DEVELOPMENT OF TRAFFIC SAFETY MODELS ON INDONESIAN TOLL ROADS

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Abstract: This paper describes a macroscopic model of traffic accidents on Indonesian toll roads. It is adopted from Oppe's (1989, 1991) models and based on two simple time dependent models with the vehicle kilometres driven being the production unit and accident rate being the estimation of the probability of failure per unit of production. The first model is an accident rate model that is found to follow the negative exponential curve. The second model is a traffic exposure model that follows an S-logistic growth function. The relationship between these two models is suggested as the third model of traffic accident prediction.

The models are applied to traffic exposure and number of accidents on five toll roads in Indonesia and the results fit reasonably well with actual data. Predictions of traffic volume and accident numbers are made by the models using statistical evidence, as a result these models could be employed to develop a traffic safety programme for Indonesian toll roads. The weaknesses of these models, however is also acknowledged since they are not modelled based on any real changes in infrastructure and other externalities.

Key Words: Traffic Safety, Macroscopic Traffic Safety Models, and Toll Roads

1. INTRODUCTION

The first toll road in Indonesia was opened in 1978 and now there are over 500 kilometres, mainly located on the Greater Jakarta area. The development of toll roads is in accordance with the Indonesian government's policy of using the existing arterial road system for local traffic and developing a new high standard of motorway for inter-regional traffic as well as intra-urban traffic. For financial reasons this network is being funded through road tolls, therefore in Indonesia toll road and motorway are synonymous and in this paper these two words are used interchangeably.

Although toll roads should be some of the safest roads, because of their high design standard, in 1998 there were 2,972 accidents involving 3,859 casualties of whom 277 were fatalities. In 1997 before the economic crisis in Indonesia these figures were even higher because of more traffic exposure level. There were 3,663 accidents involving 12,308 casualties of whom 344 were fatalities. Over the whole toll road network, current traffic safety performance indicators stand at:

- 45 accidents per hundred MVkm (million vehicles kilometre driven) for accidents
- 27 accidents/100 MVkm for KSI (killed and serious injured) rate, and
- 5 accidents/100 MVkm for fatal accidents

In Indonesia, the police are obliged to collect all accidents data, but this seems to be unreliable and underreported because of many reasons. Toll roads accident data, however are relatively more reliable since it is mandatory for the toll road operators to provide as a part of their contract / franchising agreement with government. The Indonesian highway corporation of PT. Jasa Marga (Persero) has been establishing their own traffic accident database and reporting system to complement with police data, but they have not been researched or used for modelling traffic accidents.

The main objective of this paper is to develop a simple form of traffic accident prediction model based on statistical evidence that can be used for strategic policy in the development of traffic safety programmes. This paper is the result of work by Tjahjono (2001), which discussed the impact on road widening programme in 1995 and 1996 on traffic safety.

2. METHODOLOGY

The macroscopic model of traffic accidents is a model to predict accidents in a simple form and consists of time parameters of accidents (accident rate per year) and traffic exposure (100 million vehicle kilometres driven per year). The model is assumed as a simple time dependent production system, with the vehicle kilometres driven being the production unit and accident rate being the estimation of the probability of failure per unit of production. This model is based on Oppe's models (1989, 1991a and 1991b) of accidents and which is used at the countrywide level. However, in this paper adopts it at the road-based level (i.e. toll roads or motorways). Instead of fatality rate, in these models, - the accident rate is used since it is more appropriate to describe the unit of the probability of failure per unit of production.

2.1 Model Development

Two functions were developed: First, the accident rate function was found to follow the negative exponential distribution, and; second, the traffic exposure function was assumed to follow a S-shaped logistic type of saturation model of traffic exposure. The relationship between these two functions was determined.

Two assumptions lie behind the models: (i) the fatality rate at time t changes proportionally to the value that it has reached already at that time, (ii) the growth rate of traffic exposure is proportional to the ratio of the amount of traffic that it already exists to the remaining potential traffic needed to achieve saturation level. Therefore, the model assumptions as described by Oppe are as follow:

1. There is a monotonically decreasing curve for accident rates per year (called 'the risk curve' or 'learning process curve')
2. There is a monotonically increasing S-shaped saturation curve in regard to traffic exposure in terms of vehicle kilometres driven per year.
3. As a consequence, the number of accidents per year follows from these two curves by multiplication of their respective values.

Let A_t denote the number of accidents on toll roads in year *t*, V_t is the number of vehicle kilometres driven (traffic exposure) in year *t* and V_m is the maximum number of vehicle kilometres, then R = A/V, S = V/(V_m – V), and T = A/(V_m-V) where R is the accident rate, S is the ratio of the amount of traffic that it already exists to the remaining potential traffic and T is the potential accident rate in the future.

