Effects of Design and Maintenance Requirements and Axle Loads to Flexible Pavement Lifetime Performance

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Abstract

This research aims to identify sensitivity of flexible pavement roughness (IRI) and maintenance budget on motorway due to design/maintenance criteria and repetition of axle loads. Highway Development and Maintenance Software (HDM) will be used as a tool to forecast Long-Term Pavement Performance (LTPP) and maintenance plan. Six primary distress-initiated factors including surface thickness, California Bearing Ratio of subgrade (CBR), construction defects, maintenance methods, traffic volume (AADT) and vehicle gross weight, were examined for their effects in IRI. A total of 19 case studies are set up for sensitivity test. The result shows changes in IRI and maintenance budget when each primary distress-initiated factor was changed. This research can be useful for motorway designers and decision-makers to establish strategic design and maintenance program.

Keywords: *International roughness index, HDM-4, long term pavement performance, repetition of axle load, design and maintenance criteria*

1. Introduction

A motorway is the full-controlled access highway which aims to facilitate speed and convenient to road users at a higher level (Kowanich, 2007). In order to fulfill the purpose of motorways, the procedures in motorways: designs, constructions, inspections and maintenance would be different from other highways. High standards of materials are likely to be chosen in the design of flexible pavement on motorways. Routine inspections and maintenances will always be done to ensure that the motorways are able to be fully functioned, to improve the level of service and to extend the life cycles of motorways.

Department of Highways, Thailand (DOH) is now operating 2 motorways in Thailand: Highway No.7 Bangkok – Chonburi and Highway No.9 Bangkok Outer Ring (Kanchanapisek Road). Both are toll roads with some non-tolled sections. The DOH also plans to extend motorway network to other parts of the country to support more passengers and freight transportation in the future, to facilitate convenience and speed, reduce road user cost, and reduce transport and logistics costs.

The big amount of budget from government will be needed for maintenance all year round. Therefore, the maintenance scheme must be carefully planned and executed since the government budget can be requested only once a year. The maintenance budget plan can be estimated from road maintenance statistics data in the former year. However, there are uncertainties in using statistic data to estimate maintenance cost of new motorways. Hence, the specific tool should be applied in order to estimate maintenance cost and to forecast distresses of new motorway so the maintenance plan would be set up more accurately.

2. Objectives

Since motorway aims to facilitate speed and convenient to road users, the smoothness of pavement becomes the key consideration. This research focuses on pavement roughness index which also represents other primary distresses. The level of roughness also reflects in level of maintenance cost for the more roughness on pavement, the more maintenance activities are needed.

The objectives of this research are:

1. To study sensitivity of roughness (IRI) and changes to lifetime maintenance budget on motorway due to design and maintenance requirement

2. To study sensitivity of roughness (IRI) and changes to lifetime maintenance budget on motorway due to various repetition of axle loads

3. Materials and Methods

This research considers roughness on flexible pavement of motorway when design/maintenance criteria and repetition of axle loads have changed by using the International Roughness Index: IRI as a measurement. Maintenance cost is also being considered when the distress is changed. HDM-4 is used to forecast distress on at-grade pavement. The case study of this research is new 96-km flexible-pavement motorway route No.81 Bang Yai – Kanchanaburi. The motorway will be fully-controlled access spanning over three cities. The project starts from the intersection of Highway No.9 and Rattanathibet Road in Nonthaburi and ends at highway No.324 in Kanchanaburi. The first section from Bang Yai to Nakhon Pathom is designed as a 6-lane highway and the rest from Nakhon Pathom to Kanchanaburi is 4-lane highway.

Studies show that distresses that usually occur on motorways are cracking, rutting and potholes. The motorway distresses combined with environment and structure deformation can develop to roughness on motorway pavement. This research will focus on the sensitivity of roughness on motorway for it reflects various types of distresses and it only occurs by the occurrence of other primary distresses (Kerali, 2000). The primary distresses: cracking, rutting, potholes and structure deformation are caused by 2 types of controlled variables: 1) strength-related factors and 2) load-related factors. This research will study the effect of those variables on motorway distresses representative (roughness). The controlled variables related to strength are surface thickness, California Bearing Ratio of the subgrade and construction defect. The controlled variables related to loads are annual average daily traffic and gross vehicle weight of truck. However, the negligence or low quality of maintenance can also cause pavement distresses (Burningham & Stankevich, 2005). Therefore, maintenance criteria will be considered as a controlled variable in this research. The equation below shows dependent variables X and independent variable Y that will be considered:

$$y = f\,(x_1, x_2, x_3, x_4, x_5, x_6) \tag{1}$$

When y = International Roughness Index (IRI), m/km
x_1 = surface thickness, mm
x_2 = California Bearing Ratio of the subgrade, %
x_3 = construction defect
x_4 = maintenance methods
x_5 = annual average daily traffic, veh/day
x_6 = gross truck weight, Tons

