Life cycle analysis of Guanxi freeway pavement maintenance interval

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Abstract. Life Cycle Analysis (LCA) is widely used as an environmental impact over the full life cycle of a system. This paper incorporates LCA including impacts that occur throughout the construction, operation, and, maintenance of pavement. The historical freeway database was collected to analyze the pavement life cycle responsible for substantial energy and resource consumption. The analysis was done for Guanxi section as part of Taiwan National Freeway no.3 to compare a long-cycled and short-cycle maintenances. Calibrated HDM-4 and GaBi used to simulate total life cycle conditions. Road network, climate, vehicle fleet, and traffic data were collected and analyzed. Two aspects including Pavement Condition Index (PCI) and International Roughness Index (IRI) were considered for the simulations. The result shows that short-cycle is more acceptable for maintenance in Guanxi section. Environmental analysis by Global Warming Potential (GWP) shows that short-cycle maintenance contributed the smallest GWP with 0.02% up to 0.67% lower than another maintenance type. However, Taiwan focus on increase the level of service of the freeway by setting the minimum IRI value 1.7 m/km. Likewise, this study validates that recent maintenance use in Guanxi section is better than the previous long-cycle, while reduce the maintenance frequency to 1.5 years’ might could increase the effectivity of short-cycle maintenance.

1. Introduction
Taiwan freeway was built in 1971 and completed in 1974, which was adopted the Interstate Highway System of the United States design with the length over 1054 km [1]. 95% of the roads are paved with asphalt [1]. The growing number of road in Taiwan was followed by some maintenance issues like low time interval of maintenance, lack of large-scale maintenance, and budget limitation. Those problems resulted in low pavement condition on the freeway and increase the environmental effect. High traffic volume and low pavement condition found increase the oil consumption which affect the environmental [2]. Traffic consumes more energy than road construction over the same period, depending on whether the traffic [3]. However, since 2013 Taiwan no longer focused on freeway construction and intended to focus on increase the pavement condition standard. It intended to concentrate on short-cycle maintenance instead of long-cycle maintenance. Those two maintenance types have different basic concept on maintenance timing and treatment. Short-cycle maintenance is a principal treatments used to extend pavement life, slow, or reverse pavement deterioration with small amount of pavement material and close maintenance time interval (every 0.5-2 years). It only can be applied for the pavement with minimal deterioration. While long-cycle maintenance extended the pavement life with longer maintenance time interval and greater amount of pavement material. Applied short-cycle maintenance...
indicates better road performance. However, it might increase the environmental effect due to the construction during maintenance. It becomes essential to embracing sustainability as an effective tool to assist in the selection of maintenance treatments for the roads. As an important feature of sustainability, life cycle assessment (LCA) emphasizing environmental factors in the decision-making with more systematic and organized [4]

The Ecological Energy saving Waste reduction Health (EEWH), Taiwan Green Building Rating System serves as a scorecard for the design, construction, and operation of green buildings [5]. Pavement management on its own can contribute directly to some EEWH credits. Increase road density in Taiwan should require a better maintenance and improvement management that considered on environmental effect to minimize total life cycle energy use and vehicle emissions. LCA can be used to identify and quantify the energy consumption and emissions associated with the pavement life cycle [6]. The life cycle assessment starts with a definition of the aim and scope of the study. Life Cycle Inventory (LCI) covers all of the significant environmental burdens from the pavement lifetime and will be quantified and compiled [7]. It followed by Life Cycle Impact Assessment (LCIA) which calculating and presenting the result that supports comparison or further analysis. The concept and working phases of LCA are described in the ISO14040 [7].

This study focuses on Guanxi section (Sta. 42+00 km - Sta. 110+00 km) as part of Taiwan freeway no. 3 and located in the north part of Taiwan. Special case of network level on Sta. 83+00 km - Sta. 89+00 km lane 3 was taken for worst case example in this section. This analysis will include lanes with flexible pavements and not includes some area with rigid pavement. A historical database will be collected and be used for long-cycle and short-cycle maintenance analysis which applied in Taiwan before and after 2013. It has some difficulties in the data collecting and analyzing process. Lack of data available for entire year or at least 4 years, resulted in poor calibration and analysis. Some of the data are available difficult to analyze due to the random pattern. Therefore, forecasting model will be used to fill the empty data and predict data in the future.