Model 1

$$R_t' = \frac{dR_t}{dt} = \alpha\, R_t \qquad (1)$$

If equation (1) differentiates with respect to time, *t*, then equation 1 can be solved by the quotient rule of differentiation as follows:

$$\frac{A_t'}{A_t} = \alpha + \frac{V_t'}{V_t} \qquad (2)$$

Equation 1 can be rewritten as follows:

$$\mathrm{Ln}(R_t) = \ln(A_t/V_t) = \alpha\, t + \beta \qquad (3)$$

Or, model 1 based on the assumption 1 can be also written as follows:

$$R_t = e^{\alpha t + \beta} \qquad \text{Model 1}$$

Model 2

$$S_t' = a \,.\, S_t \qquad (4)$$

Based on assumption 2, it can be stated that the growth rate is also a function of the ratio between V and (V_m – V), therefore, equation 5 can be rewritten:

$$\ln(S_t) = \ln\left(\frac{V_t}{V_m - V_t}\right) = a\,t + b \qquad (5)$$

Or, model 2 based on assumption 2, can equally be written as a logistic growth function:

$$V_t = \frac{V_m}{1 + e^{-(a t + b)}} \qquad \text{Model 2}$$

In this case, the negative exponential initially was used to describe the fatality rates. It was found later that this function is the best function to fit with traffic accident data on Indonesian toll roads. It was also found that the logistic model of traffic exposure could be employed by using its standard properties to estimate the saturation level (V_m) as described in Balakrishnan (1992). Therefore, the value of V_m is derived directly from the logistic growth model and such an empirical approximation i.e. highway capacity models are not needed to develop the models.

Model 3

In addition to model 1: $\ln R = \ln (A_t/V_t)$ and model 2: $\ln S\, [V_t/(V_m-V_t)]$ in which both are linear function to time, t, the third model use the combined assumption that describe the relation between accidents (A_t) and the maximum volume that can be reached in the future (V_m), it can be stated as follows:

$$\ln\left(\frac{A_t}{V_m - V_t}\right) = (\alpha + a)\, t + (\beta + b) \qquad \text{Model 3}$$

2.2 Determine The Value of V_m

It was found that the problem of these models was "how to determine the value of V_m" since traffic exposure follows the S-shape from zero to the saturation flow? Oppe (1989) suggested that the value of V_m is not given in advance, but it is chosen in such a way that gave the best fit to model 2 with regard to V (on the countrywide level). In this study, V_m was estimated through the simple form of the logistic growth model and it is described as follows:

Starting from model 2 with a different approach:

$$V_t = \frac{V_m}{1 + e^{-b} e^{-at}}$$

If p is substituted for e^{-b}, then model 2 equation becomes:

$$V_t = \frac{V_m}{1 + p\, e^{-at}}$$

and using the quotient rule differentiation, it shows that:

$$\frac{dV_t}{d_t} = a\, V_t - \frac{a}{V_m} V_t^2$$

One of the logistic growth model properties assumes that the growth rate, G_t, or $dV_t/V_t d_t$ decreases linearly as traffic exposure increases and becomes zero at the saturation level.

$$G_t = \frac{1}{V_t}\frac{dV_t}{d_t} = a - \frac{a}{V_m} V_t \qquad (6)$$

which 'a' and '$\frac{a}{V_m}$' can be determined, and also the value of saturation level, V_m.

However, in reality, traffic growth rate function does not always fit well as a straight line. This might be because of changes in the production system, e.g. infrastructure changes and other external factors. Discontinuous regression models deal with these problems, by knowing the production system characteristics. For example, traffic growth rate can increase after a road-widening programme, or in situations, like the Greater Jakarta area where almost main and secondary roads are already approaching their capacity, externalities will play a major role in the development of traffic growth rate. A bottleneck in the downstream exit point or upstream entry point can cause significant drops in the traffic growth rate, reducing or cancelling out any impacts of road widening. Using discontinuous regression models also allows considering of any changes in road infrastructure as well as other externalities as long as information is available. In this case V_m value will be determined by the value of the equilibrium point where traffic exposure does not increase or decrease.

3. STUDY AREA

Five toll roads were chosen. Three toll roads are located in the Greater Jakarta Area, one in the Greater Bandung Area, capital city of West Java Province and one in the Greater Surabaya area, capital city of East Java (see figure 1).