3.1 International Roughness Index

World Bank has set road service level measurement criteria called International Roughness Index: IRI (HDM Global Ltd., 2016). The index shows pavement roughness in vertical direction which results in user's comfort. IRI = 0 m/km is as smooth as glass, IRI = 5 m/km requires maintenance and IRI = 12 m/km is dilapidated pavement.

There are 26 constants called calibration factor related to IRI models in the software. However, this software was developed for developing countries. Thailand is one of the developing countries. Hence, default calibration factors from the software may represent pavement deterioration rate in Thailand.

3.2 Surface Thickness

Surface thickness is a controlled variable related to the strength of motorway pavement. The thickness of pavement has a direct effect on the structural number: SN (structural strength index of flexible pavement) or load bearing capacity of the pavement (Schnoor & Horak, 2012). The change of pavement thickness can cause a different structural number. Different structural numbers are expected to result in different numbers of IRI. This research will set 4 cases of pavement thicknesses; 100 mm, 200 mm, 300 mm and 400 mm to observe the variation of IRI.

3.3 California Bearing Ratio of the Subgrade

California Bearing Ratio of the subgrade (CBR) is a controlled variable related to the strength of the motorway pavement (IMMS, 2008). The factor also has direct effect on structural number (SN) of pavement. It is expected that the change of CBR will result in the different structural numbers and IRI. Hence, this research will focus on the change of IRI due to various CBR. CBR case studies are set to be 10%, 15%, 20% and 25%.

3.4 Construction Defect

Construction defect is a controlled variable related to the strength of the motorway pavement (Bureau of Materials Analysis & Inspection Bureau of Highway Maintenance Management, 2008). It is possible that the construction is carried out differently from the project design. So, this research will study change of IRI due to defects from construction. The defect will be considered in form of initial IRI. Case studies are set to be initial IRI equals 1.75 m/km, 2.0 m/km, 2.25 m/km and 2.5 m/km.

3.5 Maintenance Methods

The negligence or low-quality maintenance can also cause pavement distresses. This research will study the change of IRI due to maintenance methods. Case studies are set to be 4 methods; 1) Do nothing 2) Routine Maintenance 3) Routine + Preventive Maintenance and 4) Routine + Corrective Maintenance.

- Do nothing

This scenario is set with absolutely no maintenance at all to see pavement distress behaviors.

- Routine Maintenance

In this scenario, routine maintenance activities are performed regularly to ensure road user's safety and to prevent road deteriorations. The activities in this study include patching and crack sealing. The program follows M81 contract conditions.

- Crack Seal

Crack seal will be performed when there are cracks on pavement. The intervention is when the crack area is more than 1% of the total area of each section. The maintenance cost including labors, equipment and machines is 40 baht/sq.m.

- Patching

Patching will be performed when there are ravellings and potholes on pavement. The intervention is when the ravel area is more than 1% of the total area of each section or there is more than 1 pothole in the section. The maintenance cost, including labors, equipment and machines, is 1,350 baht/sq.m.

- Routine + Preventive Maintenance

This method includes both routine and periodic maintenance. For routine maintenance, the maintenance scheme is similar to the first method which includes crack sealing and patching. The purpose of periodic maintenance in this method is to prevent pavement from severe distresses (YP Maintenance, 2015). It will be called preventive maintenance.

The activities will be performed in cycle before the occurrence of distresses. Preventive maintenance in this study includes slurry seal and thin overlay. The preventive maintenance best practice scheme is borrowed from Expressway Authority of Thailand.

- Slurry Seal

Slurry seal is pavement friction maintenance. The material for this maintenance is set to be asphaltic concrete (AC40-50) for surfacing and granite for aggregate compaction. This maintenance will perform in 5-mm thickness. The maintenance cost including labors, equipment and machines is 100 baht/sq.m. Slurry seal for preventive maintenance will be carried out every 5 years to maintain required friction and prevent skidding.