HDM-4 used in this simulation analysis to predicts the life cycle pavement conditions. It provides simulation feature for environmental analysis and emissions resulted from the traffic and maintenance process, although rule out the possibility to use another life cycle program like GaBi for more detail analysis.

2. Methods

2.1. Life cycle inventory database
Freeway database includes road network database, traffic database, vehicle fleet database, road work database, and climate database. The data were collected from the beginning of Guanxi section open to traffic up to 2016. It was taken from various sources, including long-term pavement performance database from Taiwan National Freeway Bureau, Electronic Toll Collection (ETC) database, and Central Weather Bureau of Taiwan. Pavement condition and pavement roughness was obtained by conducting road survey by automatic monitoring vehicle. Pavements are responding to the influences of environmental, 2016 climate data from Taiwan Central Weather Bureau use in this analysis.

The geometric design of roads is one of engineering concerned with the positioning of the physical elements such as slope, profile, cross section, and altitude according to standards and constraints. The pavement cross section illustrated in Figure. 1. Five types of vehicles were use in this analysis, includes passenger car, SUV, light truck, heavy truck, and trailer. The traffic data were collected for both northbound and southbound base on hourly, daily, weekly, monthly pattern, also holiday patterns. Traffic composition, volume and growth rates specified as required by the purpose of the study being performed. Annual average daily traffic (AADT) was then count to predict pavement condition progression, fuel consumption and environmental impact on HDM-4 program.
2.2. Data manipulation
Statistical analyses were conducted in this study, including clustering, correlation, and regression analysis. Clustering was used to separate the traffic peak hour and traffic volume based on the time. Correlation and regression analysis were used to find the variables affecting average daily traffic and checked the relationship between two variables, included prediction result and observed data.

2.3. Pavement Condition Prediction Model
Pavement condition affect by geometric, traffic, pavement strength, historical maintenance and environmental condition. Pavement historic data, pavement deterioration, Pavement condition Index (PCI) and International Roughness Index (IRI) use as a parameter to decide the pavement maintenance interval. The simulation analysis uses 4 types of maintenance for 6 km road section (mill 5 cm, repave DGAC 5 cm, PAC 2 cm; mill 11 cm, repave DGAC 10 cm, PAC 2 cm; mill 5 cm, repave DGAC 3.5 cm, PAC 2 cm; repave PAC 2 cm) HDM-4 predicted the life cycle pavement conditions user-specified scenario of circumstances. It will be automatically analyzed the equivalent of two or more project alternatives for each of the road sections. A set of default data will be provided with the system, but users will be able to modify it to reflect Taiwan condition. This study collects 23 years’ data from the beginning of open traffic until 2016. Trial and error used to calibrate the model, due to many variables and few available data. As mentioned by Rohde, prediction can be done by compare the result with actual observed performance and HDM-4 calibration coefficient can be adjust manually to minimize different between predicted and measured distress. Important current network condition that important as monitoring indicators are follows [8]:

- Network length, network utilization distribution and surface type.
- Average network roughness divided by km and vehicle-km
- Network distribution charts
- Road network monitoring indicators.

