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Impact of Pavement Defects on Traffic Operational Performance

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Abstract: The present research investigates the influence of pavement distresses on traffic operational performance in terms of speed and capacity. The pavement distresses are expressed by the pavement condition index (PCI). Three roads of multi-lane highways located on the road network of Kafrelsheikh governorate, Egypt, were chosen as a case study. Road geometry, pavement condition characteristics, and traffic volume were collected manually from 23 sections for field data surveys. For speed measurements, spot speed data were gathered using the stopwatch method under the free-flow conditions, and the percentile speeds (V_{50}% and V_{85}%) have been calculated for different vehicles classes. Traffic capacity was determined via extrapolation of the quadratic function. Regression analysis models were created to express the relationships of both the percentile speeds and traffic capacity as dependent variables, and three independent variables (PCI, lane, and shoulder widths). These empirical mathematical relations help in developing road design and maintenance works on multi-lane highways. The main conclusion of the study demonstrated that traffic operational performance was more significantly affected by pavement distresses than road geometry. Moreover, the results indicated that pavement distresses have a significant impact on light vehicles more than heavy ones.

Keywords: pavement distress; pavement condition index (PCI); multi-lane highways; percentile speeds (V_{50} and V_{85}); traffic capacity

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1. Introduction

The road network is considered one of the main contributors to the development of countries by linking different parts of the country to facilitate traffic, serve the public, and provide safe traffic conditions. Pavement condition and operational performance of traffic are the two operational and significant factors that influence road system's efficiency. Because traffic is a significant controlling parameter on multilane highways, the analysis of traffic flow in terms of flow, speed, and density is necessary. Traffic speed is significant because it influences safety, time, and economics, and it may also be an accurate indicator of pavement condition of roadway facilities [1]. In the planning, estimating, and understanding of road capacity, traffic flow characteristics are essential [2].

Pavement surface distress is one of the characteristics of pavement conditions for evaluating pavement rehabilitation requirements [3]. The surveying of distresses is conducted to identify the type, severity, and amount of surface distress [4]. The pavement condition index (PCI) is the most suitable indicator for representing performance on Egyptian urban roads, which was defined by ASTM [5].

The pavement road functioning, safety, running costs for vehicles, and environmental sustainability can all be strongly impacted by the surface conditions of the roadways. This study's aim is to investigate how pavement surface conditions affect vehicle percentile speeds and capacity on multi-lane highways. To accomplish the main objective of the study, the following objectives were chosen.

- Specifying the important multi-lane highways in Kafrelsheikh governorate to be the subject of this study (case study).
- Assigning the flow, speed, and density of the chosen roadways' traffic streams in dry weather and during daylight hours.
- Conducting a field survey to inspect the pavement distresses visually.
- Researching the impact of various pavement distress levels on traffic efficiency.
- Building a statistical model and creating mathematical relationships based on actual data using linear regression to investigate how pavement distresses affect percentile speeds and traffic capacity.

2. Literature Review

Previous studies that discussed the impact of pavement distresses on traffic operational performance were reviewed. Ben-Edigbe [6] performed research in Nigeria to determine the poor pavement conditions using speed-flow-density relationships. The research was carried out under daylight, dry weather, and off-peak conditions on main roads. Optimum speeds were determined and assessed for un-distressed and distressed sections. It was revealed that there were 50% and 20% reductions in optimum speed and traffic flow, respectively, under poor road surface conditions. Research was conducted to investigate the impact of pavement conditions on traffic stream characteristics on rural, two-lane, two-way roads. Every site consisted of one section distressed and another un-distressed. It was discovered that the amount of change in speed increases as the PCI decreases. Moreover, pavements with a higher PCI value (i.e., pavements with less distress) experienced a smaller change in speed [7]. Setyawana et al. [8] studied the impact of road damage on vehicle speed, followed by emissions from motor vehicles. Six locations with different conditions were chosen, and the average speeds at these locations have been measured. The results of this research showed a 55% decrease in vehicle speed in very poor road conditions (PCI = 19) compared to good road conditions (PCI = 100). The impact of highway surface conditions on traffic speed was investigated by Haj-Ismail [9]. The study covered day and night time, and it was revealed that there is an inverse relationship between the level of pavement distress represented by PCI and the traffic speed. It was also concluded that there were no statistically significant differences in day time and night time speeds with the same amount of pavement distress.

A study aims to examine the effect of pavement condition on traffic flow. The examined road links were classified into road sections with surface deformation and without surface deformation. According to analyses, the pavement's surface deformations negatively influence traffic flow and service levels. Furthermore, the capacity for each investigated road section "with" surface deformation is lower than that without [10]. The impact of pavement condition on headway and average speed of travel has been investigated. Five sections were investigated (four in good condition and only one in serious condition). It was discovered that speed and headway are more affected by the condition of the pavement. Moreover, the headway value was high, and the average speed value was low in the distressed portions [11].

Ben-Edigbe and Ferguson [12] assessed the impact of pavement defects on two-way road capacity based on observations from eight sites in Nigeria. A method based on extrapolation from a vital diagram describing the connection between flow and density was used. For both road sections with and without distress, the estimated capacities were calculated. Estimated capacities were found to differ significantly between the distressed and un-distressed sections. Semeida and El-Shabrawy [1] explored how pavement distresses, pavement roughness, and longitudinal grade affect the operating speed (V_{85}) of traffic on multi-lane roads in Egypt. Using linear regression, it was found that V_{85} increased with an increase in the PCI, and it was also concluded that IRI is an effective factor on speed reduction. In addition, an increase in the number of lanes has a reasonable effect on speed increment. In a study by Chan et al. [13] to explore the association between accident frequency and pavement condition, IRI, rutting depth (RD), and PSI were used as variables for pavement condition. The findings demonstrate that IRI and PSI were important in all types of models, but the model of rutting depth was more effective at predicting accidents that happened solely at night.

3. Methodology

3.1. Road Selection Criteria

This research uses field data from multi-lane highways in Egypt. The study involved 23 sections distributed along three highways within Kafrelsheikh governorate, Egypt. Figure 1 shows the locations of these highways on the Egyptian road network. The distribution of selected sections is 12 sections on Kafrelsheikh-Tanta highway (K-T Highway), 9 sections from Kafrelsheikh-Baltim highway (K-B Highway), and 2 sections from the international coastal road (I-C Highway). The 12 sections from K-T Highway were chosen from three links; the 1st link was from Kafrelsheikh city to Elkurada police station; the 2nd link was from Elkarada police station to Damat village, while the 3rd link was from Damat village to Tanta city. The 9 sections from K-B Highway were distributed along the whole road. As for the 2 sections of the I-C Highway, they were chosen within the first 60 km from Baltim city to Alexandria direction. Each section length was 100 m. The locations of the chosen sections on the selected highways are indicated in Figure 2. Meanwhile, Table 1 shows the dimensions of the selected roads and operational speeds.

Figure 1. Location of the chosen highways on the Egyptian roads network.