The first toll road is the Jagorawi, JGR, toll road (50 km), which links Jakarta to the south. A part of this toll road (33 km) was opened in 1978 as the first toll road in Indonesia and the whole section was completed in 1980. The basic geometric standard was dual-2 motorway and then in 1996 part of this toll road (16 km) was widened to dual-3 motorway.

The second toll road is the Jakarta-Cikampek, JKP, toll road (73 km), which links Jakarta to the east and as a part of the busiest inter-urban corridor in Indonesia: the north Java Corridor. The basic geometric standard was dual-2, however, when it was opened in 1988 a part of this toll road (37 km) was only single carriageway for the first two years' operation. In 1997 a part of this toll road was also widened to dual-4 (19 km) and dual-3 (15 km) motorway.

The third toll road is Jakarta-Tangerang Barat, JTB, toll road (27 km). It was opened in 1984 and links Jakarta to the west. The basic geometric standard as the other toll roads was dual-2 motorway, but in 1997 it was widened to dual-3 for the whole section.

The fourth and fifth toll roads are Padaleunyi, PLC, toll road (dual-2, 43 km, including 8 km of branch), which dedicates as south Bandung bypass and Surabaya-Gempol, SBY toll road (dual-2, 43 km) and like JKP, the SBY toll road is a part of the north Java Corridor. The PLC and SBY toll roads were opened in 1991 and 1990 respectively and there have been no major infrastructure changes since.

Figure 2 shows the development of the five toll roads and describes major infrastructure changes that might influence the traffic growth as well as the number of traffic accidents. It should be noted that in late 1997, the economic crisis in Indonesia had a major impact to the growth of traffic exposures on all of these toll roads resulting in traffic exposure reduction in 1998.

4. DATA

Traffic accidents and exposure data were obtained from the toll operator "PT. Jasa Marga (Persero)" although the data from 1984-1988 had been found to be missing when computerisation of data began in the early 90s. The "closed toll road system" is used in these five toll roads, which record traffic at both entry and exit ramps/toll booths giving accurate traffic exposure data in term of vehicle kilometres driven. Traffic exposure and accident data are represented in the graphs in Figure 3.

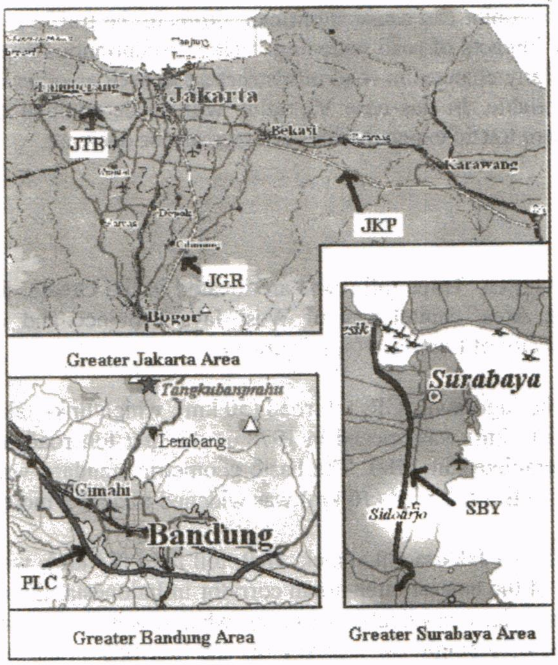


Figure 1, Study locations

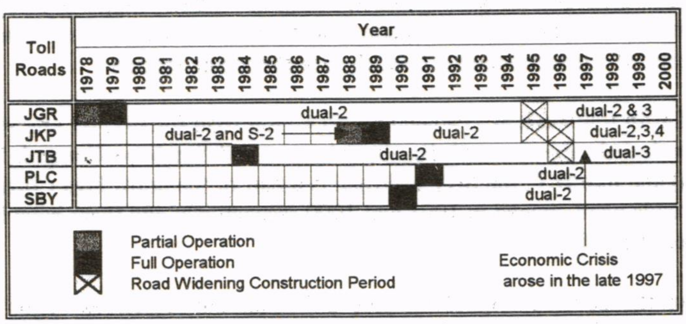


Figure 2. Development of the five toll roads

Figure 3 shows that in the opening year of these toll roads, accident rates were relatively high except on Surabaya-Gempol (SBY) toll road (93, 115, 126, 80, 30 accidents/100 MVkm on JGR, JKP, JTB, PLC and SBY respectively), and then gradually drop over time to 1999 by when they had decreased to 24, 54, 33, 15 and 22 accidents/100 MVkm respectively.

