	-2.68	0.021	0.737	<0.001
	(1\PCI)	1385.406	249.803	5.55	<0.001		
ΔV_{85C}	Constant	-12.248	5.702	-2.15	0.050	0.708	<0.001
	(1\PCI)	1231.997	238.713	5.16	<0.001		
ΔV_{85L}	Constant	-14.927	5.869	-2.54	0.027	0.750	<0.001
	(1\PCI)	1413.189	245.692	5.75	<0.001		
ΔV_{85H}	Constant	-8.201	6.408	-1.28	0.227	0.528	0.005
	(1\PCI)	941.354	268.264	3.51	0.005		

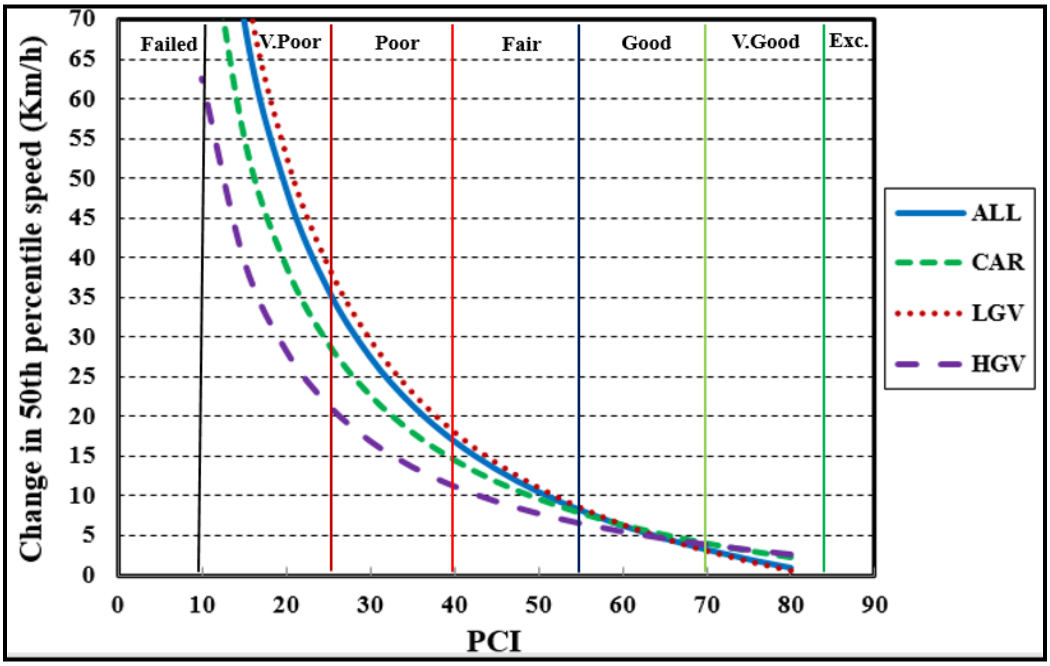


Figure 5: Relationships between change in V^{50th} and PCI for each class of vehicle