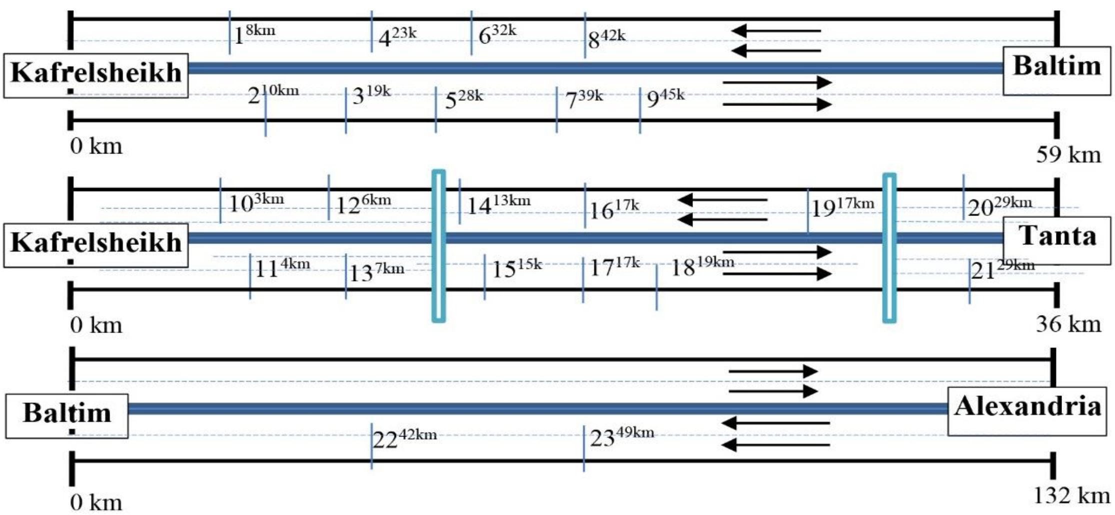

Figure 2. Locations of selected sections.

Table 1. Dimensions of the selected roads and operational speed.

Property	Road Name				
	I-C Highway	K-B Highway	K-T Highway		
			Link1	Link2	Link3
Length of the road (km)	132	59	6	10	20
lane width (m)	4.4	3.5	3.5	3.5	3.5
No. of lanes	3	2	3	2	3
Speed Limit (Km/hr)	100	90	90	90	90
NO. sections	2	9	4	6	2

A criterion for section selection has been established to clearly reflect the characteristics of the multi-lane highway, which are to be far from horizontal and vertical curves, artificial bumps, gradients, and intersections. Sections were also chosen to contain different degrees of pavement conditions (defect type and severity).

3.2. Data Collection Procedures

3.2.1. Traffic Data

Traffic surveys are the way to obtain data about traffic. It is a systemic data-gathering method that can be used in traffic engineering for different purposes. Collection of traffic data was carried out through working days during the daylight hours. During data collecting periods, the weather was clear, and the pavement was dry. The analysis's key dependent variables are vehicle speed and traffic volume. The vehicles include different classes: light vehicles (taxis, private car, microbus, and pick-up), heavy vehicles (trucks, trailer trucks, and farm and construction-equipment vehicles), and total vehicles (include all vehicles).

Speed data were collected for different classes of vehicles. Spot speed data were collected using a stopwatch method. In this research, the speeds were measured under the free flow conditions to avoid the effect of traffic flow on vehicle speed and take into account only the effect of pavement condition on speed, so the horizontal and vertical curves did not affect the speed measurements. Vehicles traveling in free-flow conditions are considered to have at least 5 s of headway [14,15]. Traffic volume was collected by manual traffic counting method, and the observations were aggregated into 5 min intervals per hour at each section. It was expressed in passenger car units (PCU) [16]. In this study, the light vehicles (LV) were represented by PC (taxis and private car), in addition to LGV (microbus and pick-up). Summary statistics of traffic data were included in Table 2.

Table 2. Traffic volume and average speed of all sections of the roads.

Section No.	No. Vehicle/5 min (Pcu/hr)			Average Speed (km/hr)		
	LV	HV	Total	LV	HV	Total
1	340	90	430	90.74	72.76	81.75
2	338	66	404	88.13	69.82	78.97
3	339.5	56	395.5	91.10	71.31	81.20
4	347	97	444	88.74	66.41	77.75
5	388	68	456	90.29	72.83	81.56
6	332.5	75	410.5	90.74	72.76	81.75
7	324	82	406	85.31	61.15	73.23
8	311	104	415	88.61	73.12	80.86
9	402.5	94	496.5	78.67	63.69	71.18

Table 2. *Cont.*

Section No.	No. Vehicle/5 min (Pcu/hr)			Average Speed (km/hr)		
	LV	HV	Total	LV	HV	Total
10	307	154	588	116.83	81.22	99.02
11	330	168	498	114.53	85.62	100.07
12	403.5	142	545.5	103.93	86.12	95.02
13	427.5	192	619.5	98.68	78.19	88.43
14	291	180	471	78.00	63.94	70.97
15	356	190	546	83.14	65.85	74.495
16	387	98	485	80.28	53.72	67.00
17	560	174	716	93.43	77.97	80.7
18	649.5	206	855.5	94.81	67.88	81.34
19	291	180	471	77.79	60.10	68.94
20	434	142	567	81.55	65.56	73.55
21	332.5	78	410.5	69.06	58.58	63.82
22	362.5	172	534.5	99.11	76.53	87.82
23	592	180	772	99.55	79.75	89.65

3.2.2. Pavement Condition Data

The surface condition of pavement at any time reflects the degree of damage caused by traffic and the environment. To collect the pavement condition data, a manual survey is performed according to ASTM D 6433 [5]. The type, quantity, and severity of each distress were assessed by visual inspection. The inspection was recoding in datasheets [17]. The Pavement Condition Index (PCI) was calculated using the Micro Paver Program software [18]. The paver system classifies pavement network to branches and sections prior to perform condition analysis. Calculation of PCI in the Micro Paver Program is seen in Figure 3. The PCI ranges from 0 to 100, where 0 represents very poor pavement condition and 100 indicates good pavement condition. The pavement condition rating is a description of the pavement condition based on the PCI value which varies as shown in Figure 4 [19]. The PCI measurement is based on surface operating conditions, and it provides indications of pavement failure, as well as the criteria for maintenance and repair.

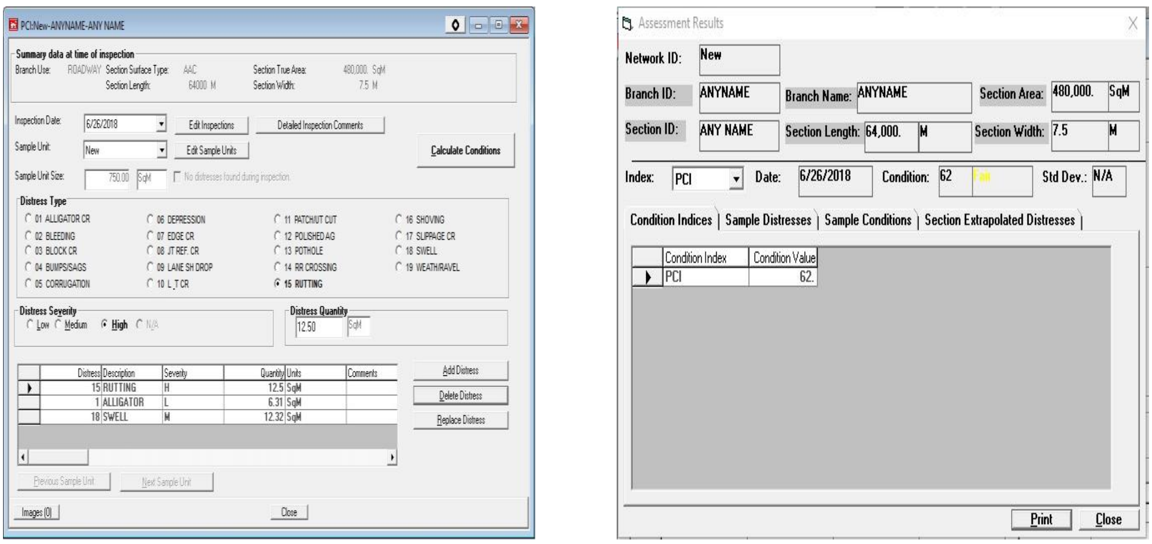

Figure 3. The PCI calculation in Micro Paver Program for section No. 8.