- Overlay

Pavement also deteriorates due to its age even if there is no traffic. The thin overlay will set to perform in a 7-year interval to maintain pavement condition. The material for this maintenance is set to be asphaltic concrete (AC40-50) for pavement surface and granite for aggregate compaction. This maintenance will be performed in 3-cm thickness. The cost of maintenance including labors, equipment and machines is 180 baht/sq.m.

- Routine + Corrective Maintenance

This method includes both routine and periodic maintenance. For routine maintenance, the maintenance scheme is similar to the first method which includes crack sealing and patching. The purpose of periodic maintenance in this method is to repair damages on pavement (YP Maintenance, 2015). The activities will be performed after the occurrence of distresses base on conditions setting so it will be called corrective maintenance. The corrective maintenance program follows M81 contract conditions. Corrective maintenance activities in this study include mill and replace.

- Mill and Replace

Pavement will be milled and replaced with new asphalt when IRI is more than 3.0 m/km. Depth of mill and replace is set to be 5 cm. The material for this maintenance is set to be asphaltic concrete (AC40-50) for pavement surface and granite for aggregate compaction. The maintenance cost including labors, equipment and machines is 290 baht/sq.m

3.6 Annual Average Daily Traffic

Traffic volume is the controlled variable as it relates to loads on pavement. It is the important factor for highway/motorway design process. However, traffic volume is forecasted based on current hypotheses which contain many uncertainties for the future. The strategic transportation model often underestimates or overestimates actual traffic volume. The discrepancy in the traffic forecast would certainly affect expected IRI. This research will study the change of IRI due to various levels of traffic volume to understand its effect. Tested scenarios involve cases where traffic is underestimated by 30%, 40% and 50%. Overestimated traffic volume (forecasted volume is more than actual volume) will not be considered since it results in less distress.

3.7 Gross Truck Weight

The study of Department of Transport, South Africa (1997) shows that pavement distresses are mostly caused by illegal loaded heavy trucks. In Thailand, the overloaded trucks can still use motorways if they are allowed by DOH or exempted from weight control authorities. This research will study the change of IRI due to different loads of heavy trucks. The heavy trucks considered are trucks with more than 6 wheels. Tested scenarios involve 10%, 20% and 30% overloaded trucks.

Highway Development and Management Software: HDM was applied as a tool to estimate maintenance cost and to forecast distresses of new motorway. The software was developed by World Bank in the late nineties. The software had continued developing until year 2002, HDM-4 version 2.0 was released. It is the latest version of the software which has been applied in 25 countries around the world. Functions of the current version are forecast distresses on flexible pavement and concrete pavement at grade level, compare pavement conditions due to different maintenance methods and prioritize project such as road improvements and highway constructions. Moreover, it’s also able to estimate costs for benefits of road users. However, the software requires several steps of configuration and calibration before its actual use. Figure 1 shows HDM-4 structure and steps (Kerali, 2000).

Configuration settings are needed in order to receive accurate results for the sample’s area. Then, users can input road network data, traffic data and maintenance information. The HDM-4 will run all modules and show results.

