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Life Cycle Assessment of Expressway Passenger Transport Service: A Case Study of Thailand

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***Abstract*—**This research work is concerned with the life cycle assessment (LCA) of an expressway, as well as its infrastructure, in Thailand. The life cycle of an expressway encompasses the raw material acquisition phase, the construction phase, the use or service phase, the rehabilitation phase, and finally the demolition and disposal phase. The LCA in this research was carried out using CML baseline 2000 and in accordance with the ISO 14040 standard. A functional unit refers to transportation of one person over one kilometer of a 3-lane expressway with a 50-year lifetime. This research has revealed that the construction phase produced the largest proportion of the environmental impact (81.46%), followed by the service, rehabilitation, demolition and disposal phases and transportation at 11.97%, 3.72% 0.33% and 2.52%, respectively. For the expressway under study, the total carbon footprint over its lifetime is equivalent to 245,639 tons CO2-eq per 1 kilometer functional unit, with the phases of construction, service, rehabilitation, demolition and disposal and transportation contributing 153,690; 73,773; 3693, 755 and 13,728 tons CO2-eq, respectively. The findings could be adopted as a benchmark against which the environmental impacts of future similar projects can be measured.

***Keywords*—**Environmental impact assessment, Life cycle assessment, LCA, Expressway passenger transport service, Carbon footprint, Eco-friendly expressway.

I. Introduction

The current environmental impact assessment of an expressway is based largely on the Environmental Impact Assessment (EIA), the practice which includes the environmental impacts attributable only to the provision of the expressway services [1]. In fact, the entire life cycle of an expressway (i.e. from the construction phase through the demolition and disposal phase), not just the service provision phase, should be taken into consideration when undertaking an environmental impact assessment in order to obtain more comprehensive assessment results. These results could be further developed into a database for evaluating the construction of expressways in the future to allow for the mitigation of the environmental impacts, the efficient deployment of resources, and the most eco-friendly use of energy [2].

This research utilizes the life cycle assessment (LCA) approach to assessing the environmental impacts of an expressway. The approach takes into account the use of resources and energy as well as the production of pollution throughout the expressway life cycle from its construction, service, rehabilitation, to finally demolition and disposal. The aim of the LCA adoption is to establish a guideline for selection of appropriate alternatives that enable efficient use of resources and fuels and thereby an eco-friendly expressway.

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II. Material and Methods

The LCA in this research involves the environmental impact assessment throughout the life cycle of an expressway in Thailand, in accordance with the ISO 14040 standard [3]. The life cycle begins with the acquisition of raw materials, the production of construction materials, the construction of the expressway, the provision of service, the rehabilitation to the demolition and disposal. The impact assessment is performed using SimaPro 7.2 CML baseline 2000 [4]. The impact categories consist of abiotic depletion (ADP), acidification (ACP), eutrophication (EUP), global warming (GWP), ozone layer depletion (ODP), human toxicity (HUP), fresh water aquatic ecotoxicity (FWAP), marine aquatic ecotoxicity (MAEP), terrestrial ecotoxicity (TEP), and photochemical oxidation (POP). The inflow indicator method in SimPro7.2 was utilized to identify the most influencing impact categories of each phase throughout the life cycle of the expressway before the sensitivity analysis technique was applied for interpretation. Strategies to mitigate the effects on the environment of the most influencing impact categories could subsequently be formulated based on the analysis results.

A. Goal and Scope

The goal and scope of LCA is typically to provide a description of the system boundaries and a functional unit [5]. The goal and scope of this research are to assess the environmental impacts throughout the life cycle of an expressway in Thailand. The cycle starts from the construction phase, the service phase, the rehabilitation phase, to the demolition and disposal phase. The acquisition of raw materials and the manufacturing of construction materials for the expressway construction are also included in the study. In addition, as the transportation of raw materials and construction materials and the machinery use are required in the construction phase, the maintenance phase and the disposal phase; the CO2 emissions of these three phases are investigated. For the service phase, this research focuses on the on-ramp and off-ramp elevated sections of the expressway, without assessing the impacts of queue length of the ground-level traffic connected to the expressway.