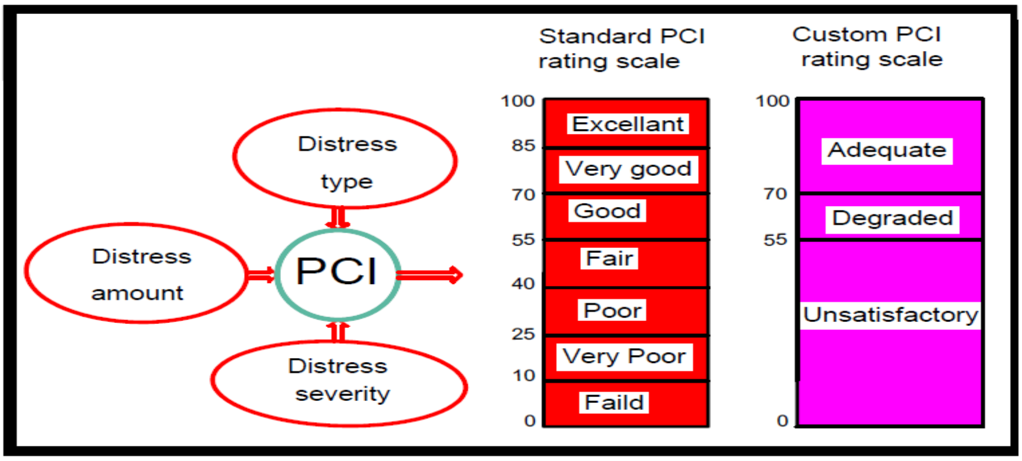

Figure 4. PCI ranges.

It was observed from inspection of all sections that the major pavement distress on K-T highway was the block cracking Figure 5a, while the rutting was the main defect of K-B highway Figure 5b, and the bleeding was the common defect on I-C highway Figure 5c. Cross section of roads is shown in Figure 6, while site characteristics and PCI values of all sections are produced in Table 3.

(**a**) (**b**) (**c**)

Figure 5. Block cracking on K-T highway (**a**), Rutting on K-B highway (**b**), and Bleeding in I-C highway (**c**).

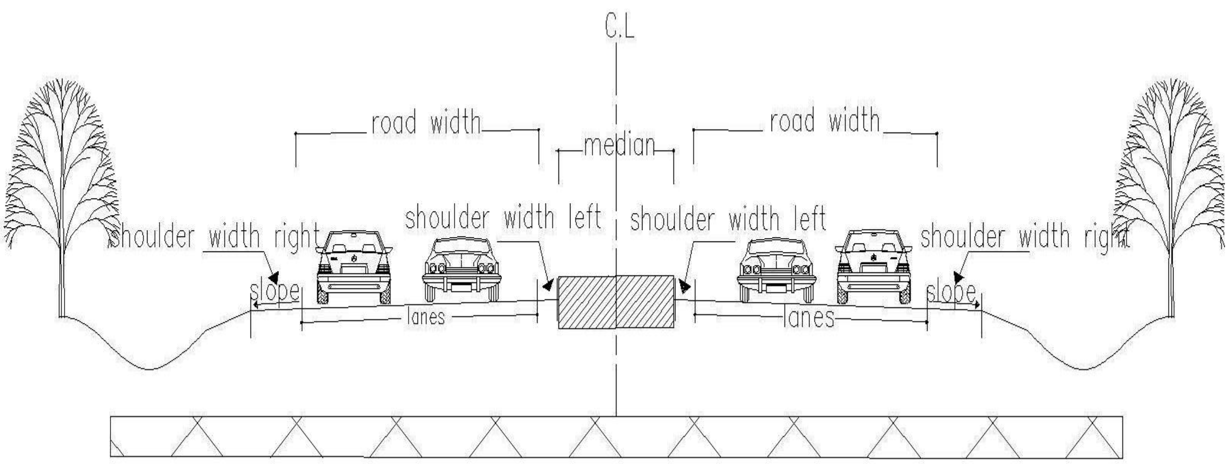

Figure 6. Cross section of road.

Table 3. Dimensions and characteristics of the selected sections.

<table>
<tr><th colspan="2">Highway Name</th><th>Section No.</th><th>Lane Width (m)</th><th>Road Width (m)</th><th>Shoulder Width Left (m)</th><th>Shoulder Width Right (m)</th><th>Average Shoulder Width (m)</th><th>PCI</th></tr>
<tr><td colspan="2" rowspan="9">K-B highway</td><td>1</td><td>3.6</td><td>7.5</td><td rowspan="9">0.5</td><td rowspan="9">1.5</td><td rowspan="9">1</td><td>38</td></tr>
<tr><td>2</td><td>3.6</td><td>7.3</td><td>47</td></tr>
<tr><td>3</td><td>3.6</td><td>7.5</td><td>44</td></tr>
<tr><td>4</td><td>3.6</td><td>7.4</td><td>51</td></tr>
<tr><td>5</td><td>3.6</td><td>7.3</td><td>59</td></tr>
<tr><td>6</td><td>3.6</td><td>7.5</td><td>57</td></tr>
<tr><td>7</td><td>3.6</td><td>7.3</td><td>53</td></tr>
<tr><td>8</td><td>3.6</td><td>7.5</td><td>62</td></tr>
<tr><td>9</td><td>3.6</td><td>7.1</td><td>43</td></tr>
<tr><td colspan="2" rowspan="2">I-C highway</td><td>10</td><td rowspan="2">4.40</td><td rowspan="2">13.2</td><td rowspan="2">1</td><td rowspan="2">3</td><td rowspan="2">2</td><td>94</td></tr>
<tr><td>11</td><td>98</td></tr>
<tr><td rowspan="12">K-T highway</td><td rowspan="4">Link 1</td><td>12</td><td>3.3</td><td>10.0</td><td rowspan="2">0.5</td><td rowspan="2">3.5</td><td rowspan="2">2</td><td>79</td></tr>
<tr><td>13</td><td>3.3</td><td>9.8</td><td>72</td></tr>
<tr><td>14</td><td>3.3</td><td>10.0</td><td rowspan="2">0.5</td><td rowspan="2">4.1</td><td rowspan="2">2.3</td><td>40</td></tr>
<tr><td>15</td><td>3.3</td><td>10.0</td><td>46</td></tr>
<tr><td rowspan="6">Link 2</td><td>16</td><td>3.6</td><td>7.5</td><td rowspan="5">0.7</td><td rowspan="5">2.3</td><td rowspan="5">1.5</td><td>28</td></tr>
<tr><td>17</td><td>3.6</td><td>7.5</td><td>73</td></tr>
<tr><td>18</td><td>3.6</td><td>7.2</td><td>80</td></tr>
<tr><td>19</td><td>3.6</td><td>7.2</td><td>32</td></tr>
<tr><td>20</td><td>3.6</td><td>7.5</td><td>54</td></tr>
<tr><td>21</td><td>3.7</td><td>8.0</td><td>0.5</td><td>3.1</td><td>1.8</td><td>23</td></tr>
<tr><td rowspan="2">Link 3</td><td>22</td><td>3.5</td><td rowspan="2">10.8</td><td rowspan="2">1.5</td><td rowspan="2">2.9</td><td rowspan="2">2.2</td><td>82</td></tr>
<tr><td>23</td><td>3.5</td><td>90</td></tr>
</table>

4. Results and Analysis

This section discusses the correlation and regression statistical analyses describing the relationships between the speed and PCI for different vehicle classes. The relation between capacity and PCI is also analyzed. The Statistical Package for the Social Sciences software (SPSS V22) [20] was used to perform the statistical analysis of the collected data.