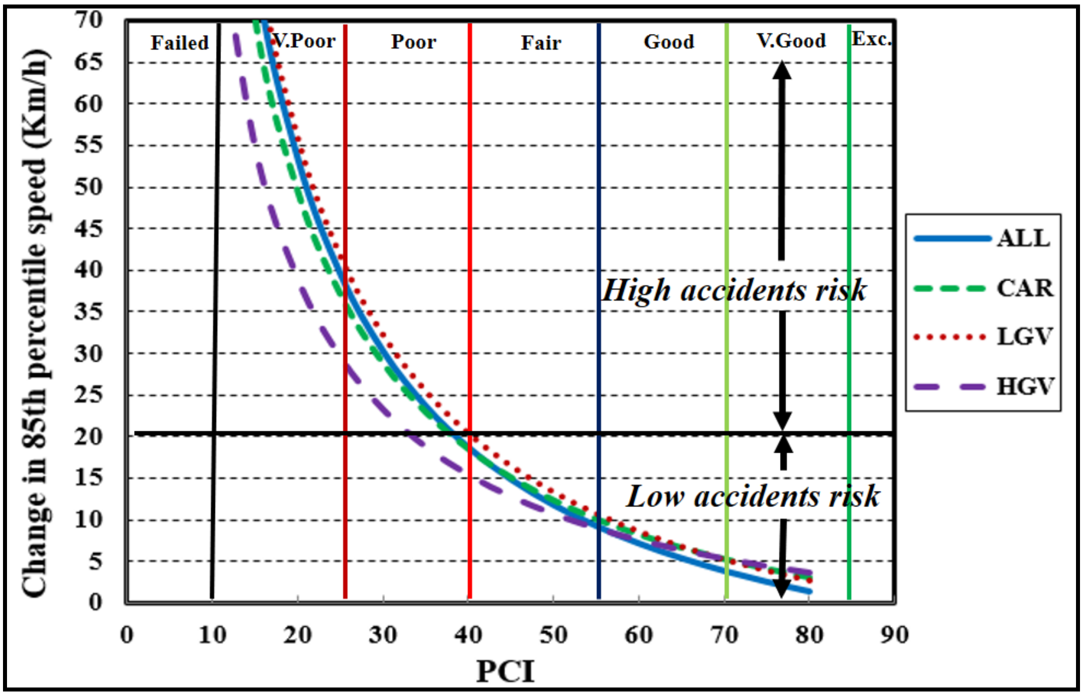


Figure 6: Relationships between change in V^{85th} and PCI for each class of vehicle

5.1. Discussion of the developed models

Several observations can be made based on the information presented in the developed models.

- The resulting coefficients of determination (R^2) are relatively high in all cases, reflecting the accuracy of these models and their capacity to be used for prediction. In the case of HGV models, the R^2 values are not as high as for other classes but are still considered fair in comparison to other similar studies [23].

- The inverse of PCI (1/PCI) is the best mathematical form of the independent variable illustrating the inverse relationship that exists between change of traffic speed and level of pavement distress (in other words, higher speed change will be associated with poor pavement condition).
- Looking to the graphical comparisons between different models, for different vehicle classes it can be seen that LGV has the maximum change in speed followed by ALL, CAR and HGV respectively, at the same level of pavement distress (i.e. PCI value).
- Based on the graphical representation of the models, it is clear that there are less changes in speed on pavements with lower degrees of distress (i.e. pavements with PCI values greater than 40). There are substantially more changes in speed as the PCI decreases (below a PCI of 40).
- Reductions in speed from un-distressed sections to distressed sections could be a critical safety issue as this is usually associated with speed deceleration; drivers may slow down suddenly and this may increase the risk of accidents. Previous studies have found that the risk of accidents increases when the changes/reductions in operating speed (ΔV^{85th}) is above 20 km/h [24]. This agrees with best guess views that road safety is improved when the road condition is suitable for drivers to be able to travel consistently closer to operating speeds (V^{85th}). The models and graphs are an important tool helping to predict changes in speed and for safety evaluations, given the pavement conditions in the sections examined (see Figure 6).
- These models may help traffic and pavement engineers to justify their decisions regarding maintenance strategies, safety and operational performance analysis, the study of vehicle operating costs and life cycle assessment (LCA) for pavement projects, due to the effect of pavement distress on vehicle fuel consumption and emissions during the 'use' phase of the pavement life cycle [25,26].
- The creation of different models for different classes of vehicles provides more explanatory power as they are more accurate regarding separate classes however, one single model for all vehicles is easier to use and more practical. Therefore, for the sake of practicality, the following two models which encompass all classes of vehicles could be useful:

$$\Delta V_{50A} = \frac{1275.372}{\text{PCI}} - 14.997$$

$$\Delta V_{85A} = \frac{1385.406}{\text{PCI}} - 15.985$$

where:

ΔV_{50A} = change in 50th percentile speed for all vehicle classes (km/h);

ΔV_{85A} = change in 85th percentile speed for all vehicle classes (km/h); and

PCI = Pavement Condition Index.

- Finally, care should be exercised in using these relationships beyond the data used for its development.