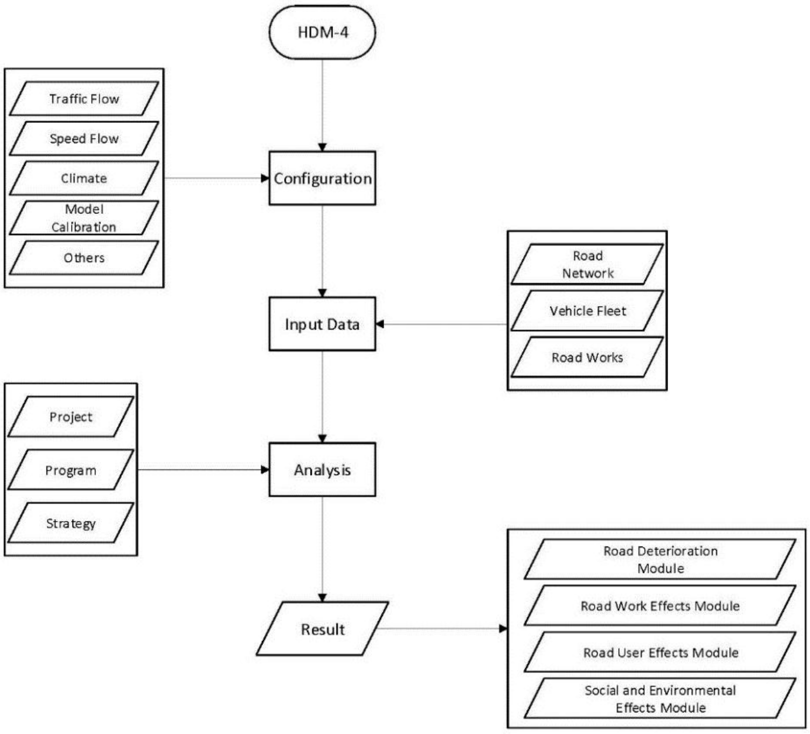

Figure 1 HDM-4 Structure

4. Results and Discussion

The first objective of this study is to identify sensitivity of roughness due to design/maintenance criteria and repetition of axle load. The tested variables are surface thickness, California Bearing Ratio of the subgrade, construction defect (in form of initial IRI), maintenance methods, annual average daily traffic and gross truck weight. This study aims to simplify the relationship of flexible pavement distresses and their causes in terms of sensitivity. Figures 1 - 6 show IRI results from HDM-4 deterioration modules.

As expected, Figure 1 shows that the average IRI increases when pavement was designed to be thinner and decreases when pavement was thicker. Using design thickness 200 mm as based case, the results from HDM-4 show that when surface thickness decreases to 100 mm, average IRI increases by 4%. On the other hand, when surface thickness increases to 300 mm and 400 mm, average IRI decreases by 1% and 2% respectively.

Figure 2 shows that average IRI increases 1% when %CBR was designed to be less than 15%. Results from HDM-4 show that average IRI decreases when %CBR reduces to 10% but there is no change in average IRI when %CBR is more than 15%.

Figure 3 shows average IRI when there were defects on construction. The defects were tested in form of initial IRI. Compared to the base initial IRI 2.00 m/km, the average IRI decreases 3% when initial IRI is set at 1.75 m/km and increases 2% and 3% when initial IRI is set at 2.25 m/km and 2.50 m/km respectively. The result shows that average IRI tends to increase when there were more defects or higher value of initial IRI.

Factors which initiate primary distress from Figure 1 – 3 represent structural number. The structural number (SN) is a load bearing capacity of flexible pavement (Schnoor & Horak, 2012). Average IRI tend to increase when pavement structural number reduces and results in a lower level of service. Surface thickness and CBR have direct variation to a structural number while initial IRI has inversely variation to structural number.