2.4. Environmental life cycle
Life cycle in pavement included many components from material phase, construction phase, use phase, maintenance phase. It should be analyzed by collect the inventory data that compose by many data includes quantifying energy and raw material requirements, atmospheric emissions, waterborne
emissions, solid wastes and other releases for the entire pavement life cycle [9]. Life Cycle Inventory (LCI) database formed into a flowchart model of processes shows inflows and outflows of the item. The second step is calculating the global warming potential (GWP) to understand their environmental significances. These processes divided into some parameters includes resources, deposited goods, emissions to air, emission to fresh water, emission to sea water, emission to agricultural soil, and emissions to industrial, which describe their impact to the atmosphere. The third steps measure how much Greenhouse gasses (GHG) trapped in the atmosphere. The analysis cycle decides to be 40 years. GaBi and HDM-4 software were used to simulate LCA. The LCA model in GaBi consisted of data from production and construction phase for all of pavement maintenance types, while LCA model in operating phase was done in HDM-4. The environmental analysis framework illustrated in Figure 2.

![Environmental analysis framework](image)

**Figure 2.** Environmental analysis framework.

3. Results and discussion

3.1. The prediction results of pavement condition index

Pavement Condition Index (PCI) is one of an important pavement condition parameter in Taiwan PMS. The pavement distress data collected two times per year or more with manual and Charge-coupled Device (CCD) automatic vehicle. Distress type and the severity are recorded, was then calculate the PCI. Standard PCI 85-100 used to control the pavement condition to stay in excellent condition. The PCI data in this study use two years’ data in a row from May 2015 to May 2017. Figure. 3 shows the PCI progression based on five types of distress progression (cracking, pothole, rutting, raveling, edge
break). All of distresses count as light distress, since Taiwan freeway always stay in excellent condition. However, this result has different progression with the survey result with R-squared 0.3 thus maybe cause by the distress type use for the analysis. The real shows 10 kind of distresses exist in Guanxi section with patching dominated, while HDM-4 only analyzed 5 types of distresses without patching. This factor finds as the HDM-4 software limitation.

Figure 3. PCI progression based on distress progression

IRI is the most important pavement condition indicator to decide maintenance both in Taiwan and HDM-4. Taiwan freeway increase the IRI threshold requirement year by year, and recently applied 1.75 m/km IRI as a standard minimum the pavement to stay in excellent condition. The Figure 4 bellow shows the long-cycle and short-cycle of maintenance before and after 2013. Long-cycle shows done every few years with IRI threshold 3.5 m/km, while short-cycle has been done every year or half year to make the pavement condition stay around 1.75 m/km.

Figure 4. Average IRI.

Calibration was done by compare the prediction of HDM-4 and actual observed performance. Calibration factor adjusted to minimize the difference between the predicted and observed distress and IRI. Trial and error for calibration factor was use to adjust the simulation model. Figure 5 shows the IRI progression for 4 types of maintenance applied in Guanxi section, includes long-cycle and short-cycle (repave PAC 2 cm). The linear regression between observed IRI and predicted IRI from HDM-4 after calibration shows $R^2$ 0.88 which means the model fits the data. It convincing that calibration need to do to make the results become closer with the real condition. The simulation result shows after 20
years use short-cycle maintenance; the pavement condition become not stable due to aging of the under layer. The pavement become worst faster than original condition. This condition similar with maintenance with DGAC 5 and DGAC 3.5. To control this condition, major rehabilitation need to improve the road condition after 20 years. As simple alternative, mill and repave with 10cm of DGAC and 2cm PAC (or another pavement types) also could be apply in this section. The conditions with rehabilitation after 20 years’ cycle can be simulate like in Figure 5.

![Figure 5. IRI progression with rehabilitation alternative.](image)

3.2. Impact analysis of Guanxi section

3.2.1. Material.
This analysis uses four types of surface materials for 6 km road section, with the typical road section in Guanxi section. The analysis conduct per 1 km of road length for one lane. Flexible pavement consists of fine aggregate, coarse aggregate, and bitumen. Road construction involves a huge amount of energy and non-renewable materials. To construct and maintain flexible roads, a considerable amount material that include bitumen, aggregates and additives are needed which consumes a significant amount of energy for the material production, transportation and paving of roads. Emissions from these activities impact air, water and soil pollution, loss of biodiversity and threat on human life. Since Taiwan data only available for 1 ton of aggregate (4.72 kg CO₂-e) [10], another coefficient uses the default coefficient value from GaBi software.