4.1. Speed Results

4.1.1. Analysis of Vehicle Speed

The investigation was done to examine how different types of vehicles behaved when travelling at different speeds. This comparison was carried out in this part using the ANOVA test. The three groups into which the vehicle speeds were separated were total vehicles (TOTAL), light vehicles (LV), and heavy vehicles (HV). For all parts taken into consideration, comparisons between the mean speeds of various vehicle classes were made. An illustration of the test of ANOVA for Section No. 2 is shown in Table 4. It is evident that the *p*-values are less than 0.05, which shows that the mean speeds for the various vehicle classes differ significantly from one another.

Table 4. Example of ANOVA results at section No. 2.

NO. Section	Significance	Multiple Comparisons (Significance)			
			LV	HV	TOTAL
2	0.000	LH	-	0.000	0.035
		HV	0.000	-	0.000
		TOTAL	0.035	0.000	-

4.1.2. Normality Test

When traffic conditions are typically more or less uniform, speed data on a highway tend to follow a normal distribution. To compare the degrees of similarity between the recorded speed data and the normal distribution, this phase of the study focuses on this issue. The normal distribution of speed data was examined using the Kolmogorov–Smirnov one-sample test (K-S one-sample test). This test for goodness-of-fit determines if the observations might have originated from a normal distribution. In the event that the "D" statistic, which measures the biggest absolute difference, is substantial, the assumption that the distribution is normal should be disproved. The findings of the speed testing for each component are presented in Table 5.

Table 5. 1-Sample K–S test results for all sections.

Section No.	TEST STATIC(D)	Asymp. Sig. (2-Tailed)	PCI	Section No.	TEST STATIC (D)	Asymp. Sig. (2-Tailed)	PCI
1	0.382	0.000	38	13	0.127	0.000	72
2	0.087	0.000	47	14	0.055	0.048	40
3	0.104	0.000	44	15	0.066	0.081	46
4	0.100	0.000	51	16	0.085	0.001	28
5	0.082	0.008	59	17	0.056	0.200	73
6	0.075	0.030	57	18	0.073	0.200	80
7	0.060	0.200	53	19	0.075	0.048	32
8	0.086	0.179	62	20	0.056	0.066	54
9	0.075	0. 022	43	21	0.047	0.000	23
10	0.086	0.073	94	22	0.058	0.028	82
11	0.068	0.062	98	23	0.042	0.200	90
12	0.084	0.001	79				

From Table 5, the p-value is listed here as Asymp. sig. (2-tailed). The p-value is less than 0.05 ($p < 0.05$) in the majority of the sections that have a bad case of paving. This means that the speed data deviated from the normal distribution. This means that poor pavement conditions may have an impact on the behavior of vehicle speeds. Vehicle speeds vary greatly as a result of this.

4.1.3. Descriptive Statistics of Speed Percentiles

In this study, V_{50} and V_{85}, which are the speed percentiles, (V_{50}% is the speed below which 50% of all the vehicles and V_{85}% is the speed below which 85% of all the vehicles), were calculated for each vehicle class. The two percentiles were calculated regardless of the direction of travel. To do this, the measured speeds in both directions were merged to a single database. Table 6 presents the values of the speed percentiles for different classes of vehicles. Table 7 presents the summary statistics of the speed percentiles values. Figure 7 depicts the mean values and standard deviations for the 50th and 85th speed percentiles for each vehicle class.

Table 6. The values of the speed percentiles for different classes of vehicles.

Section No.	Light Vehicle		Heavy Vehicle		Total Vehicle	
	V_{50L}	V_{85L}	V_{50H}	V_{85H}	V_{50T}	V_{85T}
1	75	93	61	69	76	91
2	84	102	62	76	82	97
3	81	94	68	74	80	93
4	88	100	66	84	86	98
5	84	102	66	80	82	101
6	85	108	69	84	84	106
7	82	93	60	72	78	90
8	86	98	72	80	84	94
9	72	94	65	74	70	91
10	109	124	82	97	106	122
11	111	137	85	98	108	127
12	99	116	80	90	97	112
13	91	114	74	85	89	110
14	74	86	60	73	71	84
15	80	90	64	72	75	87
16	70	86	58	71	68	84
17	91	108	74	85	89	106
18	97	114	80	92	94	113
19	74	88	55	67	66	79
20	77	95	63	75	74	90
21	66	78	54	69	64	76
22	95	113	79	93	93	111
23	104	125	81	95	102	117

V_{50L} means 50th percentile speed for LV (km/h); V85L means 85th percentile speed for LV (km/h); V50H means 50th percentile speed for HV (km/h); V85H means 85th percentile speed for HV (km/h); V50T means 50th percentile speed for TOTAL (km/h); V85T means 85th percentile speed for TOTAL (km/h).

Table 7. Statistics of speed percentiles (V50th and V85th).

Variable		Min.	MAX.	Avg.	SD
V_{50} (Km/h)	LV	66	111	86	12.1
	HV	54	85	68.3	9.9
	Total	64	108	83.4	12.5
V_{85} (Km/h)	LV	78	137	102.3	14.2
	HV	67	101	81.1	10.4
	Total	76	127	99.1	13.9
PCI		23	98	60	20

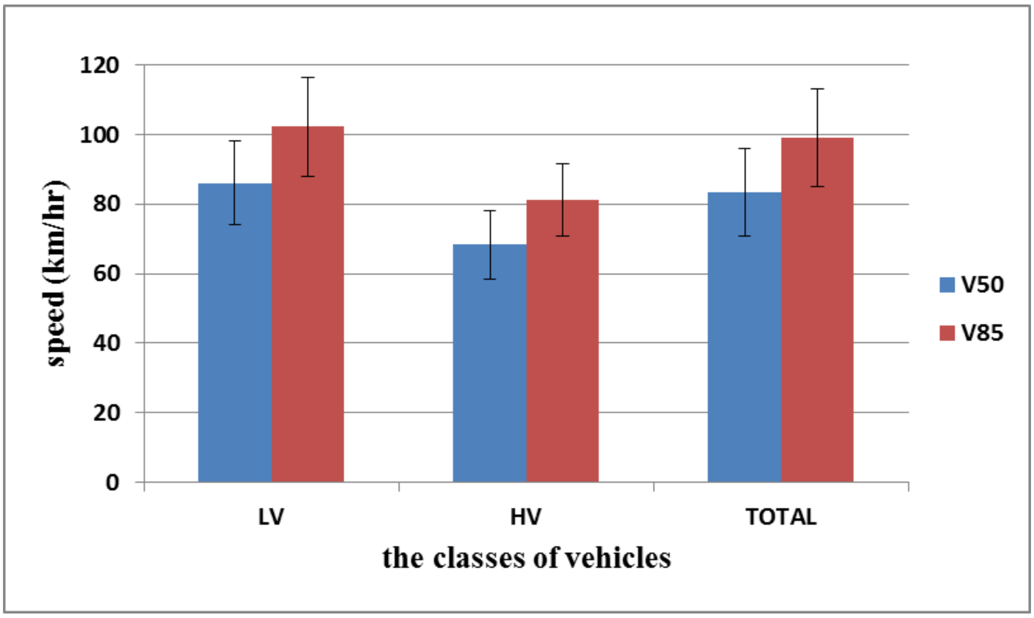

Figure 7. Means and standard deviations for 50th and 85th speed percentiles.