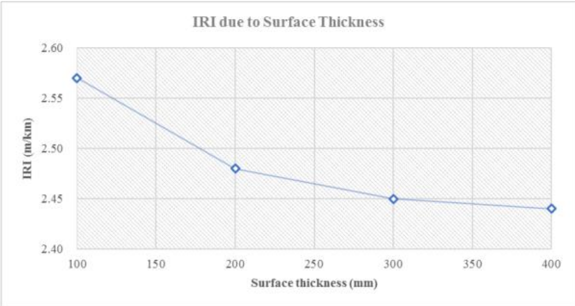

Figure 1 Sensitivity of IRI due to surface thickness

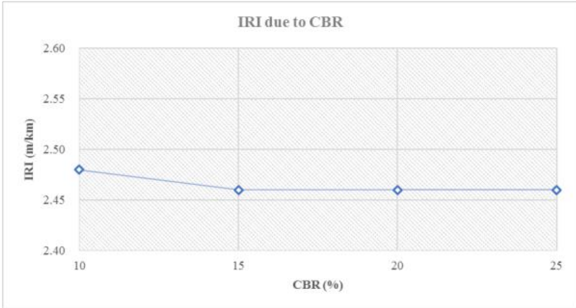

Figure 2 Sensitivity of IRI due to %CBR

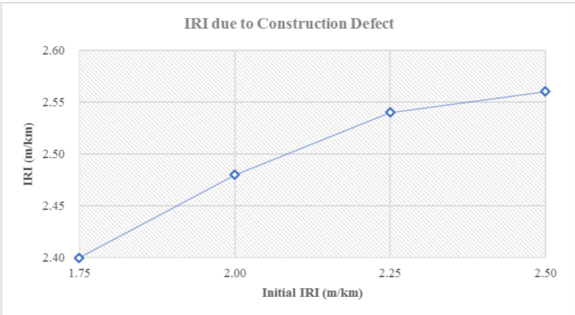

Figure 3 Sensitivity of IRI due to construction defect

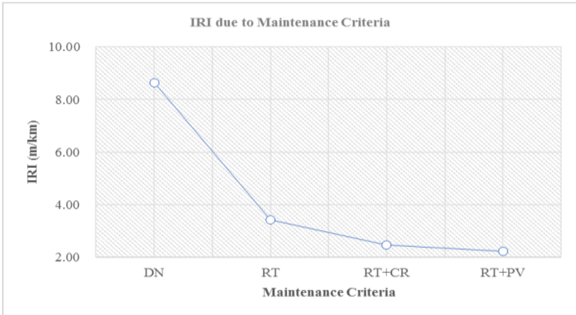

Figure 4 Sensitivity of IRI due to maintenance criteria

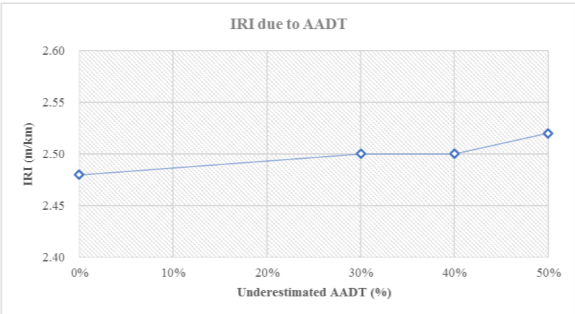

Figure 5 Sensitivity of IRI due to traffic volume

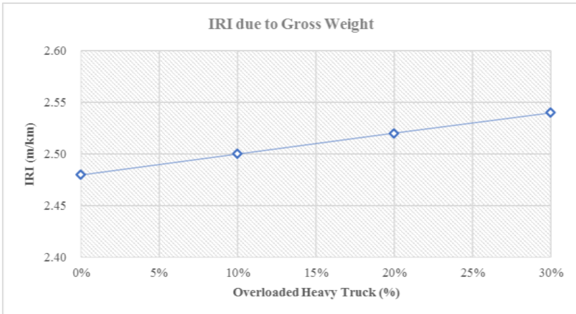

Figure 6 Sensitivity of IRI due to truck gross weight

Figure 4 shows variation of average IRI due to the maintenance criteria. When the pavement is constantly in use without any maintenance, the average IRI is up to 8.6 m/km. When routine maintenance activities such as crack sealing and patching are performed, average IRI is down to 3.4 m/km. However, crack sealing and patching only fix primary distresses on the pavement are cracks, potholes and raveling. Adding mill and replace and overlay which directly fix pavement roughness can significantly reduce average IRI to be less than 3.0 m/km. HDM-4 result shows that maintenance after damage (corrective maintenance) and before damage (preventive maintenance) only causes slight difference in average IRI; 2.48 m/km and 2.22 m/km respectively.

Figure 5 shows sensitivity of average IRI due to changes in traffic volume. Result shows that average IRI increased 1% when traffic volume exceeds the forecasted value by 30% - 40% and increase by 2% when traffic volume is 50% greater than forecasted traffic.

Figure 6 shows effect of truck gross weight on IRI. Result shows that when truck gross weight increases by 10% - 30%, average IRI increases by 1% - 2%.

Factors which initiate primary distress from Figure 5 - 6 represent traffic load acts on pavement. Result shows that both traffic volume and truck gross weight have slightly affected average IRI (1% - 2%). Traffic volume has to exceed 30% of forecasted volume to make 1% change on average IRI and significantly increases when the volume exceeds 50% of forecasted. For truck gross weight, the graph tends to grow higher as more loads were added.

Sayers et al. (1986) has plotted IRI scale compared to vehicle speed. The graph shows that IRI 0.0 – 2.0 m/km is smooth enough for airport runways and super highways. IRI 1.5 – 3.0 m/km represent new pavements. Older pavements normally have IRI in a range of 2.5 to 6.0 m/km. The higher value of IRI represents unpaved and damaged roads (Pavement Interactive, 2019). Combining information from Sayer's IRI graph and level of service concept from Roess (2014), Table 1 shows IRI, speed and level of service as design/maintenance criteria and repetition of traffic load were changed.