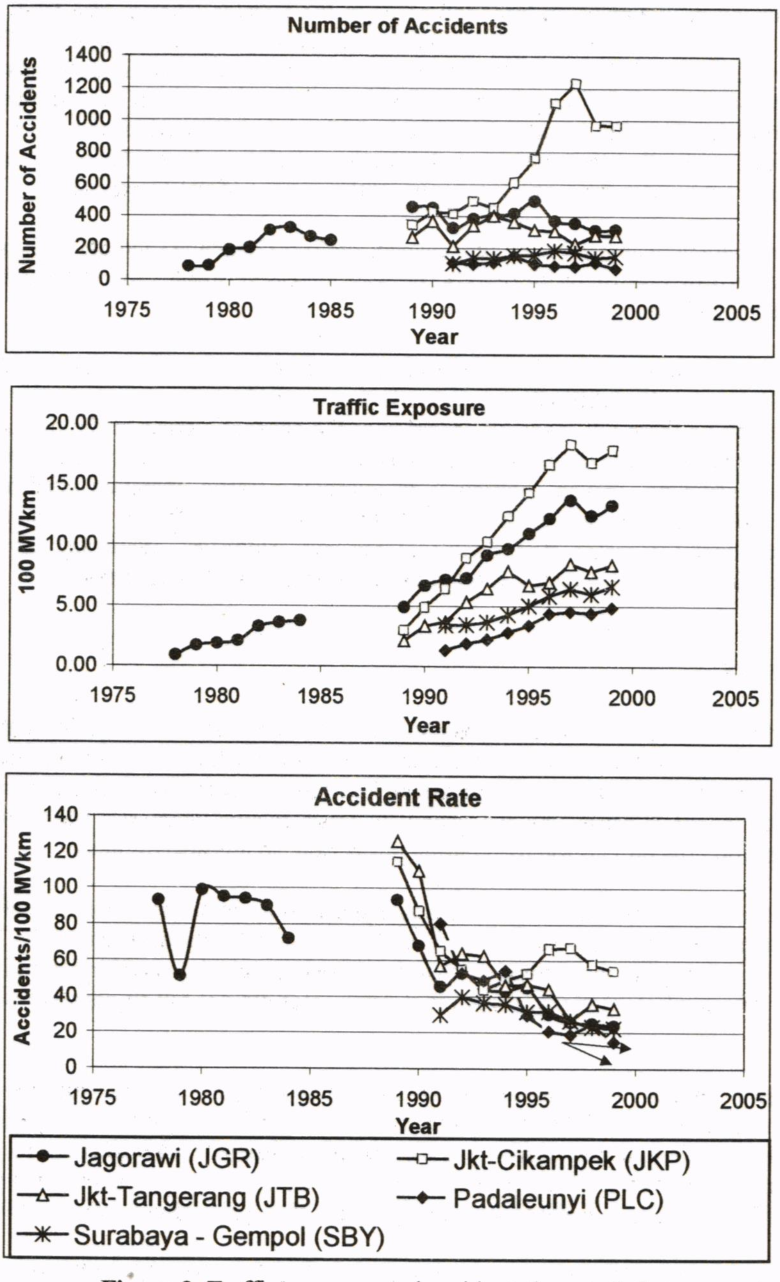


Figure 3. Traffic exposure and accident characteristics

The impact of having a single carriageway on a part of JKP toll road in the first two years also resulted in high numbers of traffic accidents, however the highest accident rate was recorded on JTB toll road in 1999 (126 accidents/100 MVkm).

Road widening programmes on three toll roads in the Greater Jakarta Area (JGR, JKP and JTB toll roads) has also had a major impact on accidents and traffic exposures. During the construction on JGR (1995) and JKP (1996-1997), the number of traffic accidents increased quite significantly but this did not happened on JTB (1996). There was no significant impact on the growth of traffic exposure on both JGR and JKP during the road widening construction, except that the annual growth rate was slightly reduced. However, on the JTB toll road, the road-widening programme reduced the amount of traffic exposure.

Since there were no major infrastructure changes on PLC (Bandung) and SBY (Surabaya) toll roads, the growth rate of traffic exposures was increased steadily until 1997 before the economic crisis hit Indonesia.

As an impact of economic crisis in Indonesia, the amount of traffic exposure was reduced from 1998 onward. It is difficult to judge whether the lack of increase in traffic flow after road widening on these toll roads was because of the economic crisis at the time or because of the day-time saturation on local roads, causing bottlenecks up- and downstream of the toll road. Road widening, maybe contributes in improving traffic operation condition, but in terms of traffic safety is still disputed. A study carried out by Turner and Thomas (1986) found that dual-3 is safer than dual-2 motorways. However, Walmsley et al. (1999) concluded the opposite that dual-2 is relatively safer than dual-3 motorways.