The data in Table 7 and Figure 7 have revealed that PCI values vary greatly across all sections, with a maximum of 98 and a minimum of 23. The means and standard deviations of all values are 60 and 20, respectively, indicating the diversity of the properties of the sections surveyed.

Figures 8–10 show the relations between the speed percentiles (V_{50th} and V_{85th}) and PCI for light, heavy, and total vehicles. The ranges of failed, very poor, poor, fair, good, very good, and excellent in this figure are a description of the pavement condition, which the PCI ranges was introduced earlier in Figure 4. It is observed from these figures that R-squared for all fitted lines is more than 0.9. It means that the relations between the PCI values and each of V_{50} and V_{85} for all categories (L, H, and T) are consistent. This means that as the pavement distresses increase (decrease in PCI value), the speed decrease.

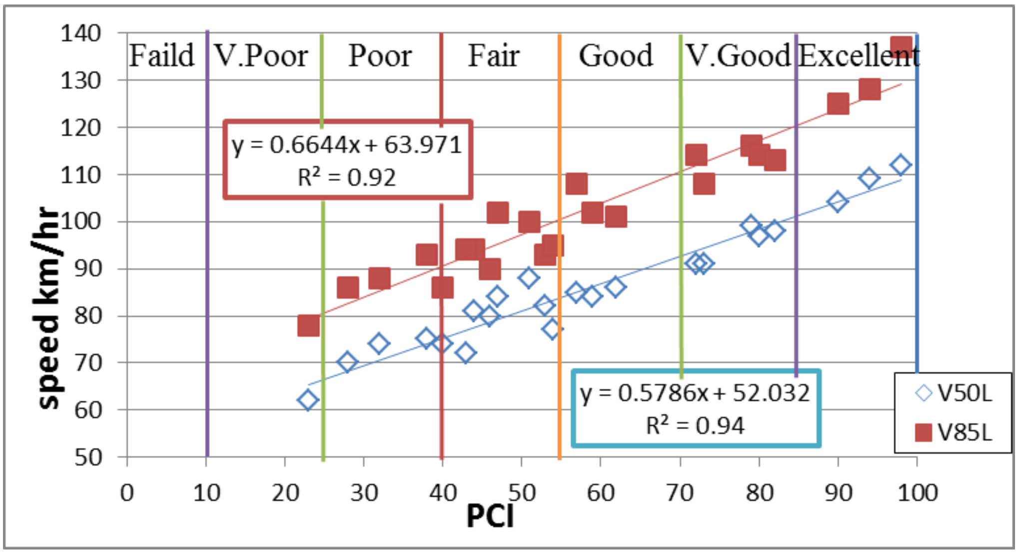

Figure 8. Relation between PCI and speed percentiles (V_{50}, V_{85}) for light vehicles.

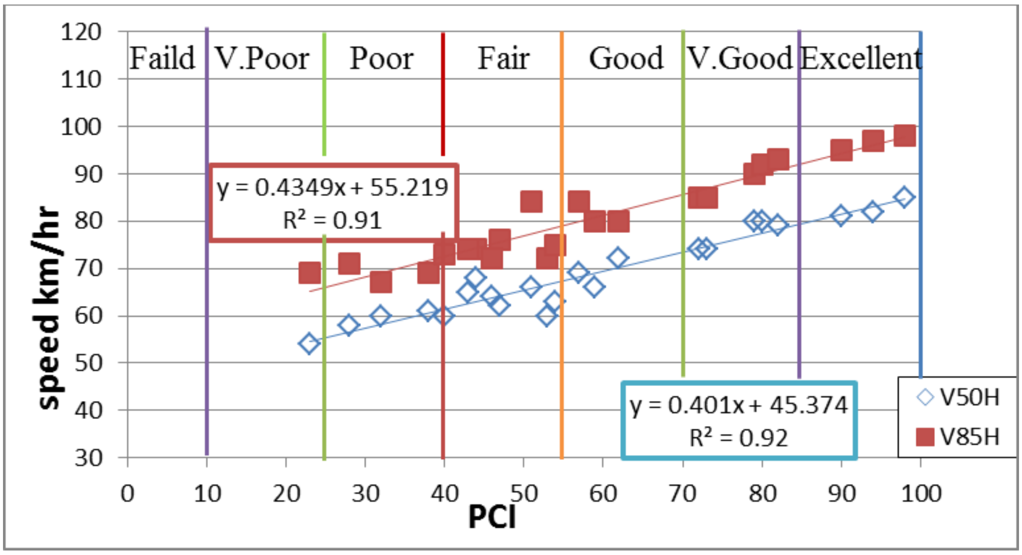

Figure 9. Relation between PCI and speed percentiles (V_{50}, V_{85}) for heavy vehicles.

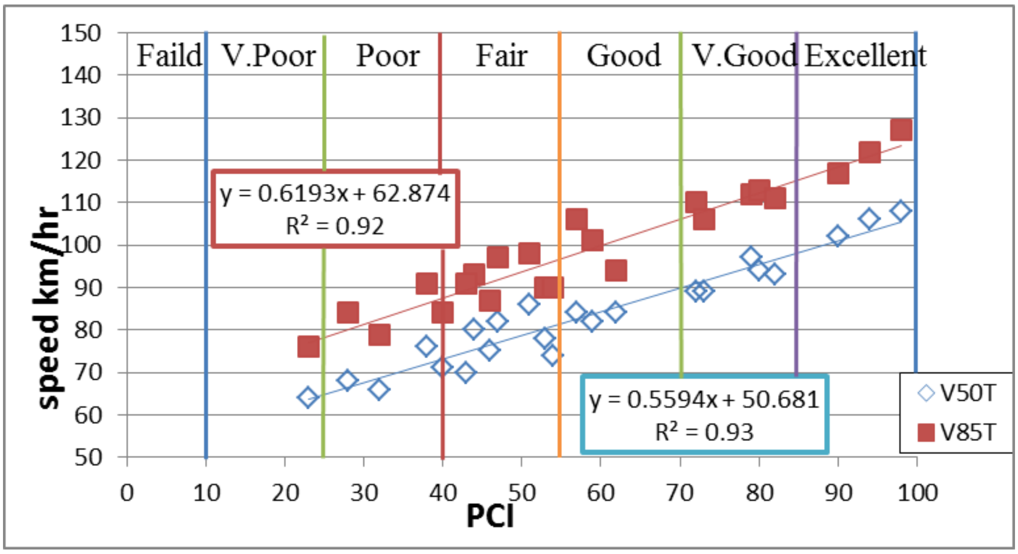

Figure 10. Relationships between PCI and speed percentiles (V_{50}, V_{85}) for total vehicles.

Figures 11 and 12 display comparisons for each of V_{50th} and V_{85th} for light and heavy vehicles, respectively. It is observed from figures that the slopes of trend lines of V_{50L}, V_{85L} are greater than that of V_{50H}, V_{85H}. This in turn indicates that pavement distresses (represented in the PCI values) have a significant impact on light vehicles more than heavy ones. The explanation for this could be attributed to the fact that heavy vehicle tire sizes are larger than light vehicles, which does not cause a major problem to the driver of the heavy vehicle when passing through the defective sectors compared to the driver of the light vehicles.