B. Functional Unit

In LCA, a functional unit denotes a quantitative description of the service performance of the investigated product system [6]. The functional unit is translated into reference flows, which are specific product flows for each of the compared systems required to produce one unit of the function [5]. The functional unit of expressway construction involves the lifetime of structure of 50 years [7]. and the time period of rehabilitation (surface overlay) of 5 years [8] for travels on three lanes of expressways in cars with, on average, a 2000 cc displacement engine fuelled by gasohol 95 benzene and two passengers per car. In this research study, the selected routes are the inbound and outbound lanes of the Ramindra-At Narong elevated expressway since they have the same origin-destination, the same number of lanes as well as the same travel distance as illustrated in Fig. 1 [9].

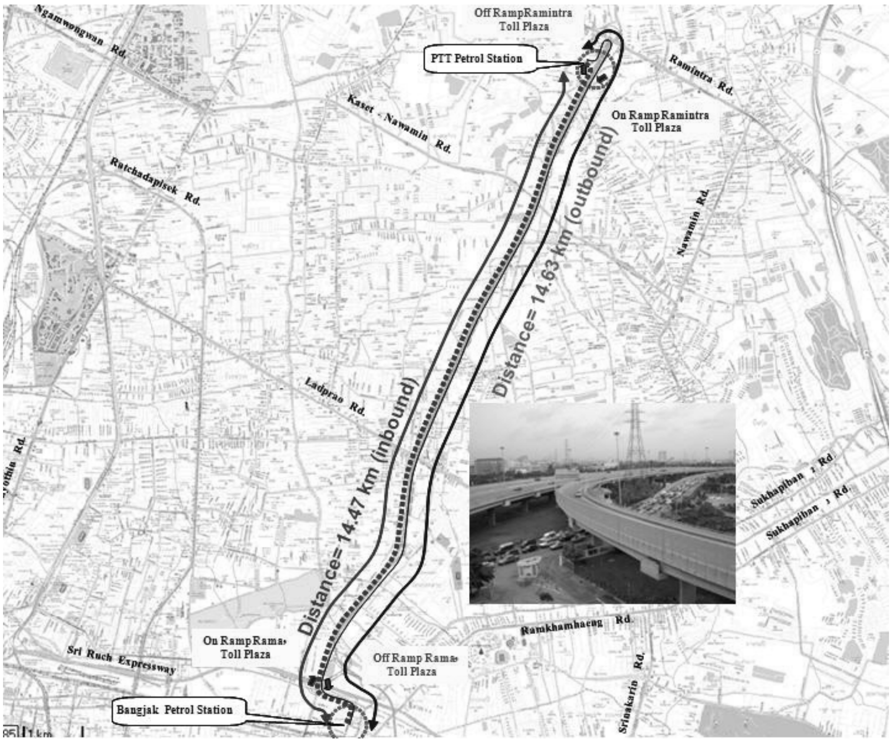


Fig. 1 The selected routes on the elevated Ramindra to At-Narong expressway.

