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

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***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.

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

Fig. 1b. The traffic flow conditions.

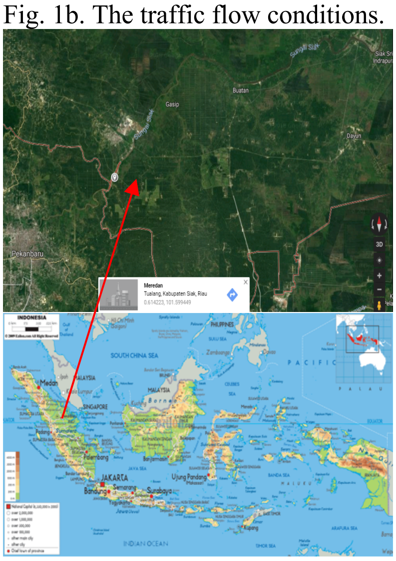

Fig. 2. Research location in Meredan, Siak, Indonesia (goole.co.id, 2018)

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 IP_f 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. Under this circumstance, the condition of an initial road design (for example 10 years) becomes shorter. The pavement surface index will be degraded before reaching its lifespan [9, 10.11, 12, 13, 14].

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:

ESAL of single axle single wheel (front wheel) $= \left[\frac{1}{5.40}\right]^4 = 0.0012$ (1)

ESAL of single axle single wheel (rear wheel)

$= \left[\frac{1}{5.40}\right]^4 = 0.0012$ (2)

As the single axel 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.

$$TF = \frac{ESAL}{N} \quad (3)$$

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 has 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 1.
THE AVERAGE DAILY TRAFFIC VOLUME (LHR) IN 2010 AND 2013 IN MEREDAN ROAD.

Vehicle type	Number		Average daily traffic volume	
	2010	2013	2010	2013
Private car	546	621	546	621
Small bus	18	36	18	36
Big bus	10	14	10	14
Truck 2 axle	296	314	296	314
Truck 3 axle	198	226	198	226
Truck 5 axle	13	20	13	20
Trailer	4	6	4	6
		Total	1085	1237

Source: the Siak Transportation Department, 2015

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

Daily traffic volume (LHR) year n = base LHR $(1 + i)^n$ (4)

Daily traffic volume (LHR) 2010 = 1085 vehicle/day

LHR 2013 = 1237 vehicle/day

LHR 2010 $(1 + i)^3$ = LHR 2013

$1085 (1 + i)^3 = 1237$

$(1 + i)^3 = 1.140$

$i = (\sqrt[3]{1,140}) - 1$

$i = (1.04-1) \times 100\ \%$

$i = 4\%$ (per 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 4^{th} order.

TABLE 2.
ESAL OF AN INITIAL POWER EQUATION OF 4^{TH} ORDER FOR LOADED VEHICLES.

No	Vehicle Types	Weight Total (ton)	As 1 % Load (%)	As 1 Axle Load (ton)	As 1 Type of Axle	As 1 ESAL	As 2 % Load (%)	As 2 Axle Load (ton)	As 2 Type of Axle	As 2 ESAL	As 3 % Load (%)	As 3 Axle Load (ton)	As 3 Type of Axle	As 3 ESAL	ESAL Power Equation	Total ESAL 2013
1	Light Vehicle	2.00	50%	1	SAST	0.0012	50%	1	SAST	0.0012					4	0.0024
2	Small Bus	7.71	34%	2.62	SAST	0.0554	66%	5.09	SADT	0.1514					4	0.2068
3	Big Bus	9.01	34%	3.06	SAST	0.1031	66%	5.95	SADT	0.2827					4	0.3858
4	Truk 2 Axle	13.50	34%	4.59	SAST	0.5220	66%	8.91	SADT	1.4215					4	1.9435
5	Truk 3 Axle	38.00	28%	10.64	SAST	15.0727	72%	27.36	DADT	15.6311					4	30.7039
6	Truk 5 Axle	44.98	18%	8.19	SAST	5.2913	18%	8.19	SAST	5.2913	64%	28.60	TADT	5.77402	4	16.3566
7	Trailler	79.86	13%	10.44	SAST	13.9710	35%	27.82	DADT	16.7092	52%	41.60	TADT	25.84567	4	56.5258