5. RESULTS

A discontinue regression model was applied to JGR since there was missing data between 1984 and 1988. Logistic growth rate functions were used for the growth rate figures between 1989 and 1996 for the purpose of determining V_m. Figures from 1997 onward were excluded because of the drop caused by the economic crisis facing Indonesia. Major road works reduced traffic flow on JTB toll road during this period, so it is also excluded.

It should be noted, that toll increases/changes are also a major influence on traffic growth rates. There was a dramatic toll increase in 1990 caused by devaluation of the Indonesian Rupiah and a change in the method of charging based on vehicles travelling per kilometre by different vehicle classifications. However, growth rates did not fall to negative value at this time.

The results of model 1 (traffic accident rate model) and model 2 (traffic exposure model) are presented in Table 1 and Table 2 respectively. It was found that model 1 did not fit JKP data very well, even though the negative exponential curve was still the best curve to fit the data compared to other curves. This was due to the high accident rates in the first two years as an impact of having a single carriageway motorway and through road widening in 1996-1997.

The β value on PLC is the highest, and followed then by JTB, JGR, SBY and JKP. This means that the learning process on JTB is the highest, nevertheless in 1999, the lowest accident rate was on PLC followed by SBY and JGR. It found that SBY is the only toll road which has had accident rates of less than 40 accidents/100 MVkm or below average accident rates since its opening year.

Furthermore, the V_m (saturation) value is found to be the highest on JKP followed by JGR and JTB. The impact of reducing traffic flow in 1998 and 1999 has not had a major impact of the linearity of model 2's curve, since it was found to be only a temporary fluctuation.

Table 1. Parameters of model 1

Location	Year of Data	α	β	R^2
JGR	1978-1984 1989-1999	- 0.0603	123.900	0.73
JKP	1989-1999	- 0.0431	90.171	0.28
JTB	1989-1999	- 0.1309	264.97	0.84
PLC	1991-1999	- 0.1980	398.48	0.88
SBY	1991-1999	- 0.0584	119.86	0.65

Table 2. Parameters of model 2

Location	Year of Data	V_m (100 MVkm)	a	b	R^2
JGR	1978-1984 1989-1999	14.6240	0.2175	- 432.68	0.94
JKP	1989-1999	20.3115	0.3914	-779.93	0.95
JTB	1989-1999	9.6661	0.3011	- 599.76	0.86
PLC	1991-1999	6.3226	0.3193	- 636.91	0.95
SBY	1991-1999	9.8360	0.1913	- 381.72	0.93

It shows that the amount of traffic in 1997 on JGR, JKP and JTB (in the Greater Jakarta area) was already 94%, 90% and 89% of the saturation level respectively. In reality, these values can be accepted, since during the peaks most of dual-2 motorway segments become dual-3 and some of dual-3 (particularly in JGR) become dual-4 through use the hard shoulder as an additional lane. Therefore, these figures do not give the right value for maximum empirical capacity, but on PLC (in the Greater Bandung Area) and SBY (in Greater Surabaya Area) these values were only 77% and 67% respectively.

It should be noted that V_m value is determined from the growth rate function of logistic growth model (based on equation 6). Therefore, given the same geometric design standard does not necessary have the same values. For example although SBY and PLC have the same geometric standard (dual-2), the V_m value on SBY is 1.5 higher than on PLC. This is caused by the low growth rate on PLC compared to SBY and indirectly as a result of the region in which the toll road is located. SBY serves the Greater Surabaya area, the second largest city in Indonesia and as a part of the North Java Corridor, while PLC serves Greater Bandung area, the fourth largest city in Indonesia. The other reason is that PLC is not located on the main corridor on Java Island and the main toll road link is only 35 km since this toll road has a branch linking to the Bandung' City Centre.

It can be seen from Table 1 and Figure 4 that the relationship between traffic exposure and accident rate parameters from model 1 and model 2 are very strictly. Although, this is no prior argument as Oppe results (1989), show, the 'a and b' parameters are related to the growth rate of traffic exposure and the ratio between these parameters are constants.