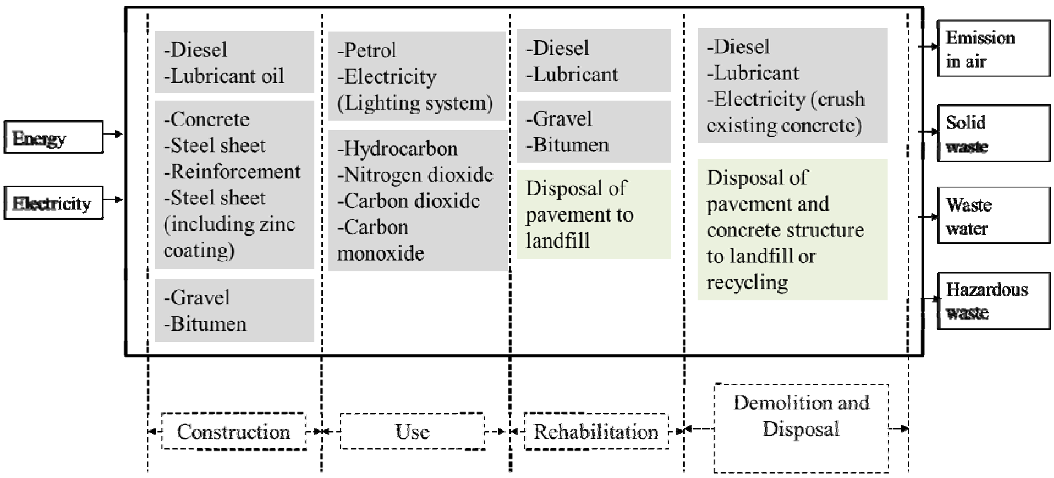


Fig. 2 Product system of the life cycle assessment of the expressway

The product system comprises three-lane elevated roads of 12.70m. in width, 10m in height from the ground and 30m. in length for the girder. The structure of the elevated parts of the expressway is of the reinforced concrete structure, similar to that of a bridge, and contains two mains parts, i.e. superstructure and substructure. The superstructure consists of reinforced concrete slabs and precast I-girder systems. The substructure comprises the cross beam, pier and footing on a group of piles. The expressway pavement is of asphaltic concrete of 8 mm. in thickness.

C. System Boundary

According to ISO 14041, the system boundary separates between the product system and the environment. The product system comprises a number of process units which are classified as either the production of raw materials, energy, manufacturing or transportation [3]. The product system of this research is a simulation that consists of several process units or activities. The entire process units are linked by the input-output flow and the product flow. The environmental impacts of the construction, the rehabilitation, and the demolition and disposal phases of this research are assessed based on the activities performed with heavy machinery fuelled by diesel [10], [11] and with lubricating oil use [12]. For the service phase, the fuel consumption and emissions to the air by a probe vehicle are determined by the driving cycle method [13]. The product system of this study is in accordance with the process illustrated in Fig. 2.

D. Construction of Expressway

The procedures for data collection on the expressway construction vary with construction activities. The main activities in the construction phase include those that are carried out in the pre-construction (e.g. site clearance, cut and fill, mobilization); that consume energy (fossil fuels); that use the materials; and that require transportation. The expressway construction process is as follows [14]: (1) clearing and grubbing; (2) the structure work of the elevated structure, the approach structure and the bearing unit. The elevated structure includes 0.8-meter-diameter bored piles, footings, piers, cross beams, I-girders, and deck slabs. The approach structure encompasses the bored piles for bridge approaches, reinforced concrete (RC) slabs on pile, RC walls, RC beams and approach girders. The bearing unit consists of 0.26x0.26m square driven piles, mat footing and RC slabs on pile; (3) paving with asphaltic concrete; and (4) installation of the street lighting system and other fittings.

E. Service of Expressway

The service or usage of an expressway produces a multitude of environmental impacts, e.g. air pollution, noise pollution, light pollution, odor and vibration from traffic. Of particular concern is the air pollution caused by the pollutants from the engine combustion of travelling vehicles, e.g. carbon dioxide (CO2), hydro carbons (HCs), nitrogen oxide (NOx), and carbon monoxide (CO). The emission of pollution from vehicles is calculated using the power-based motor vehicle model, which is the evaluation of traffic flow, car following behavior, stability analysis and following speed as well as acceleration behavior[13]. The model assesses the driving behavior based on the data collected second-by-second with a GPS device. The collected data reflect the actual traffic under the stop-and-go condition or traffic congestion [15].

The models of fuel consumption and emission are derived from the trip data in the GPS device's data logger. The trip data are the driving cycle data, which consist of a series of cruises, accelerations, decelerations and idling times under actual traffic conditions. The data collection period started from July to September 2010 on both the inbound and outbound routes during the A.M. peak, off-peak and P.M. peak. The average driving cycle distance (inbound-outbound) was 14.55 km., which represents the daily travel under the present traffic condition on the elevated Ramindra-At Narong Expressway.

F. Pavement Rehabilitation

The overlay pavement method is typically employed in pavement rehabilitation. The method involves the following activities [14]: (1) Surveying the alignment and level of the road to be paved; (2) paving with tack coat 0.4-0.8 liter per square meter of the road; and (3) overlaying with hot mixed asphalt and re-paving with the spreader before compacting with a tender steel wheeled roller and then a pneumatic tired-wheeled roller.

G. Demolition and Disposal

The demolition and disposal phase of the superstructure and substructure requires energy for heavy machinery and transportation associated with the removal of on-site materials and concrete structures as well as the disposal or recycling of the materials. The demolition and disposal phase consists of the following activities [14]: (1) The removal of the superstructure, i.e. removal of the pavement, RC slab and I-girder; (2) the removal of substructure, i.e. removal of the RC structures of cross beams, piers and footing; (3) the removal of on-ramp and off-ramp, i.e. removal of pavements, RC slabs, beams, columns, walls of approach slabs and footing; and (4) loading the rubble of the above activities onto trucks to the crushers where the rubble is crushed to smaller sizes prior to transportation to landfill or being recycled.