Table 1 Speed limit and level of service due to IRI

Criteria	Average IRI (m/km)	Speed (km/h)	LOS
Surface Thickness			
100mm	2.57	90 – 95	A
200mm	2.48	95 - 100	A
300mm	2.45	95 - 100	A
400mm	2.44	95 - 100	A
CBR			
10%	2.48	95 - 100	A
15%	2.46	95 - 100	A
20%	2.46	95 - 100	A
25%	2.46	95 - 100	A
Construction Defect			
IRI = 1.75 m/km	2.40	95 - 100	A
IRI = 2.00 m/km	2.48	95 - 100	A
IRI = 2.25 m/km	2.54	90 – 95	A
IRI = 2.50 m/km	2.56	90 – 95	A
Maintenance Method			
Do nothing	8.64	65 - 70	D
Routine	3.42	85 - 90	A
Routine+Corrective	2.48	95 - 100	A
Routine+Preventive	2.22	95 - 100	A
AADT			
Actual forecasted	2.48	95 - 100	A
+30%	2.50	90 – 95	A
+40%	2.50	90 – 95	A
+50%	2.52	90 – 95	A
Truck gross weight			
Actual limit	2.48	95 - 100	A
+10%	2.50	90 – 95	A
+20%	2.52	90 – 95	A
+30%	2.54	90 – 95	A

The second objective of this study is to observe sensitivity of maintenance budget through lifetime pavement due to design/maintenance criteria and repetition of axle load. Figures 7 - 12 shows maintenance budgets from HDM-4 road work effect modules.

