Mitigating Overloading Vehicle Effects in Relation to the Liddle Power Equations for Designing Road Pavement Lifespan

Ari Sandhyavitri, Arief Aditya, and Muhamad Yusa

Abstract—This paper objective is to mitigate to what extent the Liddle empirical formula (which the initial power equation of 4th order) may suit in designing road pavement lifespan for overloading vehicle roads. A case study was conducted in the Meredan highway, Siak, Riau, Indonesia. It was identified that the Truck Factor (TF) > 1 in this road. During 3 years project operation, the pavement condition has been deteriorated (Road Surface Index fail, IPf = 1.5). Hence, the road was proven to be a failure before reaching its designated project lifespan (10 years). This study conducted various calculations by adjusting the Liddle empirical exponential formula (from power equation of 4th to 6th order) in order to fulfill the pavement lifespan which was capable to serve the overloading traffic loads in this road. This research has identified that there is a need to adjust the Liddle empirical formula by power equation of 6th order to accommodate the current overloading vehicles.

Index Terms—overloading, pavement, Liddle formula, Equivalent Axle Load (EAL), Cumulative Equivalent Standard Axle (CESA) load.

1 INTRODUCTION

The traffic flow at the Meredan Junction passing Sultan Syarif Hasyim’s Bridge at Siak, Riau Province, Indonesia has been dominated by heavy vehicles [1]. The types of heavy vehicles were mainly encompassing trucks and trailers carrying wood, palm oil, and CPO (Figure 1a). These heavy vehicles were considered as overloading vehicles with the total axle load were more than a standard axle load of road class III (8 tons). The wheel axle load data were obtained from the Siak Transportation Department and Dirjen Bina Marga Department [1, 2]. The traffic flow of this road was also relatively heavy (Figure 1b). The location of the study area is shown in Figure 2.

Fig. 1a. Overloading vehicles passing the Meredan roads, Siak, Indonesia

Fig. 1b. The traffic flow conditions.

Fig. 2. Research location in Meredan, Siak, Indonesia (google.co.id, 2018)

The road was fully operated in 2010 and it designated project lifespan would be 10 years (up to 2019). Unfortunately, in 2013 the road surface condition has been deteriorated (Figure 3) and the IPf reached 1.5. Figure 3 shows the damage of the Meredan pavement condition after approximately 3 years of the project operation which confirmed that
the actual design lifespan was shorter than it should be.

Fig. 3. Road damage in Meredan, Siak, Indonesia, 2015.

It was acknowledged that, various pavement calculations have been reviewed in many publications and literatures, but the common applications of the pavement thickness design in Indonesia have been empirical methods [3, 4, 5]. The component analysis method 1987 was used to conduct the pavement design which was then replaced by the Bina Marga flexible pavement design Pt.T-01-2002-B. This was based on the AASHTO 1993 method. The pavement design manual No. 22.2/KPTS/Db/2012 was then latterly issued as a compliment to the Pt.T -01-2002-B Manual [3, 4, 5].

The existing Liddle’s formula for the equivalent axle load (EAL) calculation uses the power equation of 4th order [6, 7, 8]. As the fact, the overload vehicles passing the Meredan road are very common then as a consequence the road lifespan might be shorter. It was assumed that the existing soil, sub-base, and pavement layers were in good condition and were constructed according to the standard [5].

Under the standard design condition, most of the engineers in Indonesia have calculated pavement road design using an empirical method based on the Bina Marga design manual of Pt.T-01-2002-B. The results of the implementation of this manual, in general, have satisfied the objectives of road stakeholders, except for a certain condition of the road with overloading vehicle and truck factor >1. Hence, this study has investigated whether the location of this study was overloaded road or not.

II. LITERATURE REVIEW

A. Equivalent Single Axle Load (ESAL)

The Equivalent Single Axle Load (ESAL) is a ratio of damage factor value caused by the single axle load (with a standard single axle load of 8.16 ton or 18,000 lbs) [13, 14, 15]. The ESAL of each configuration of the axle load is calculated based on the distribution of the vehicle wheel loads e.g. for a single axle wheel configuration is:

\[
\text{ESAL of single axle single wheel (front wheel)} = \frac{1}{5.40} = 0.0012 \quad (1)
\]

As the single axle front wheel and rear wheel are similar, thus it’s ESAL (with using Liddle empirical power equation of 4th order) = 0.0012. This study investigated the applicability of this Liddle empirical power equation of 4th order for the Meredan overloading road, in Siak, Indonesia.