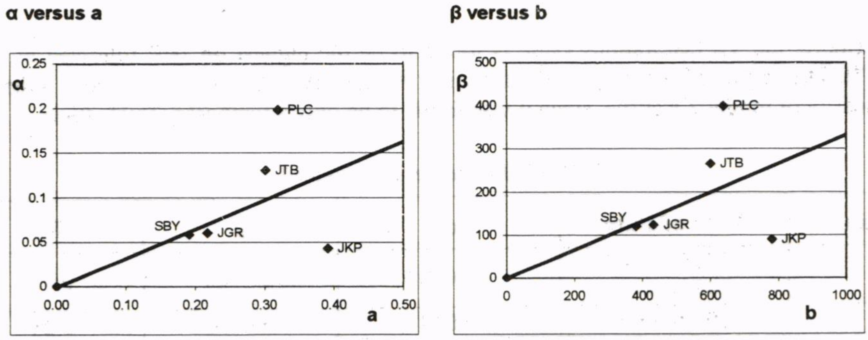


Figure 4. Relation between parameters of model 1 and model 2

Similarly, the 'α and β' are related to the decreasing rate of accident rates and the ratio between these parameters are also constant. It can be concluded that model 1 and model 3 are symmetrical, hence:

$$\ln\left(\frac{A_t}{V_t}\right) = -\ln\left(\frac{A_t}{V_m - V_t}\right)$$

or

$$A_t = c \cdot \sqrt{V_t \cdot (V_m - V_t)} \qquad (7)$$

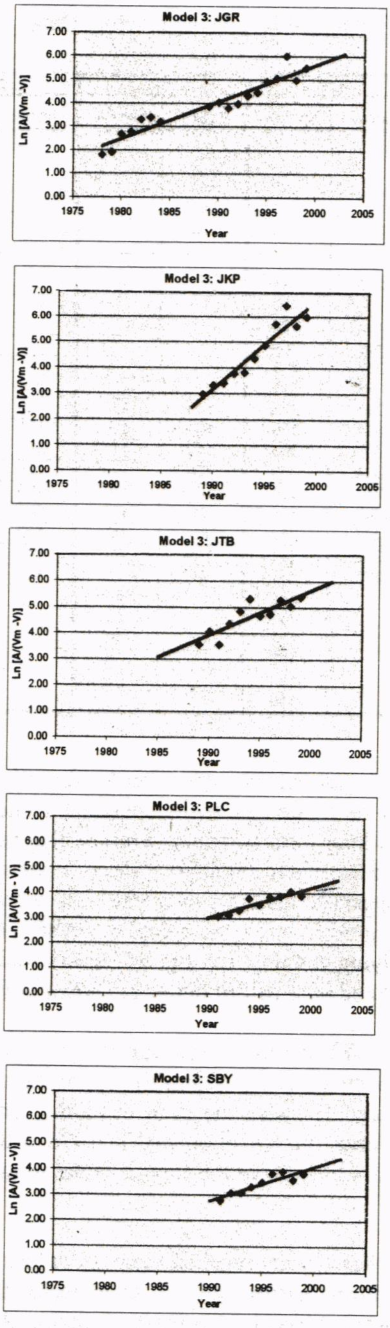
As a result of the symmetrical condition as shown in Figure 4, it also can be used directly for estimation of the V_m for each toll road through the number of accidents (A_t) and traffic exposure (V_t) variables. Theses figures can be treated as the relationship between risk factor (y line) and traffic volume (x line) and follows Oppe's suggestion (1989) that the relation between traffic system and traffic safety is very strong and is not than just correlation between them. Any improvement in the traffic system operation it also have a direct benefit on traffic safety.

Finally, Figures 5a and 5b show model 3 and comparison of the actual number of accidents and predicted values respectively (also presented in Table 4). The Kolmogorov-Smirnov (K-S) one-sample test (Siegel and Castellan, 1988) was used to check the goodness-of-fit between actual and predicted values. For all of five traffic accident models, the *null hypothesis* that the distribution of actual accidents follows the traffic accident models was accepted at the significant level of 5% (see Table 3).

Table 3. K-S One Sample Test Results

Toll Road	Year of the Observation	Number of Samples	Maximum Deviation $\lvert Fa(x_i) - Sp(x_i)\rvert$*	Critical Value of $\lvert Fa(x_i) - Sp(x_i)\rvert$* at the significant level of 0.05
JGR	1978-1985 and 1989-1999	19	0.158	0.301
JKP	1989-1999	11	0.105	0.391
JTB	1985 and 1989-1999	12	0.158	0.375
PLC	1991-1999	9	0.053	0.432
SBY	1991-1999	9	0.158	0.432

* $Fa(x_i)$ and $Sp(x_i)$ are cumulative relative for actual data and predicted results respectively