H. Transportation

This phase encompasses the in-country road transportation of materials by 16-ton trucks to the elevated expressway construction site during the construction and maintenance stages (excluding the packaging of construction materials for transportation). It also includes the transportation of materials from the elevated expressway construction site during the stage of demolition (including transportation of recyclable materials by trucks to the recycling facilities). The transportation distances in this research were estimated using the Google map (http://maps.google.co.th/) based on one-way trips (i.e. without empty return trips).

I. Analysis of Life Cycle Inventory

The life cycle inventory (LCI) analysis is carried out to determine the quantities of materials used in all construction activities and of fuel and engine oil for heavy machinery during the construction process, the maintenance and rehabilitation of asphalt concrete pavements, and the demolition and disposal [7]. Thus, the LCI elements of each phase are materials, energy, electricity, emission to air, and solid waste.

The data collection in the construction, rehabilitation, and demolition and disposal phases of the expressway follows the process-based modeling approach. The input-output quantities of materials are calculated from bills of quantities (BOQ) and the technical specifications of materials in the expressway construction feasibility study final report [14]. The quantities of energy and lubricating oils used were estimated from the running time of the machinery in all activities for the construction, the rehabilitation, the demolition and the disposal of the expressway. The life cycle inventory data, as presented in Table I, on the material production, associated energy use, and leachate concentrations were derived from the Simapro program. For the service phase, the GPS device with data logger was installed on the probe vehicle to record second-by-second traffic data on the Ramindra-At Narong elevated expressway, as shown in Fig. 2 The collected data sets were transferred to a workstation to integrate with the power-based model [16] to estimate travel time, distance trajectories, fuel consumption, and pollutant emissions.

TABLE I
LIFE CYCLE INVENTORY DATA FROM SIMAPRO AND THAI DATABASES

Item	Material/Process	Database in SimaPro	Source of data
1	Concrete	Concrete not reinforced ETH	ETH-ESU 1996 [16]
2	Formwork	Reinforcing steel, at plant/kg/RER	Ecoinvent unit process [3]
3	Reinforced steel	Reinforcing steel, at plant/kg/RER	Ecoinvent unit process [3]
4	Zinc coating	Zinc coating	ETH-ESU 1996[16]
5	Fuel for heavy machinery	Diesel in building equipment	ETH-ESU 1996[16]
6	Electricity for street lighting*	Electricity in Thailand	Thai National Life cycle Inventory Database [17]
7	Landfill for asphalt	Asphalt to HA chemical landfill U	ETH-ESU 1996[16]
8	Gravel	Gravel I	IDMAT 2001[16]
9	Bitumen	Bitumen refinery CH U	ETH-ESU 1996 [16]
10	Fuel for passenger cars*	Gasoline in Thailand	Thai National Life cycle Inventory Database [17]
11	Diesel*	Diesel in Thailand	Thai National Life cycle Inventory Database [17]
12	Transportation 16 tons*	Truck 16 t	Thai National Life cycle Inventory Database [17]
13	Gasoline *	Gasoline in Thailand	Thai National Life cycle Inventory Database [17]
14	Tap water*	Tap water in Thailand	Thai National Life cycle Inventory Database [17]
15	Disposal of RC. Slab pavement	Disposal, building, concrete gravel, to final disposal/CH U	Ecoinvent unit process [3]
16	Disposal of substructure	Disposal, building, reinforced concrete, to final disposal/kg/CHU	Ecoinvent unit process [3]
17	Disposal of bitumen pavement	Disposal, building, bitumen sheet, to final disposal/kg/CH	Ecoinvent unit process [3]
18	Concrete to landfill	Concrete (inert) to landfill U	ETH-ESU 1996 [16]

Note: *The LCI from the field data or existing research works in Thailand.