B. Truck Factor (TF)

The truck factor (TF) is one of the main causes of pavement deformation and pavement damage [16, 17]. These are determined by the ratio of the equivalent standard axle load to the average number of traffic loads.

\[
\text{TF} = \frac{\text{ESAL}}{N} \quad (3)
\]

Where

- TF : Truck Factor
- ESAL : Equivalent Standard Axle Load (Total)
- N : Average number of traffic load.

A road was categorized as an overloaded one when the TF>1. Hence, this study investigated whether the location of this study was overloaded road or not.

III. RESULTS

A. Traffic volume for the design lane

This study compiled daily traffic volume in 2010 and 2013. The following table shows the average daily traffic volume in 2010 and 2013.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Number 2010</th>
<th>Number 2013</th>
<th>Average daily traffic volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Private car</td>
<td>546</td>
<td>621</td>
<td>546</td>
</tr>
<tr>
<td>Small bus</td>
<td>18</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>Big bus</td>
<td>10</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>Truck 2 axle</td>
<td>296</td>
<td>314</td>
<td>296</td>
</tr>
<tr>
<td>Truck 3 axle</td>
<td>198</td>
<td>226</td>
<td>198</td>
</tr>
<tr>
<td>Truck 5 axle</td>
<td>13</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>Trailer</td>
<td>4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1085</strong></td>
<td><strong>1237</strong></td>
<td></td>
</tr>
</tbody>
</table>

Source: the Siak Transportation Department, 2015

Based on Table 1, it can be calculated that the projected traffic growth (i) was as follow:

\[
n = \text{base LHR} \times (1 + i)^n \quad (4)
\]

Daily traffic volume (LHR) year

\[
\text{LHR 2010} = 1085 \text{ vehicle/day}
\]
\[
\text{LHR 2013} = 1237 \text{ vehicle/day}
\]
\[
\text{LHR 2010} \times (1 + i)^3 = \text{LHR 2013}
\]
\[
1085 \times (1 + i)^3 = 1237
\]
\[(1 + i)^3 = 1.140\]
\[i = \left(\sqrt[3]{1.140}\right) - 1\]
\[i = (1.04 - 1) \times 100\%\]
\[i = 4\% \text{ (year)}\]

Thus the projected traffic growth in this road was 4% per year.

**C. Equivalent Standard Axle Load (ESAL) calculation using Liddle exponential 4th order**

The Equivalent Standard Axle Load (ESAL) or number of load repetitions (which was converted to an axle load standard) was calculated for each type of vehicle. The following Table 2 shows an example of the ESAL of loaded vehicles using an initial power equation of 4th order.

<table>
<thead>
<tr>
<th>Axle</th>
<th>Load (ton)</th>
<th>% Load</th>
<th>SAST</th>
<th>DADT</th>
<th>TADT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.073</td>
<td>64%</td>
<td>28.60</td>
<td>41.60</td>
<td>56.52</td>
</tr>
<tr>
<td>2</td>
<td>15.631</td>
<td>4%</td>
<td>27.36</td>
<td>52%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>30.7039</td>
<td>27%</td>
<td>15.07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This table uses a standard vehicle axle load. For example, the distribution of truck 5 axle load was as follows; every single axle 1 and 2 compromising 18% of load, thus the distribution of axle 3 would be 48%.

Based on vehicle volume data in 2013, the ESAL total per day is presented in the following table.

<table>
<thead>
<tr>
<th>Year</th>
<th>ESA/day</th>
<th>ESA/year</th>
<th>CESA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>4,039.34</td>
<td>1,474,360.21</td>
<td>1,474,360.21</td>
</tr>
<tr>
<td>2011</td>
<td>4,200.92</td>
<td>1,533,334.62</td>
<td>3,007,694.84</td>
</tr>
<tr>
<td>2012</td>
<td>4,368.95</td>
<td>1,594,668.01</td>
<td>4,602,368.42</td>
</tr>
<tr>
<td>2013</td>
<td>4,543.71</td>
<td>1,658,454.73</td>
<td>6,260,817.57</td>
</tr>
<tr>
<td>2014</td>
<td>4,725.46</td>
<td>1,724,792.92</td>
<td>7,985,610.49</td>
</tr>
<tr>
<td>2015</td>
<td>4,914.48</td>
<td>1,793,784.63</td>
<td>9,779,395.12</td>
</tr>
<tr>
<td>2016</td>
<td>5,111.06</td>
<td>1,865,536.02</td>
<td>11,644,931.14</td>
</tr>
<tr>
<td>2017</td>
<td>5,315.50</td>
<td>1,940,157.46</td>
<td>13,585,088.60</td>
</tr>
<tr>
<td>2018</td>
<td>5,528.12</td>
<td>2,017,763.76</td>
<td>15,602,852.36</td>
</tr>
<tr>
<td>2019</td>
<td>5,749.24</td>
<td>2,098,474.31</td>
<td>17,701,326.67</td>
</tr>
</tbody>
</table>