This table uses a standard vehicle axle load. For example, the distribution of truck 5 axle load was as follow; every single axle 1 and 2 compromising 18% of load, thus the distribution of axle 3 would be 100%-(18%x2) = 64%. Using the ESAL equation with power equation of 4^{th} order as follow;

ESAL (loaded vehicle) $= \left[\frac{8.19}{5.40}\right]^4 + \left[\frac{8.19}{5.40}\right]^4 + \left[\frac{28.60}{18.45}\right]^4 =$ 16.3566 (Table 2)

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

TABLE 3.
ESAL TOTAL PER DAY

Vehicle Types			ESA Front	ESA Rear 1	ESA Rear 2	Sum ESA	Vehicle Volume 2013	ESA TOTAL PER DAY
1			2	3	4	5	6	7
Light Vehicle							657	
1	Light vehicle	(LV)	0.0012	0.0012		0.0024	621	1.461
			STRT	STRT				
2	Small Bus	(LV)	0.055	0.151		0.2068	36	7.445
			STRT	STRG				
Heavy Vehicle							580	
1	Big Bus (LT)	Load	0.103	0.283		0.3858	14	5.401
			STRT	STRG				
2	Truk 2 axle	Load	0.522	1.422		1.9435	157	305.132
		Unload	0.338855	0.924		1.2627	157	198.244
			STRT	STRG				
3	Truk 3 axle (LT)	Load	15.073	15.631		30.7039	113	3469.535
		Unload	0.73503	1.828		2.5632	113	289.637
			STRT	SDRG				
4	Truk 5 axle (LT)	Load	5.291	5.291	5.774	16.3566	10	163.566
		Unload	1.524158	1.524158	1.678	4.7267	10	47.267
			STRT	STRT	STrRG			
5	Trailler (LT)	Load	13.971	16.709	25.846	56.5258	3	169.577
		Unload	1.524	1.828	2.863	6.2155	3	18.647
			STRT	SDRG	STrRG			
ESAL Total								4675.912

Notes : STRT (One Single Axe One Wheel)
STRG (One Single Axe Tandem Wheels)SDRG (Double Axes Tandem Wheels)
STrRG (Triple Axes Tandem Wheels)

ESAL total for this Meredan road per day was 4,675.9 (Table 3), hence in a single year ESAL = 4,675.9 /day x 365 day = 1,706,707.95 axle load standard (2013). This ESAL will be used in the calculation of Cumulative Equivalent Standard Axle (CESA) load.

D. Equivalent Standard Axle (ESA)

Based on the Siak Transportation Department (2015) it was stated that in 2010, the ESA of this road was at the average of 4039.3 vehicles. As ESA (in Indonesia is also known as LEP and W18) can be calculated as follow:

ESA (Indonesia = LEP) in 2010 = 4039.3
Road design life (n) = 10 years
Traffic growth (i) = 4 % = 0.04 (Based on the calculation of (i) above).

Hence, ESA/day (i=0) $= [LEP\ (1 + i)^n]$ (5)

$= [4039.34\ (1 + 0{,}04)^0]$

$= 4039.34$

ESA/year $= [(ESA/day) \times 365]$ (6)

$= [4039.34 \times 365]$

$= 1{,}474{,}360.21$

Then it was calculated the cumulative Equivalent Standard Axle (CESA) by multiplication of ESA x 365 days. Table 4 shows the calculation results of CESA from 2010-2019 (as an initial projected road design lifespan).

TABLE 4.
THE CUMULATIVE EQUIVALENT STANDARD AXLE (CESA) LOAD 2010-2019

Year	ESA/day [LEP (1 + i)n]	ESA/year [(ESA/day)x 365]	CESA
2010	4,039.34	1,474,360.21	1,474,360.21
2011	4,200.92	1,533,334.62	3,007,694.84
2012	4,368.95	1,594,668.01	4,602,362.84
2013	4,543.71	1,658,454.73	6,260,817.57
2014	4,725.46	1,724,792.92	7,985,610.49
2015	4,914.48	1,793,784.63	9,779,395.12
2016	5,111.06	1,865,536.02	11,644,931.14
2017	5,315.50	1,940,157.46	13,585,088.60
2018	5,528.12	2,017,763.76	15,602,852.36
2019	5,749.24	2,098,474.31	17,701,326.67
AE 18 Kip SAL			**17,701,326.67**

Hence the ESA = 4,675.9/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 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.