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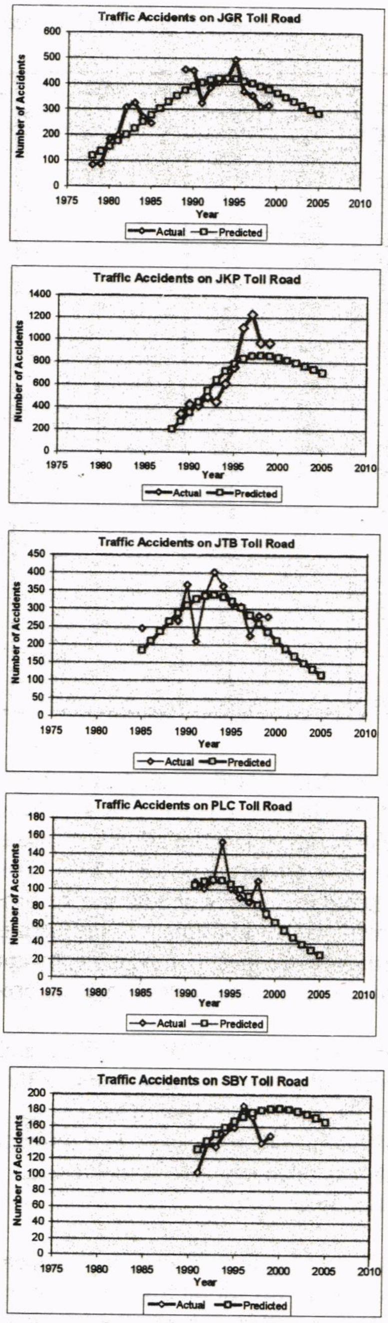

5b

Figure 5. Model 3 (Traffic Accident Model) and comparison between expected results and actual data

Table 4. Comparison Between Expected Results and Actual Data

Year	JGR		JKP		JTB		PLC		SBY	
	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
1978	83	118								
1979	87	136								
1980	185	155								
1981	199	177								
1982	308	200								
1983	325	225								
1984	269	251								
1985	245	277			246	184				
1986	n.a	304			n.a	210				
1987	n.a	330			n.a	237				
1988	n.a	353	n.a	207	n.a	264				
1989	457	375	343	275	267	289				
1990	452	392	426	357	367	311			n.a	120
1991	326	406	418	450	211	327	108	105	103	132
1992	386	416	493	547	341	336	101	109	138	141
1993	408	421	452	641	403	338	110	111	135	151
1994	420	422	611	724	364	333	154	110	154	159
1995	495	419	758	788	314	321	101	106	159	167
1996	371	413	1107	832	307	304	91	100	186	173
1997	356	404	1231	856	227	283	86	92	172	178
1998	313	392	971	863	282	261	110	83	140	181
1999	318	379	969	857	280	237	72	73	149	183
2000		365		842		214		64		183
2001		349		821		192		55		182
2002		334		796		171		46		180
2003		318		768		152		39		176
2004		302		740		134		33		172
2005		287		711		119		27		167

Since, accident data fluctuated over the time (an extreme case can be found on JTB), the predicted value for a given year should not be treated as an independent value as the real accident counts, it is more reliable to use the long-term (running) average that represents the stable safety property (Hauer, 1997). Therefore when employing these models in a traffic safety programme they should not be based solely on the single value of actual accidents. There will also an adjustment of the learning process curve after implementation of any major infrastructure changes. For example, by applying running average of 5 years accident counts, the correlation between actual data and predicted data will fit better as shown in Figure 6.

Four of the toll roads (JKP, JTB, PLC and SBY) had the largest growth in volume less than five years after their opening years, at the point when $Ln(V/V_m\text{-}V) = 0$ or equivalent to the half of the saturation flow. This growth coincides with the high economic growth during 1990-1995 in Indonesia. JGR is a different case since it is opened in 1978 when economic growth was relatively low. It took eleven years to achieve the flow is equal to the half of the saturation flow.

Basically, the number of predicted accidents has already reached the peak values on these toll road locations, except on SBY where it is still increasing and will be expected to do so until 2001. However this is due to the learning process based on current condition. As mentioned earlier the model does not directly consider infrastructure changes and others externalities. It is obvious that the growth of number of accidents will change if infrastructure changes. An adaptation to the new demands is expected and it is suggested that these models should be reviewed periodically in order to deal with these problems and any incidental fluctuations e.g. economic crises and other social and political problems in Indonesia.