Hence the ESA = 4,675.9 per day was reached in the period of 2013-2014. As it was reported that, in 2013-2014 (3-4 years project operation) the road pavement condition has been deteriorated \( \text{IPf} = 1.5 \). However, it was designated that the project design...
life span would be 10 years (up to 2019) with the total CESA in 2019 of 17,701,326.67.

Hence, this study mitigated the degradation of this road with the assumption that there was an effect of overloading vehicle (truck factor) on the Liddle power equations for designing the road pavement lifespan.

\[
\text{TF} = \frac{ESAL}{N}
\]

(7)

\[
\text{TF} = \frac{4.675,912}{580} = 8.0619 > 1
\]

As the TF is higher than one (>1), then the road section is considered overloaded. It was identified that heavy vehicles in this road section were higher than the standard stated in the highway design capacity (HCM) manual 1983, 1987 and 1997 (for sub-urban roadway) [5, 13, 18].

The numerical calculation used to calculate the existing cumulative traffic flow. This is presented as follow;

\[
W = W_{18} \times \left(1 + g\right)^n - 1
\]

(8)

Where

\[
W_i = \text{Sum of the cumulative axle load within the designated design lifespan}
\]

\[
W_{18} = \text{cumulative axle load for one year}
\]

\[
n = \text{designated design lifespan (n)}
\]

\[
g = \text{traffic growth (%)}
\]

**E. Backward Analysis for the Cumulative Equivalent Standard Axle (CESA)**

As the Meredan road pavement condition in the field was already deteriorated in 2013 (not in 2019), there was necessary to conduct the backward analysis by shifting the order of the Liddle equation which will closely match with CESA of 17,701,326.67.

Trail and error approaches were applied in the calculation [19, 20]. It was tried initially by conducting calculation using of 4th power exponential. The result was stated that the projected project lifespan was 10 years with CESA design of 17,701,326.67 (Table 4).

Then it was tried to apply 5th power exponential in the calculation. The results were obtained as follow; the projected project life span was 7 years with CESA approximately 17,306,145. Again it was tried to apply the power exponential of 6th order from the Liddle equation (Table 5).

**TABLE 5.**

<table>
<thead>
<tr>
<th>No</th>
<th>Vehicle Types</th>
<th>Weight (ton)</th>
<th>% Load (%)</th>
<th>Axle Load (ton)</th>
<th>ESAL.</th>
<th>% Load (%)</th>
<th>Axle Load (ton)</th>
<th>ESAL.</th>
<th>% Load (%)</th>
<th>Axle Load (ton)</th>
<th>ESAL.</th>
<th>Power Eq.</th>
<th>ESAL Eq.</th>
<th>Total ESA 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Private Vehicle</td>
<td>2.00</td>
<td>50%</td>
<td>1.00004</td>
<td>1</td>
<td>0.00004</td>
<td>1</td>
<td>0</td>
<td>0.00004</td>
<td>1</td>
<td>0</td>
<td>0.000061</td>
<td>6</td>
<td>251,918.11</td>
</tr>
<tr>
<td>2</td>
<td>Small Bus</td>
<td>7.71</td>
<td>35%</td>
<td>2.62305</td>
<td>60%</td>
<td>5.09087</td>
<td>66%</td>
<td>2.07198</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Big Bus</td>
<td>9.91</td>
<td>34%</td>
<td>3.0603211</td>
<td>60%</td>
<td>5.50302</td>
<td>64%</td>
<td>3.08194</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Truck 2 Axle</td>
<td>13.50</td>
<td>34%</td>
<td>4.5903715</td>
<td>60%</td>
<td>8.910485</td>
<td>66%</td>
<td>6.88813</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Truck 3 Axle</td>
<td>38.00</td>
<td>28%</td>
<td>10.647169</td>
<td>72%</td>
<td>27.361376</td>
<td>66%</td>
<td>27.361376</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Truck 5 Axle</td>
<td>44.98</td>
<td>18%</td>
<td>8.1912.17141</td>
<td>64%</td>
<td>28.601348</td>
<td>66%</td>
<td>38.21734</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Trailer</td>
<td>70.86</td>
<td>13%</td>
<td>10.44522043</td>
<td>35%</td>
<td>27.822043</td>
<td>66%</td>
<td>104.3812</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For example, the distribution of truck 5 axle load was as follow;