Truck Factor (TF)

$$TF = \frac{ESAL}{N} \quad (7)$$

$$TF = \frac{4.675,912}{580} = 8.0619>1$$

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;

$$W_t = W_{18} \times \frac{(1+g)^n - 1}{g} \quad (8)$$

Where

W_t = Sum of the cumulative axle load within the designated design lifespan

W_{18} = cumulative axle load for one year

n = designated design lifespan (n)

g = 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 matche with CESA of 17,701,326.67.

Trial 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.
ESAL OF TRIAL AND ERROR FOR POWER EQUATION OF 6TH ORDER.

No	Vehicle Types	Weight (ton)	Axle 1			Axle 2			Axle 3			Power ESAL Equation	Total ESAL 2010
			% Load (%)	Axle Load (ton)	ESAL	% Load (%)	Axle Load (ton)	ESAL	% Load (%)	Axle Load (ton)	ESAL		
1	Private Vehicle	2.00	50%	1	0.00004	50%	1	0.00004				6	0.000081
2	Small Bus	7.71	34%	2.62	0.01305	66%	5.09	0.05891				6	0.071952
3	Big Bus	9.01	34%	3.06	0.03311	66%	5.95	0.15030				6	0.183411
4	Truck 2 Axle	13.50	34%	4.59	0.37715	66%	8.91	1.69483				6	2.07198
5	Truck 3 Axle	38.00	28%	10.64	58.51769	72%	27.36	61.79964				6	120.31734
6	Truck 5 Axle	44.98	18%	8.19	12.17141	18%	8.19	12.17141	64%	28.60	13.8745	6	38.21734
7	Trailler	79.86	13%	10.44	52.22043	35%	27.82	68.30180	52%	41.60	131.3959	6	251.91811

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

ESAL (loaded vehicle) = $\left[\frac{8.19}{5.40}\right]^6 + \left[\frac{8.19}{5.40}\right]^6 + \left[\frac{28.60}{18.45}\right]^6 =$ 38.217 (Table 5)

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.
CESA VALUES USING THE 6TH ORDER OF LIDDLE EQUATION

Year	*ESA/day [LEP (1 + i)n]*	*ESA/year [(ESA/day)x 365]*	*CESA*
2010	13,498.19	4,926,838.92	4,926,838.92
2011	14,038.12	5,123,912.48	10,050,751.39
2012	14,599.64	5,328,868.97	15,379,620.37
May 2013	15,183.63	5,542,023.73	17,708,448.39
2013	15,183.63	5,542,023.73	20,921,644.10
2014	15,790.97	5,763,704.68	26,685,348.78
2015	16,422.61	5,994,252.87	32,679,601.65
2016	17,079.52	6,234,022.98	38,913,624.64
2017	17,762.70	6,483,383.90	45,397,008.54
2018	18,473.20	6,742,719.26	52,139,727.80
2019	19,212.13	7,012,428.03	59,152,155.83
	AE 18 Kip SAL		**59,152,155.83**

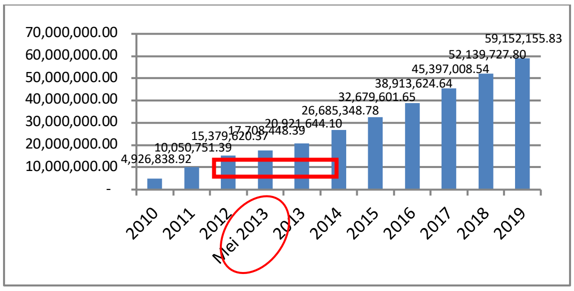

Fig. 4. Correlation of CESA and year

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.

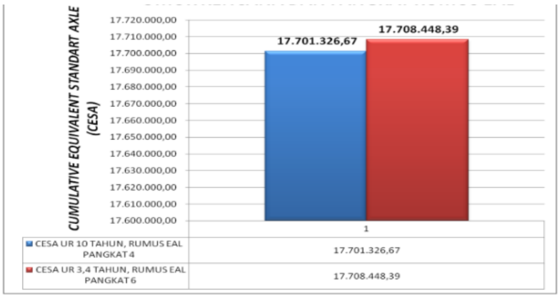

Fig. 5. CESA comparison of the 4th and 6th order of Liddle exponential equation

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.

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