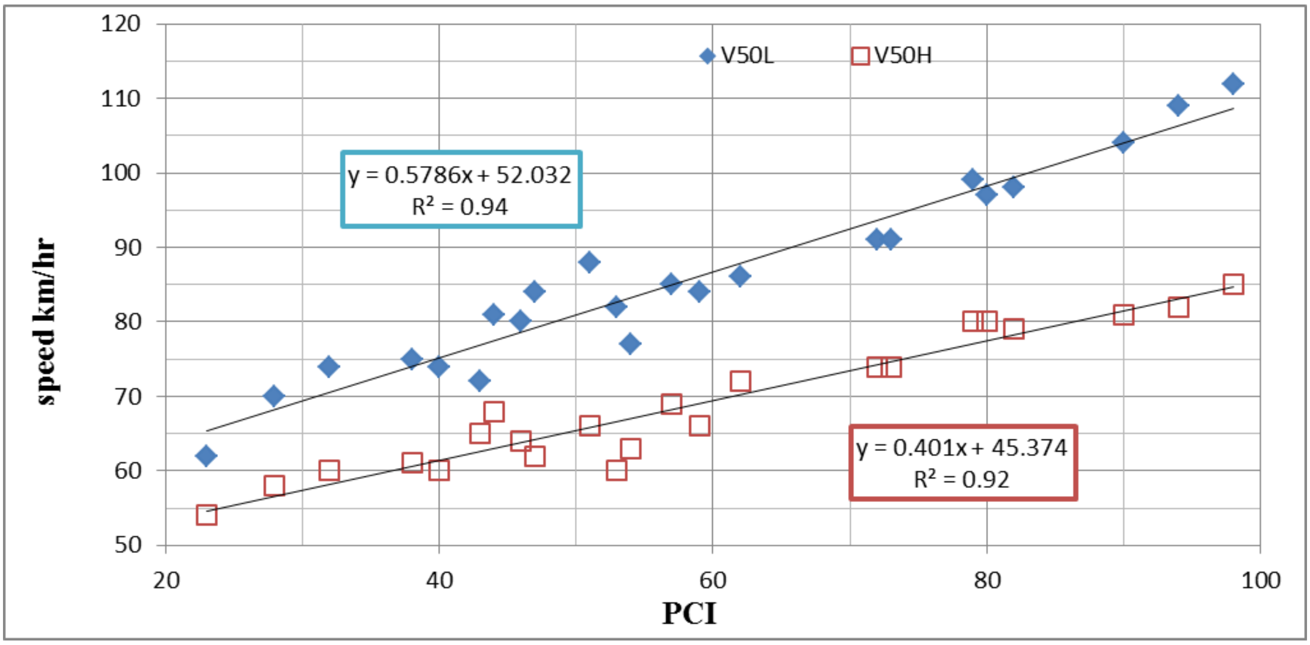

Figure 11. Comparison between V50th percentile for light and heavy vehicles.

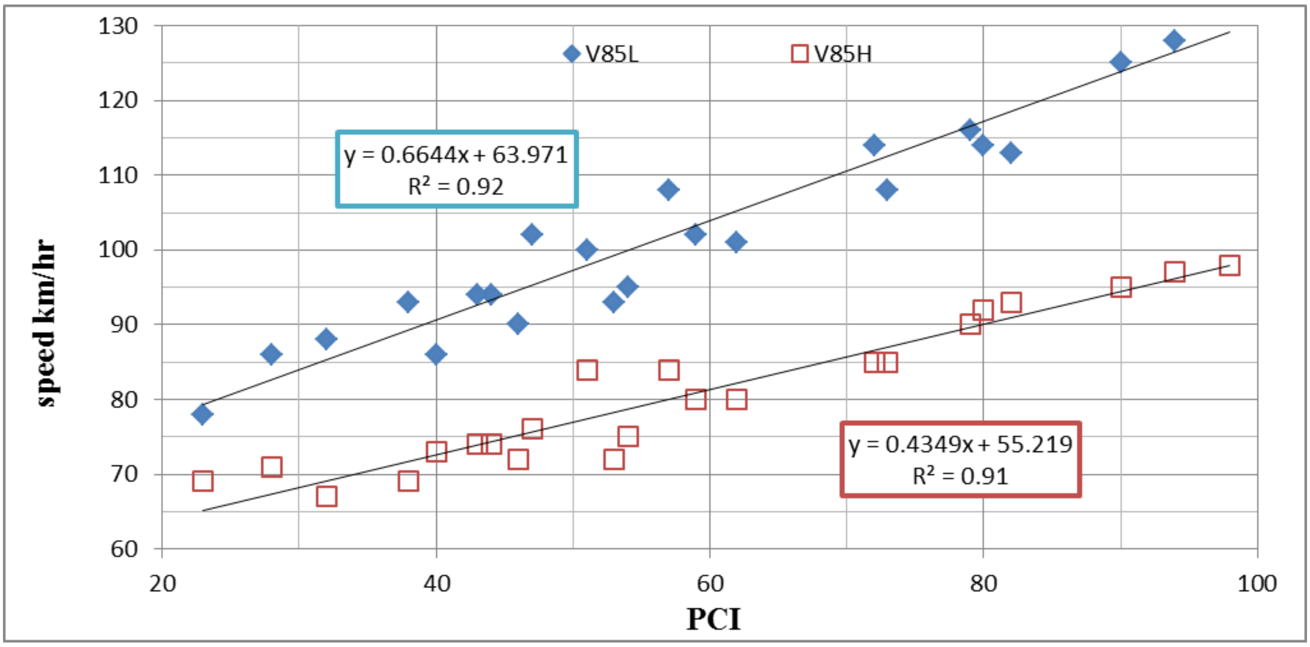

Figure 12. Comparison between V85th percentile for light and heavy vehicles.

4.1.4. Regression Models

Regression analysis was used to represent the relationship between the PCI and each of percentile speeds and capacity. The study of regression provided several independent variables mathematical models. The mathematical form of linear regression is shown in the next form:

$$Y = B_o + \sum_{i=0}^{n} B_i \times X_i \quad (1)$$

where Y is the capacity, X_{ii} the explanatory variables from 1 to n, B_o is the regression constant, and B_i is the regression coefficient [21].

The stepwise regression analysis is used to combine the most statistically significant independent variables with the dependent variable in one model, while keeping only the statistically significant terms in the model. The procedure was applied so that the selected model should have smallest number of independent variables and the highest R^2 value.

Speed Models. One of the primary objectives of this study is to develop models which estimate the association between the percentile speeds and the pavement distresses. For this reason, the analysis used spot speeds data to determine V_{50} and V_{85}. Speed data were collected under the free-flow conditions to avoid the effect of traffic volume and minimize the effect of other variables. Simple linear regression was used to check the correlation coefficient between the PCI, lane width (L), and shoulder width (S) as independent variables and the percentile speeds as dependent variable. Speed data were merged into one single database for all sections with regardless of traffic direction for all sections. Table 8 presents the top models for various vehicle types together with information on the regression analysis.

Table 8. Models for different classes of vehicles.

Model No.	Model	R^2	t (*t*-Test)		Sig. of (F)
			Constant	PCI	
1	V_{50L} = 52.03+ 0.58 × PCI	0.94	26.05	18.00	0.000
2	V_{85L} = 63.97+ 0.66 × PCI	0.92	24.40	15.75	
3	V_{50H} = 45.37 + 0.40 × PCI	0.92	29.14	16.00	
4	V_{85H} = 55.22 + 0.43× PCI	0.91	30.23	14.79	
5	V_{50T} = 50.68+ 0.56 × PCI	0.93	23.73	16.27	
6	V_{85T} = 62.87 + 0.62 × PCI	0.92	24.56	15.21	

From the results in Table 8, the resulting coefficient of determinations (R^2) is higher than 0.9 which is considered significant and reflects high goodness of the model fit. It is also found significant at the 95% confidence level and the significance of F statistic < 0.001. Two variables are excluded from the final model due to poor correlation with speed which are lane width (L) and shoulder width (S). The exclusion of L and S indicates that they do not affect the percentile speeds (V_{50}% and V_{85}%) of different vehicles classes. This conclusion complies with the previous studies in that speeds were not affected greatly by lane and shoulder widths [22,23]. Additionally, as revealed from the traffic data results, the three selected multi-lane highways were not crowded, so the lane and shoulder width did not appear to affect the percentile speeds.