3.2.2. Transportation.
HDM-4 determines effects of emissions and noise, predicts numbers of road accidents and amounts of energy consumption with features to calculate emissions by the road work. Traffic information used to calculate energy used by vehicles. The energy use related to vehicle size, weight, design, age, road characteristics and condition, traffic characteristic, fuel consumption, lubricating oil, tire wear, and vehicle part consumption. Vehicle emissions output includes hydrocarbon, carbon monoxide, nitrous oxide, Sulphur oxide, carbon dioxide, and some particulates. Those pollutants gave effect to the air quality, health, damage the environmental and result on global warming [11].

Project alternative in this research or Guanxi section use the real maintenance type and compare long-term and short-cycle. The real data in this section available in more detail.

3.2.3. Asphalt Production (Maintenance).
LCI study focused on asphalt pavements was initiated in 1998 by European Asphalt Pavement Association (EAPA) and Eurobitume [12]. Meanwhile, Eurobitume carried out a partial LCI study on bitumen covering the life period from crude oil extraction to refinery deposit [13]. During the production of asphalt mixes, there are several factors that may affect energy consumption such as moisture content of aggregate, ambient temperature, as well as binder type. Moisture Content and Gradation Increased
aggregate moisture content increases the amount of energy used to dry the aggregate in the asphalt plant especially for finer aggregates [14]. Thus, temperature and aggregate size influenced the amount of fuel needed to dry/heat.

3.2.4. Construction.
The construction phase includes mixture paving and compacting. In this case equipment data was taken from many companies that related to the mixture paving and compacting. Engine power and fuel consumption were obtained. In the life cycle inventory calculations of asphalt pavers only the direct fuel consumption and the production of the corresponding amount of fuel have been taken into account based on material weight and total layer (5 cm per layer). Compaction process apply based on density and requirement void by performing rolling patterns on a test strip. There is no standard for determining the number of passes and coverage location by the compactor instead use experience. However, the default compaction setting from GaBi used in this analysis with consider the layer thickens.

Impact analysis includes total flows and emission for maintenance and operation phase. It includes milling, production, laying, compaction, and transportation. Asphalt milling flow result show that road section which applied 11 cm milling contribute more emission flow due to double milling process and more transport flow to discard the disposal material. Flow result for asphalt laying and compaction shows much shorter than another maintenance activity, since it is only use some vehicles on the location.

Asphalt production phase simulation result present that asphalt production requires a lot of natural resources and stockpile goods. It is required average 50.8 % of the total flow. Despite of material needed, this process shows contribute much effect to the air, fresh water and sea water. Emission to air dominated by CO$_2$ that contribute 50.5% from the emission to air followed by NO, CO, NO$_2$, SO$_2$, CH$_4$ and another particle. This process also affects the water by the needed of water on production process and for cleaning the equipment. Moreover, pavement also found contaminate the storm water and groundwater [15]. This study found that pavement production contributes in emission to water around 47% and 0.15% to sea water.

Every kilometer of road contribute different emission based on material use and maintenance type use on the road. Sta. 83+00 shows contribute bigger emission compare with another mileage caused it to repave the road more with 10 cm DGAC, while another road dominate with repave 5 cm or 3.5 cm DGAC. Total flow for short-cycle analysis for asphalt production much lower than total flow on long-cycle maintenance. It worth to do to reduce emission per year analysis. However, Figure 6 shows different result for the flows of long-cycle and short-cycle in 40-years analysis. Short-cycle maintenance that conduct every year will contribute more emission compare with another types of maintenance with longer cycle. It shows asphalt production flow of short-cycle maintenance is two to three times more than asphalt production flow of long-cycle.