J. Energy Consumption of and Emission from Heavy Machinery

Heavy machinery is normally deployed in all phases from construction, rehabilitation, to finally demolition and disposal of an expressway to minimize labor use and expedite the completion of the project. Examples of the heavy machinery are bulldozer, vibration hammer, 50-to-60-ton-capacity crane and bucket, excavator, mobile crane, mobile concrete pump, mobile concrete vibrator, self-powered paver, tender steel wheeled roller, and bituminous distributor. In addition, the heavy machines require lubricating oil and fuel, the quantities of which can be determined respectively with (1) [11] and (2) [10]. The air pollution from the heavy machine is calculated with (3) [10].

$$O = \frac{Hp \times Eff \times 0.006^{*}\ lb/hp\text{-}hr}{7.4\ lb/gal} + \frac{C}{T} \quad (1)$$

$$E = \sum \frac{HP \times LF \times EF \times Tons}{Prod} \quad (2)$$

$$ER = \sum Tons \times FE \times \frac{EV}{VOL} \times \frac{1}{Prod} \quad (3)$$

where O is the quantity of lubricants in gallons per hour, HP is the horsepower of the machine (according to the manufacturer's specification), Eff is the operating factor, C is the capacity of the crankcase(gal). T is the number of hours between oil changes and the common time interval for an oil change is 200 hours after the last change for a large capacity fuel tank of manual heavy machinery, E is the emission, LF is the loading factor of the machine, EF is the emission factor. ER is the energy required, Tons is the weight in metric ton of the materials processed, FE is the fuel economy. Prod is the productivity of a machine (i.e. material carried per load × cycles per hour), EV is the energy value of fuel, and VOL is the volume of oil used (according to the manufacturer's specification). Furthermore, the asterisk (*) in (1) indicates that the quantity of oil consumed per horsepower hour between changes is 0.006 lb.

K. Assessment of Fuel Consumption and Emission to Air in the Service Phase

The data on fuel consumption and emission to air in the service phase are in the form of second-by-second velocity and acceleration. The data are inputs of the power-based motor vehicle model (i.e. (4)-(6)) to determine the fuel consumption and air pollution emission rates [18].

$$\frac{dE(X)}{dt} = \alpha + \beta_1 R_T v + \left[\frac{\beta_2 M a^2 v}{1000}\right]_{a>0}, R_T > 0 \quad (4)$$

$$\frac{dE(X)}{dt} = \propto, R_T \leq 0 \quad (5)$$

$$R_T = b_1+b_2v_2+\left(\frac{M_a}{1000}\right)+g\left(\frac{M}{1000}\right)\frac{G}{10} \quad (6)$$

where E(x) is the rate of fuel consumption (ml/s) or emission (g/s), RT is the total tractive force required to drive the vehicle (4), (5), M is the vehicle mass (kg), and α is the idling fuel consumption/emission rate. β1 is an engine efficiency parameter (mL or g per kJ) relating fuel consumption/emission to energy provided by the engine, β2 is a second efficiency parameter (mL or grams per kJm/s2) relating fuel consumption/emission during positive acceleration to the product of inertia and acceleration, v is the velocity (kph), and a is the acceleration (mpss). RT can be computed according to (4) and (5), where g is the gravitational acceleration (m/s2), G is the percent gradient, b1 is the rolling resistance, and b2 is the aerodynamic resistance. The capacity of all power used to drive the vehicle (RT) is determined by (6). The unit inventory fuel consumption or emission loading of vehicles (g/km) can be calculated by multiplying the number of vehicles (Veh, vehicle) by the rate of fuel consumption (FC, ml/s) or emission (EM, g/s) and travel time (T, s). In other words, fuel consumption or emission loading (g/km, ml/km) = Veh (vehicle) × FC (ml/s/vehicle) or EM (g/s/vehicle) × T(s).

L. Impact Assessment by CML Baseline 2000

The impact assessment carried out using CML baseline 2000 involves the use of quantities of pollutants as inputs to determine the potential environmental impacts. The CML baseline 2000 method consists of two steps [6]. In the first step, categorize the impacts and characterize the relationships between the linear potential impacts, the latter of which converts the quantities of various types of impacts under each category into equivalent quantities of a reference impact, thereby yielding one single impact indicator for each impact category. Each impact indicator retains the unit of measurement of the quantity as shown in (7). The potential environmental impacts can be categorized into 10 categories: ADP, ACP, EUP, GWP, ODP, HUP, FWAP, MAEP, TEP and POP. In the second step, the impact profiles of the ten potential impacts are normalized according to (8) to obtain the impact indicators which are then compared with their corresponding annual global environment impact indicators and thereby are dimensionless.