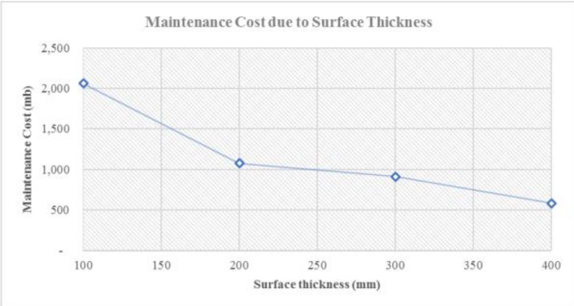

Figure 7 Sensitivity of maintenance budget due to surface thickness

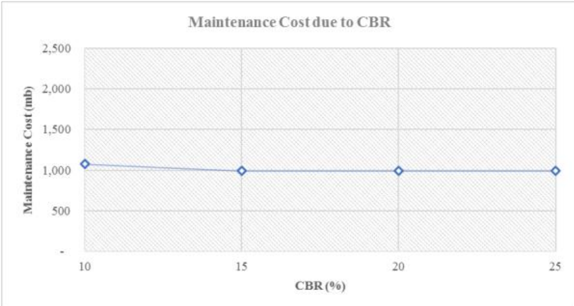

Figure 8 Sensitivity of maintenance budget due to %CBR

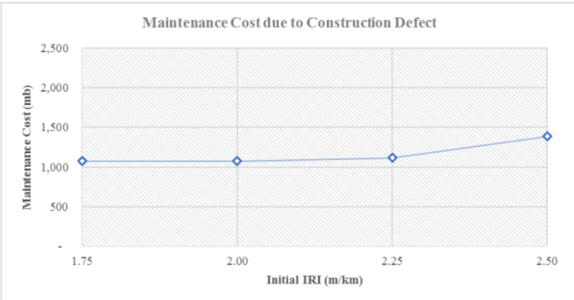

Figure 9 Sensitivity of maintenance budget due to construction defect

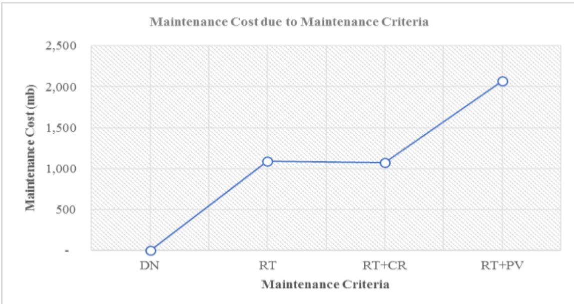

Figure 10 Sensitivity of maintenance budget due to maintenance criteria

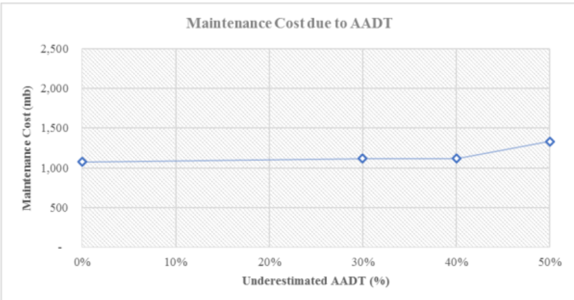

Figure 11 Sensitivity of maintenance budget due to traffic volume

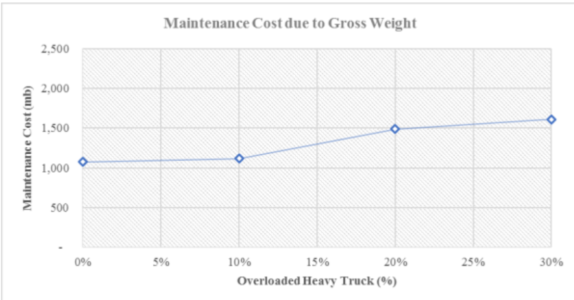

Figure 12 Sensitivity of maintenance budget due to truck gross weight

While Figure 1 shows a slight difference of average IRI value, as Figure 7 shows a significant maintenance budget change as a result of surface thickness alteration. The budget is up to 2,000 million baht when surface thickness is 100 mm. The spending tends to be lower as the surface is thicker. The budget is down to 600 million baht when the surface is designed at 400-mm thickness.

Figure 2 shows slightly different of average IRI when %CBR were changed, and so is Figure 8. The figure shows that maintenance budget of the case using 25% CBR is only 9% less than the case using 10% CBR.

Figure 9 shows maintenance budget when initial IRI changes. HDM-4 result shows that the budget did not change when initial IRI is less than 2.00 m/km. The budget increased 4% when initial IRI is 2.25 m/km and 29% when initial IRI is 2.50 m/km.

Figure 10 shows significant change when the maintenance method was different. Do nothing scheme has zero maintenance cost. Routine scheme, crack sealing and patching, required 1,090 million baht. Corrective maintenance: activity performed after damage occurs, requires 1,074 million baht. Preventive maintenance: activity performed before the damage occurs, is the most expensive method requiring 2,074 million baht throughout the project life of 30 years.

The traffic volume has only 1% - 2% effect on average IRI through 30 years analysis on this pavement according to Figure 11. However, an increase in AADT raises maintenance budget by 4% when the actual traffic exceeds demand forecast by 30% - 40%. When AADT increases up to 50% greater, maintenance budget raised up to 29% compared to the base budget for forecasted traffic.

Gross weight is expected to affect lifetime maintenance budget. Figure 12 confirmed the hypothesis. Maintenance budget costs 4% more when truck gross weight increases by 10%. The budget rose up to 38% and 50% when truck gross weight increases by 20% and 30% respectively.

5. Conclusion

- The sensitivity study of IRI due to the design criteria which results in structural number and pavement strength, shows that the average IRI changed only 1% - 2%. All the cases are in the level of service A. Result shows that surface thickness has significant change to pavement lifetime performance for it resulted in a high range of maintenance budget. The larger amount of budget and small changes in IRI shows that pavement will be damaged and the need more maintenance activities to maintained required quality.
- The sensitivity study of IRI due to maintenance criteria shows that without maintenance activities, motorway's level of service drops to D. On the contrary, if the maintenance activities are regularly carried out, the level of service remains at A. Maintenance budget required for a 30 year-period is 1,000 – 2,000 million baht according to maintenance criteria. The activities performed after damaged occurrence require a lower budget and result in higher IRI. The activities performed before damaged occurrence require more budgets and result in lower IRI.
- The sensitivity study of IRI due to repetition of axle loads shows that underestimated traffic volume 30% - 40% only increased average IRI by 1% and require 4% more for budget than expected. When the actual volume exceeds 50% of forecasted, average IRI was 2% higher and require 24% more budget. The study shows that underestimated traffic volume forecast would not have significant effects on IRI and maintenance budget unless the actual volume is 50% higher than the estimation.

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