![Figure 6. Total flows for asphalt production activities in 40 years.](image-url)
3.2.5. **Operation Phase.**

This analysis considers the transportation during operation phase of Guanxi section. Analysis conducted by HDM-4 which considered AADT, equivalent single axle load (ESAL), road geometric and pavement conditions. The fuel consumption carbon footprint value in Taiwan for gasoline and diesel marked to be 0.671 and 0.752 respectively [10]. Operation phase emitted more GHG compared to another phases due to high volume of traffic. Pavement roughness are identified give influence to the vehicles’ oil consumption. This analysis includes HC, CO, NO, SO$_2$, CO$_2$, Pb, and particle. Figure 7 presented the GHG emission in Guanxi section. The GHG quantities shows different per kilometer road affected by road length, AADT, ESAL, road geometric, rise and fall. Every lane has different GHG emission rate based on the vehicle proportion. However, the result per lane shows almost similar proportion. Only lane 1 and 2 have more Pb that emitted from small vehicle that use gasoline.

![Figure 7. GHG emission on Guanxi section](image)

3.3. **GWP of Guanxi section**

The GWP for milling process in six km road of Guanxi section depend on the section length. While transportation GWP depend on the layer thickness. Figure. 8 illustrated the total GWP for production phase in six kilometers of Guanxi section. It shows that 80% GWP for production comes from transportation of truck when take the materials from asphalt plant followed by fine aggregate production, mixing process, bitumen refinery, and coarse aggregate production. Transportation is a sector where measures need to be taken in order to reduce the energy demand and environmental impact.

GWP for construction phase consist of GWP for pavement laying and pavement compaction presents in Figure 8. In this result can be seen that the GWP is mostly affected by laying process. GWP for laying affected by total materials use for the construction, while compaction affected by the thickness of construction.

Laying and compaction process was design for every 5-cm layer. Repave for 5 cm and 3.5 cm shared same energy, however repave with 10 cm layer need two times energy which reaches 125.00 kg CO$_2$-e. This analysis shows that different types of maintenance proportion and road length resulted in different GWP.

This session focus on environmental impact of different maintenance alternatives on Guanxi section as part of Taiwan National Freeway No. 3. This simulation was conducted on GaBi and HDM-4 software for life cycle phases, especially production and construction (maintenance) phase and use phase. It conducted LCI, LCIA and calculate GWP to evaluate the different maintenance alternatives and maintenance cycle. Comparison analysis between long-cycle maintenance and short-cycle maintenance
in 40 years shows that average short-cycle give slightly higher environmental impact compare with long-cycle as shown in Figure. 10, since it is conduct in every year. However, when it combined with the vehicle operation, short-cycle maintenance contributed the smaller GWP with 60.8% lower than another maintenance type. Maintenance interval, material consumption and pavement roughness are identified give influence to the environmental. Moreover, further analysis need to make sure the short-cycle worthy to conduct in Taiwan freeway to replace long-cycle maintenance.

**Figure 8.** Each km GWP for production phase in Guanxi section.

**Figure 9.** Each km GWP for construction in Guanxi section.
4. Conclusion

This research aims to collect historical pavement life cycle database and predict pavement life cycle of Guanxi section. Two different maintenance interval (short-cycle and long-cycle) used to predict road network performance in different maintenance standards. Environmental effect due to pavement maintenance process and increase in vehicle number was then considered and analyzed by LCA. In accordance with policy objectives within environmental constraints. This research concludes:

- Transportation or operation phase emitted more GHG than the asphalt production or maintenance. Pavement roughness are identified give influence to the vehicles’ oil consumption.
- Short-cycle is more acceptable for maintenance in Guanxi section, which resulted in better IRI value and pavement condition.
- Environmental analysis by GWP shows that short-cycle maintenance contributed the smaller GWP with 60.8% lower than another maintenance type. Maintenance interval, material consumption and pavement roughness are identified to influence to the environmental.
- Reduce the maintenance interval to 1.5 years might decrease the cost of short-cycle maintenance with similar pavement condition. This maintenance method could be used as future maintenance strategy in another freeway sections in Taiwan.
- When inquiring about life cycle analysis, more precisely define the big continuous local database in continuous time is required to maintain the better calibration and simulations.

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