There is a significant change in ESAL for the initial calculation (Table 2) and the final calculation (Table 5). The final calculation of ESAL (Table 5), especially for trucks and trailers, become 2 to 5 times greater than those in the initial one. This calculation will be used for calculating the CESA (Table 6).

It was obtained that the CESA design became 17,708,448.39 (Table 6) and it was almost similar to 17,701,326.67 (Table 4). It was also projected that the road pavement lifespan may be reached in 2013-2014 (with heavily damaging condition of IPf= 1.5).

The table 6 and figure 4 demonstrated that, by utilizing the exponential 6th order of the Liddle equation, it may yield CESA value of 17708448.39 in May 2013 (3 years 5 months) which is similar to 10 years of the designated project lifespan with CESA value of 17701326.67 of 4th order of the Liddle equation for 2019.

**TABLE 6.**

<table>
<thead>
<tr>
<th>Year</th>
<th>ESA/day [LEP (1+i)n]</th>
<th>ESA/year [ESA/day]x365</th>
<th>CESA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>13,498.19</td>
<td>4,926,838.92</td>
<td>4,926,838.92</td>
</tr>
<tr>
<td>2011</td>
<td>14,038.12</td>
<td>5,123,912.48</td>
<td>10,050,751.39</td>
</tr>
<tr>
<td>2012</td>
<td>15,599.64</td>
<td>5,538,868.97</td>
<td>15,379,620.37</td>
</tr>
<tr>
<td>May 2013</td>
<td>15,183.63</td>
<td>5,542,023.73</td>
<td>17,708,448.39</td>
</tr>
<tr>
<td>2013</td>
<td>15,183.63</td>
<td>5,542,023.73</td>
<td>20,921,644.10</td>
</tr>
<tr>
<td>2014</td>
<td>15,790.97</td>
<td>5,763,704.68</td>
<td>26,685,348.78</td>
</tr>
<tr>
<td>2015</td>
<td>16,422.61</td>
<td>5,994,252.87</td>
<td>32,679,601.65</td>
</tr>
<tr>
<td>2016</td>
<td>17,079.52</td>
<td>6,234,022.98</td>
<td>38,913,624.64</td>
</tr>
<tr>
<td>2017</td>
<td>17,762.70</td>
<td>6,483,383.90</td>
<td>45,397,008.54</td>
</tr>
<tr>
<td>2018</td>
<td>18,473.20</td>
<td>6,742,719.26</td>
<td>52,139,727.80</td>
</tr>
<tr>
<td>2019</td>
<td>19,212.13</td>
<td>7,012,428.03</td>
<td>59,152,155.83</td>
</tr>
</tbody>
</table>

AE 18 Kip SAL: 59,152,155.83
Figure 4 and 5 show that the CESA value of 17,708,448.39 would be reached in the period of 3 years 5 months using Liddle power exponential equation of 6th order.

Both CESA values obtained from the trial and trial error analyses utilizing 4th and 6th order of the power exponential are similar to the projected project lifespans of 10 years and 3.4 years respectively.

IV. CONCLUSION

The percentage of overloading vehicles in Meredan, Siak, Indonesia was 47% with the Truck Factor (TF=8.06) > 1, thus this road is categorized as overloading road. Hence the existing road pavements were deteriorating (IPf=1.5) before reaching the designated project lifespan of 10 years. Then this study has applied various Liddle's empirical equation for calculating the damage factor or EAL from the power exponential of the 4th to 6th order. This study identified that the road lifespan would be reached IPf=1.5 in the period of 3.4 years of the project operation with the CESA of 17,708,448.39. Hence it is recommended to consider the Liddle power exponential of 6th instead of 4th order for designing this road lifespan in Meredan, Riau, Indonesia.

REFERENCES