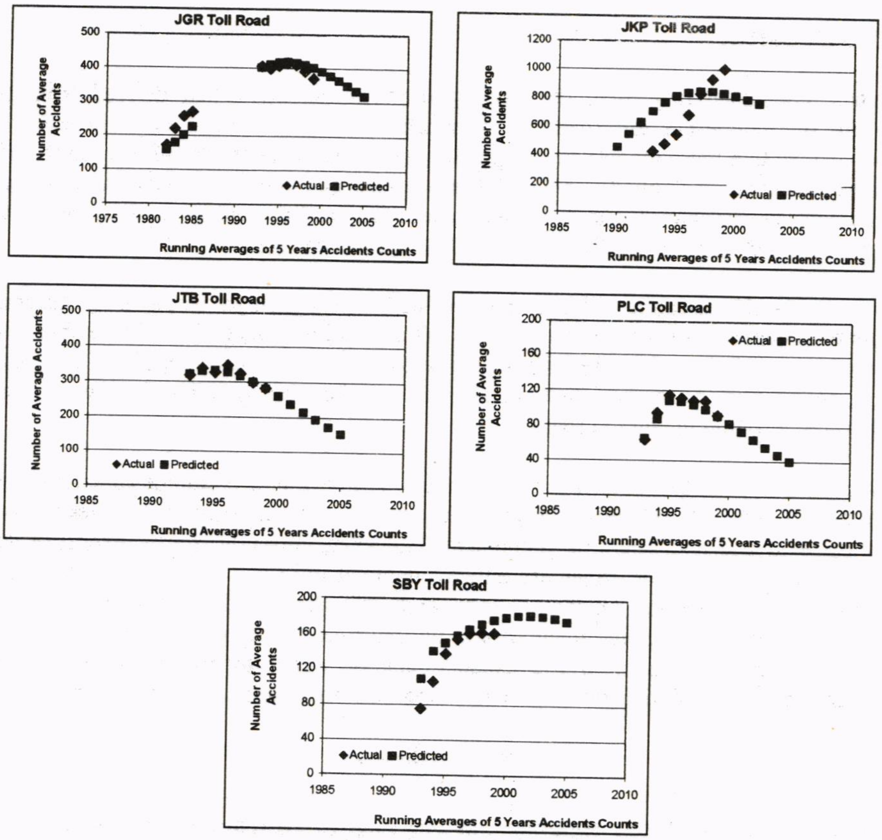

Figure 6. Running Average of 5 Years Accident Counts

Particular to three toll-roads in the Greater Jakarta Area, the main issue was the impact of the road-widening programme on the traffic safety performance since the initial objective was only to increase road capacity. It can be seen from Figure 5b that during the road widening on JKP and JTB the number of accidents increased above predicted values, but on JTB was the other way round since the major impact was decreasing the traffic exposure.

After completion of road widening, it was shown that on JGR the number of traffic accidents dropped below the predicted values, but on both JKP and JTB the actual values were above the predicted values. Initially, it maybe concluded that during road widening on JTB, the traffic was disrupted and, as a result, the traffic exposure dropped as well as the number of traffic accidents. However on both JGR and JKP traffic exposures still increased and therefore, the number of traffic accidents also increased significant caused by construction works on motorway. After construction, it was only on JGR that the actual number of accidents fell below the predicted values. However, more evidence is needed to judge whether after road widening on JGR traffic safety performance improved, while on the other two toll-roads it became worse. At least these models will be able to help to set some initial evidence that can be elaborated by more "in-depth" study to explain traffic accident beyond the scope of this paper.

6. CONCLUSION

It can be concluded that: first, the models of traffic accidents that derived from traffic exposure on Indonesian toll roads fit reasonably well with actual data. However it is acknowledged that these models cannot possibly take into account any infrastructure changes and other externalities explicitly. Second, these models can allow for predicting missing data (as can be seen in Table 4), and in the absence of any traffic accident models, these models can be employed for an evaluation tools of infrastructure changes.

Further "in-depth" research will undertake to link the explanatory variables of interest and accidents as dependent variables and to establish evaluation models that will be able to make a comparison of before and after infrastructure changes. The main benefit of this research will be to establish traffic accident models that can be employed for the development of traffic safety programme on toll roads.

Additionally they suggest means for developing a nationwide programme of safety research since there is no comprehensive programme currently in existence in Indonesia based in statistical evidence and scientific judgement. However, currently, traffic exposure data in terms of vehicle kilometres driven are only available at toll roads. Therefore, it is suggested that traffic data collection on major urban and interurban roads that already carried-out annually by Indonesian government should be extended to estimate of 100 MVkm at the corridor base level. Improving traffic accident database system by police is also suggested as is recognised as a foundation for a systematic approach to a traffic safety programme.

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