To prove the effect of lane width on the percentile speeds, Table 9 compares the data of K-B and K-T highways. The shown sections (for each highway) were selected based on the variation in the PCI values not exceeding 10% from the section of high PCI. It is shown from Table 9 that the lane width of K-T highway is less than that of K-B highway, but the speed does not decreased (as it was expected). The reason for that is clear from the table results as the PCI value of K-T highway is much higher than that of K-B highway. Consequently, it can be said that the percentile speeds (V50% and V85%) are affected more with the PCI values to the extent that eliminates the lane width effect. Additionally, the effect of lane width on speeds did not appear because the change in lane width was not significant.

Table 9. Lane width, Avg. PCI, Avg. V_{50T}, and Avg. V_{85T} for some sections.

Road Name	Sec No.	Lane Width	Avg. PCI	Avg. V_{50T}	Avg. V_{85T}
K-B	5, 6, 8	3.6	59	83	100
K-T	22, 23	3.5	86	97	114

4.2. Capacity Results

At each 5 min interval, the average travel speed (ATS) of all cars was calculated in km/h. Following that, the density (veh/km) can be estimated using the equation:

$$K = q/ATS \quad (2)$$

K represents density; *q* represents flow rate, and *ATS* represents average travel speed [24]. As stated in Table 10, the flow rate (pcu/hr) was calculated by multiplying 12 by the number of vehicles each 5 min. Table 10 and Figure 13 indicate the calculation of densities and the relationship between flow rate and density for section No. 12.

Table 10. Calculation of flow rate, average travel speed, and density.

Time	No. Vehicle/5 min			q Pcu/hr	ATS Km/hr	K Veh/km
	LV Pcu	HV Pcu	Total Pcu			
10:00–10:05	26	14	40	480	98.12	4.89
10:05–10:10	26	14	40	480	97.37	4.93
10:10–10:15	35	10	44.5	534	95.13	5.61
10:15–10:20	43	22	65	780	93.65	8.33
10:20–10:25	38	12	49.5	594	95.34	6.23
10:25–10:30	41	8	48.5	582	99.06	5.88
10:30–10:35	45	18	63	756	96.46	7.84
10:35–10:40	40	4	44	528	98.73	5.35
10:40–10:45	30	14	44	528	98.98	5.33
10:45–10:50	24	14	38	450	93.94	4.79
10:50–10:55	31	8	38.5	462	100.28	4.61
10:55–11:00	27	4	31	372	91.25	4.08

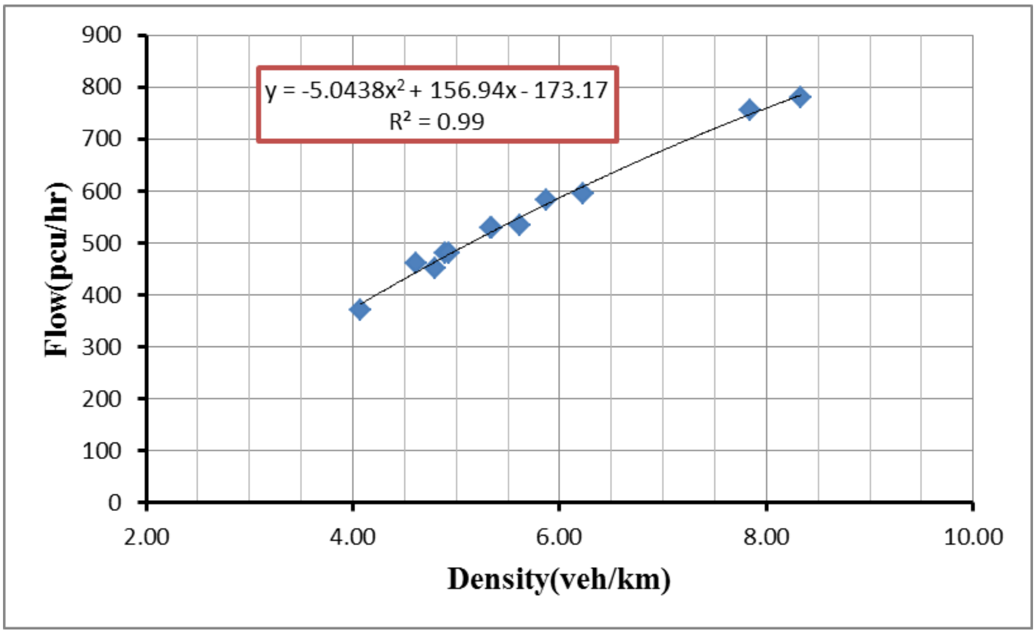

Figure 13. Flow rate and density relationship.

The critical density can be mathematically extrapolated until the maximum flow-density relationship is reached. The relationship of flow-density has been described as having a quadratic form [25,26]. Density (k) is utilized as the control parameter, while the flow rate (q) is used as the objective function, as presented in this equation:

$$q = -\beta 0 + \beta 1 \times k1 - \beta 2 \times k2 \quad (3)$$

The coefficient signs are a negative sign for $\beta 2$ and $\beta 0$ and a positive sign for $\beta 1$, as defined in the equation stated early, to satisfy the concavity requirement of the flow–density curve. When the flow–density relationship is used to calculate roadway capacity, the critical density is reached when the flow reaches its maximum $\partial q/\partial k = 0$, which is at the summit point. In this paper, it is possible to determine traffic capacity by a quadratic function, and the point of the extrapolated curve represents capacity. This point is a function of critical density and is determined by differentiating the density flow, which presents an example at one of the study sites in Figure 14. It is worth noting that this method was used earlier by Ben-Edigbe and Ferguson, in different applications [16]. Table 11 displays the capacity values (Q_{max}) of all sections.

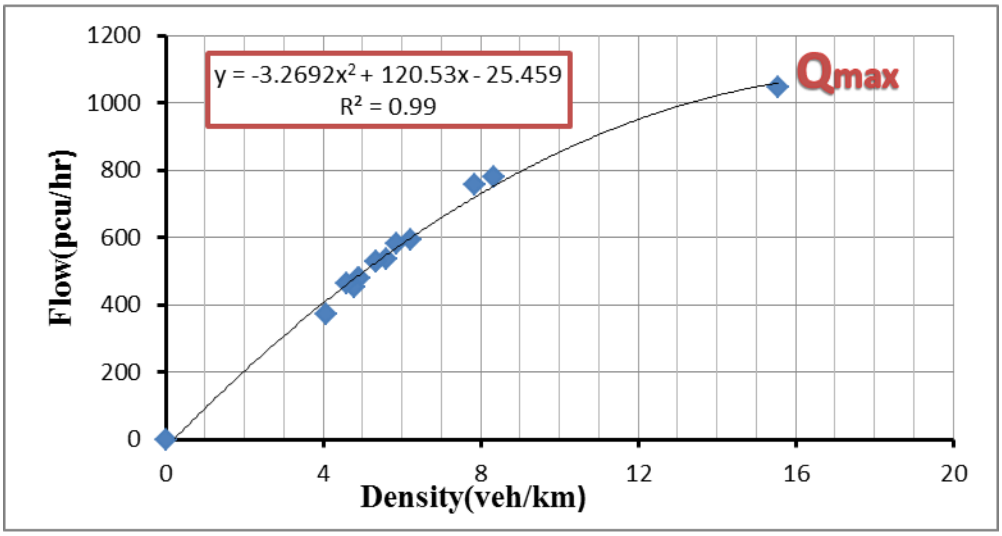

Figure 14. Extrapolation of maximum capacity.