6. Summary and Conclusions

The overall aim of this research was to study the impact of pavement condition on traffic stream characteristics with a specific emphasis on speed. Following a thorough review of the relevant literature, data were collected for a substantial sample of road sections in Menoufia and Gharbya governorates, Egypt. The main conclusions drawn may be summarized as follows:

- The current study examined rural, two-lane, two-way roads over 13 sites in the governorates of Menoufia and Gharbya. Each site consisted of two sections, distressed and un-distressed. Road geometry and pavement condition characteristics were collected manually in the field. Traffic surveys were carried out using automatic traffic recorders whereby two automatic traffic recorders were placed at each site and at both sections for at least 6 hours.
- Speed analyses for distressed and un-distressed pavement sections, indicated that poor pavement conditions cause a significant variation in vehicle speed. The analyses confirms that in general, pavement condition has a pronounced influence on vehicle speed and consequently on traffic operational performance.
- Higher standard deviations of speeds occurred mainly in distressed sections. This means that greater uniformity of speeds can be expected where there are good pavement conditions confirming previous findings that pavement conditions have an impact on traffic safety.
- Analyses of the mean speeds for different classes of vehicles has provided support for the need to separate vehicles into separate classes.
- Several models were developed to describe the relationship between change in speed and pavement condition, for different classes of vehicle. For all models regarding the relationships between change in speed and pavement condition, the inverse of PCI (1/PCI) is the best mathematical form of the independent variable. This means that as the PCI decreases (lower pavement quality) the amount of change in speed increases. There is a smaller change in speed on pavements with lower degree of distresses (i.e. pavements with PCI values greater than 40). The change then increases sharply as PCI decreases.
- Comparing models, at a constant PCI, LGV has the maximum change in speed followed by ALL, CAR and HGV.
- In conclusion, these models can be used to estimate changes in speed given the level of pavement distress (PCI). They can help traffic and pavement engineers justify their decisions regarding maintenance strategies, to carry out safety and operational performance analysis and studies on vehicle operating costs, as well as perform life cycle assessment (LCA).
- This research is based on observations from thirteen sites at selected roads in Menoufia and Gharbya governorates, Egypt. Although the number of sites and their relative area is more or less the same as that from previous work, the results here relating speed change to pavement condition constitute the groundwork for further study as they can be considered applicable to the specified range of data.

- That said, the hypothesis that pavement condition has a pronounced effect on speed change remains valid but it is recommended to extend this research using comprehensive field data from various regions and governorates in Egypt.

References

[1] I.A. Haj-Ismail. “The Effect of Roadway Surface Condition on Traffic Speed During Day and Night Operations.” PhD Thesis, Texas A&M University, 1989.

[2] S. Islam, and B. William. “Effect of Pavement Roughness on User Costs.” Transportation Research Record: Journal of the Transportation Research Board. 2285:47-55, 2012.

[3] H. R. Al-Masaeid. “Impact of pavement condition on rural road accidents.” Canadian Journal of Civil Engineering, Vol. 24, No. 4, pp. 523-531, 1997.

[4] H. Zeng, M.D. Fontaine, and B.L. Smith. “Estimation of the Safety Effect of Pavement Condition on Rural, Two-Lane Highways.” Transportation Research Record: Journal of the Transportation Research Board, 2435:45-52, 2014.

[5] J. Ben-Edigbe, and N. Ferguson. “Extent of capacity loss resulting from pavement distress.” Proceedings of the Institution of Civil Engineers: Transport 158 Issue TR1. pp. 27-32, 2005.

[6] R. Vaiana, G.F. Capiluppi, V. Gallelli, T. Iuele, and V. Mi. “Pavement Surface Performances Evolution: An Experimental Application.” Procedia-Social and Behavioral Sciences, Volume 53, pp. 1149-1160, 2012.

[7] I. Hashim, and T. Abdel-Wahed. “Effect of Highway Geometric Characteristics on Capacity Loss.” Journal of Transportation Systems Engineering and Information Technology, Vol.12, pp. 65-75, 2012.

[8] TRB. “Highway Capacity Manual.” 5th Edition, Transportation Research Board, National Research Council, Washington, D.C., 2010.

[9] M. A. Karan, R. Hass, and R. Kher. “Effect of pavement roughness on speeds.” Transportation Research Record 602, National Research Council, Washington, D.C., pp. 122-127, 1978.