Table 11. Maximum capacity values for all studied sections.

Section No.	The Capacity in One Direction (pcu/h)	Section No.	The Capacity in One Direction (pcu/h)
1	614	12	1048
2	648	13	1000
3	657	14	942
4	684	15	811
5	730	16	616
6	992	17	1070
7	741	18	1047
8	936	19	640
9	629	20	925
10	1354	21	574
11	1396	22	1089
		23	1302

Figure 15 shows the relation between total vehicle traffic capacity and PCI values for all studied sections. It is obvious that the relationship is positive linear, which means the more the PCI, the more the capacity. The relation also shows that the two variables are strongly correlating in which R^2 = 0.9. To put it another way, the more the pavement is distressed, the less PCI value decreases the speed on the defected sector resulting in decreasing in traffic volume.

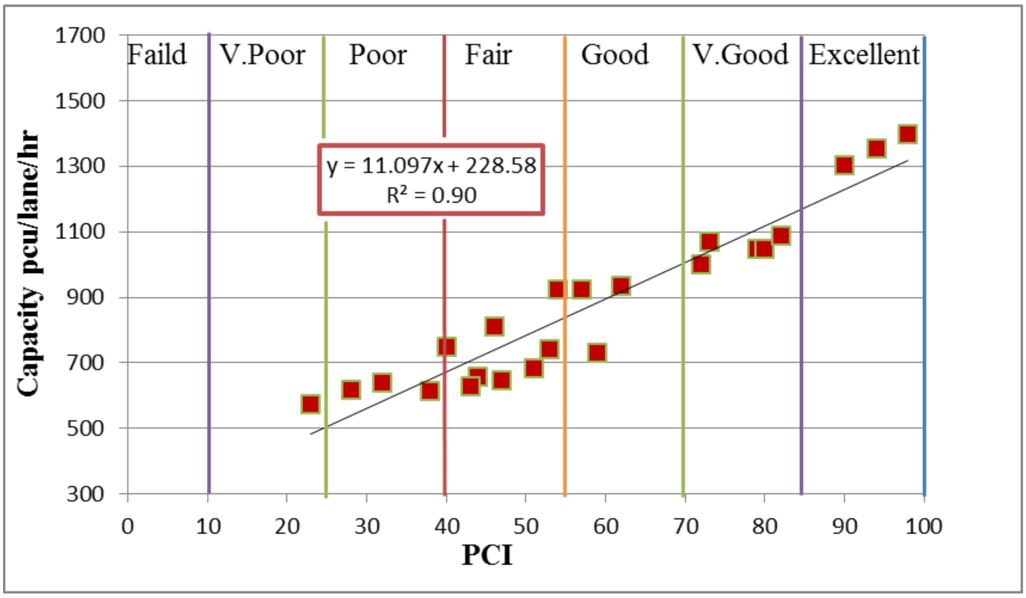

Figure 15. Relation between capacity and PCI for total vehicles.

Capacity Models

To investigate the relationship between PCI, L, and S as independent variables with capacity as dependent variable, regression analysis was used. Using the tool of step-wise regression in SPSS package program, the best model is obtained and presented in the equation:

$$Q_{max} = -372.08 + 8.84\, PCI + 119.76\, S + 152.02\, L \quad (4)$$

For capacity results, the resulting coefficient of determination (R^2) = 0.95 which is considered important. It is found to be significant at a 95% confidence level, as the significance of the F statistic is less than 0.001. The *t*-value indicates the relative importance of the variables in the model, as the greater the *t*-value, the greater the contribution of the variables to the model. The most influential variable on capacity was the PCI followed by *S* and then *L*, as indicated by the *t*-values of 10.55, 3.47, and 2.98, respectively. The positive sign of the independent variables means that as *PCI*, *S*, and *L* increase, capacity also increases, as expected.

5. Conclusions

The main objective of this study was to develop a relationship between pavement conditions and traffic operational performance on multi-lane highways. Only 23 sections on three multi-lane roads in Kafrelsheikh governorate (Egypt) have been chosen for data collection. The collected data of geometric characteristics, traffic volume, pavement conditions, and spot speeds of vehicles on these sections were analyzed. The most important findings of this paper can be summarized as follows.

- By representing the relationship between pavement distresses (in terms of PCI values) and speed percentiles, it is observed that R^2 for all fitted lines is more than 0.9, meaning that the relations between the PCI and both V_{50} and V_{85} for the three classes of vehicles are consistent. It means that as PCI value decreases (more pavement distresses), the speed decreases, in addition to the relation between traffic capacity and PCI values. It is obvious the more the PCI, the more the capacity.

- In the comparison between the effect of paving defects on both V_{50} and V_{85} for light and heavy vehicles, it is deduced that pavement distresses have a significant impact on light vehicles more than heavy ones.
- The ANOVA test was performed to compare and analyze the speed behavior of vehicles for different classes. The necessity to categorize vehicles into multiple groups has been supported by analyses of the mean speeds for various categories of vehicles.
- A 1-sample K–S test was implemented to examine the normal distribution of speed data. It was found that the speed data for most of the section deviated from the normal distribution. This means that poor pavement conditions may have an impact on the behavior of vehicle speeds.
- Using regression analysis, six models were developed to describe the relationships between the percentile speeds (V_{50} and V_{85}) and three variables, namely PCI, lane width (L), and shoulder width (S). Additionally, one model only was developed to describe the relationship between capacity and the previous three variables.
- For the speed analysis, R^2 values for all models were more than 0.9 which reflects the high goodness of models. The results of the best linear regression model showed that the most influential variable on the percentile speeds was the PCI. However, S and L were excluded from the final model due to poor correlation with percentile speeds.
- For the capacity analysis, the R^2 value was 0.95, expressing the goodness of the model fit. The most influential variable on capacity was the PCI followed by S then L. A strong positive correlation was found between capacity and the three investigated independent variables (PCI, L, and S).
- According to the conclusions of this study, the relationships of the developed models can be a useful resource for road and traffic practitioners and field engineers to build roads for defined speed or capacity.
- Finally, speed models can be used to estimate speed given the level of pavement distress (PCI), and the capacity model can also be used to estimate the capacity given PCI, S, and L. They can help traffic and pavement engineers justify their decisions regarding maintenance strategies and carry out safety and operational performance analysis and studies on vehicle operating costs. From these models, a practical framework for analysis and correlation can be provided, so that an appropriate speed adjustment warning can be issued for road safety. Additionally, road standards can be set by determining the speed of these roads by knowing the condition of their pavement.

It is recommended to extend in the area of impact of pavement distresses on speed and traffic capacity on multi-lane roads using comprehensive field data from various regions and governorates in Egypt. Future studies on Egyptian roadways should primarily focus on the effects of pavement surface defects on moving speeds, traffic, and road safety capacity of multi-lane highways on wet pavement. Additionally, it is obvious the more the PCI, the more the capacity. However, the results might have appeared different if sudden and abrupt changes in pavement conditions exist. Therefore, we suggest studying it in the future.

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