[10] S. Chandra. “Effect of Road Roughness on Capacity of Two-Lane Roads.” Journal of Transportation Engineering, Volume 130, Issue 3, pp. 360-364, 2004.

[11] B. Yu, and Q. Lu. “Empirical model of roughness effect on vehicle speed.” Internal Journal of Pavement Engineering, Volume 14, Issue 4, pp. 345-351, 2014.

[12] T. Wang, J. Harvey, J. Lea, and C. Kim. “Impact of Pavement Roughness on Vehicle Free-Flow Speed.” Journal of Transportation Engineering, ASCE, 140(9), 2014.

[13] K. A. Ghazlan, B. H. Al-Omari, and M. A. Mahmoud. "Effect of Pavement Condition on Multilane Highway Free Flow Speed." Institute of Transportation Engineers. ITE Journal 85(8) pp. 31-36, 2015.

[14] S.I. Sandberg. "Road Macro- and Mega Texture Influence on Fuel Consumption." ASTM STP 1031 page 460-479, 1990.

[15] I. Zaabar, and K. Chatti. "A Field Investigation of the Effect of Pavement Surface Conditions on Fuel Consumption." Transportation Research Board, Annual Meeting, Paper #11-3280, 2011.

[16] I. H. Hashim. "Safety and the Consistency of Geometry and Speed on Rural Single Carriageways." PhD Thesis, School of Civil Engineering and Geosciences, Newcastle University, United Kingdom, 2006.

[17] ASTM International. "Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys." ASTM Designation D6433-07, 2007.

[18] M.Y. Shahin, and J.A. Walther. "Pavement Maintenance Management for Roads and Streets using the PAVER System." CERL Technical Report M-90/05, Champaign, IL, 1990.

[19] M.A. Younes. "Assessing the Influence of Pavement Condition on Traffic Stream Characteristics." Master Thesis, Civil Engineering Department, Faculty of Engineering, Menoufia University, Egypt, 2013.

[20] I. H. Hashim. "Analysis of Speed Characteristics for Rural Two-Lane Roads: A Field Study from Menoufia Governorate, Egypt." Ain Shams Engineering Journal (ASEJ), Elsevier, Volume 2 Issue 1, pp. 43–52, 2011.

[21] R. A. Krammes, R. Q. Brackett, M. A. Shafer, J. L. Ottesen, I. B. Andeson, K. L. Fink, K. M. Collins, O. J. Pendleton, and C. J. Messer. "Horizontal Alignment Design Consistency for Rural Two-Lane Highways." Report FHWA-RD-94-034, FHWA, U.S. Department of Transportation, McLean, VA, 1995.

[22] K. S. Schurr, P. T. McCoy, G. Pesti, and R. Huff. "Relationship of Design, Operating, and Posted Speed on Horizontal Curves on Rural Two-Lane Highways in Nebraska." Transportation Research Record, Transportation Research Board, National Research Council, Washington, D.C., 1796, pp. 60-71, 2002.

[23] I. H. Hashim. "Development of Operating Speed Models for Different Vehicle Classes on Rural Two-Lane Highways." Engineering Research Journal (ERJ), Faculty of Engineering, Menoufia University, Volume 31, Issue 4, pp. 413-418, 2008.

[24] R. Lamm, B. Psarianos, and S. Cafiso. "Safety Evaluation Process for Two-Lane Rural: A Ten-Year

Review." Transportation Research Record, Transportation Research Board, National Research Council, Washington, D.C., 1796, pp. 51-59, 2002.

[25] L. Trupia, T. Parry, L.C. Neves, and D.L. Presti. "Rolling resistance contribution to a road pavement life cycle carbon footprint analysis." The International Journal of Life Cycle Assessment, V.22, Issue 6, pp 972-985, 2017.

[26] F. Perrotta, L. Trupia, T. Parry and L.C. Neves. "Route level analysis of road pavement surface condition and truck fleet fuel consumption." Pavement Life-Cycle Assessment Proceedings of the Symposium on Life-Cycle Assessment of Pavements (Pavement LCA 2017), April 12-13, 2017, Champaign, Illinois, USA.