$$EP_J = \sum (Q_i x EF_{ij}) \quad (7)$$

where EPj is the environmental impact potential for any types of impact (kg substance equivalent), Qi is the quantity of j substance emitted (kg substance), and EFji is the equivalent factor of j substance causing the j environmental impacts (kg substance equivalent/kg substance j)

$$NP = WF_j x EP \quad (8)$$

where NP is the normalized environmental impact potential of any j environment after weighted ($year^{-1}$) and WFj is the weighting factor with emphasis on any j environmental impacts in any targeted year.

M. Life Cycle Interpretation

The life cycle interpretation to identify the sources of the ten impact categories of each phase to minimize the environmental impact is carried out as follows: 1) Determine the most influencing impact categories of each phase using the flow indicator method, and 2) the sensitivity analysis method is then applied to the most influencing impact categories of each phase to examine their uncertainties. In this research, the uncertainties of each phase's most influencing impact categories were varied between -25%, -15%, 15% and 25%, ceteris paribus, to assess the trend of LCA process improvement.

III. Results and Discussion

The components of an expressway that require most construction materials and thus affect the use of resources throughout its product life cycle are one 30-meter-long pier per span and the approach slab bearing units at the on-ramp and off-ramp approximately 48.4 meters and 73.2 meters in length, respectively[14]. Large proportions of resources are used for the construction of the substructure, in which 9,488m^3 of concrete (92% of the total concrete requirement); 5,368 m^2 of all formwork (54% of the total formwork) and 709,332 kg of reinforcement (88% of the total reinforcement) for concrete are required. Table II presents the contributions of main materials to each construction component.

In Table III, the functional unit of LCI analysis is one kilometer of 3-lane expressway with a 50-year lifetime. The primary and secondary data are inputs of SimaPro7.2 to perform the life cycle assessment. As shown in the table, the assessment starts from the material acquisition, the construction phase, the service phase, the rehabilitation to the demolition and disposal phase.

TABLE II
CONTRIBUTIONS OF MAJOR MATERIALS TO EACH CONSTRUCTION COMPONENT

Item	Description	Concrete (m^3)	Formwork (m^2)	Reinforcement (kg)	Asphaltic Concrete (m^3)	Cut-Fill (m^3) Cut	Fill
1. Elevated Segment - span 30 meters (Traffic area=12.7×30=381 m^2)							
1.1	Superstructure						
1.1.1	Deck slab	76	402	22,516	19	-	-
1.1.2	Girder	157	1,410	34,240	-	-	-
	Total 1.1	233	1,812	56,755	-	-	-
1.2	Substructure						
1.1.3	Cross beam	106	154	28,242	-	-	-
1.1.4	Pier	39	86	6,117	-	-	-
1.2.1	Footing	143	68	14,432	-	25	33
1.2.2	Pilling	2,111	-	84,327	-	-	-
	Total 1.2	2,399	307	133,117	-	-	-
2. Approach slab - span 48.4 meters (Traffic area=12.7×48.4=615 m^2)							
2.1	Superstructure						
2.1.1	Slab	177	590	26,001	30	-	-
2.1.2	Beam	233	1,400	11,081	-	-	-
	Total 2.1	410	1,990	37,082	-	-	-
2.2	Substructure						
2.1.3	Column	22	144	6,473	-	-	-
2.2.1	Wall	203	1,334	22,510	-	-	-
2.2.2	Footing	123	260	12,436	-	709	-
2.2.3	Pilling	6,032	-	240,934	-	-	-
	Total 2.2	6,379	1,738	282,353	-	-	-
3. Bearing unit - span 73.2 meters (Traffic area=12.7×73.2=930 m^2)							
3.1	Superstructure						
3.1.1	Bearing unit Slab	235	784	5,570	39	-	-
3.2	Substructure						
3.2.1	Bearing wall	90	3,254	282,526	-	-	-
3.2.2	Pilling	272	-	-	-	-	-
3.2.3	Mat footing	347	69	11,335	-	347	-
	Total 3.2	709	3,323	293,861	-	-	-
Total	Superstructure (1.1+2.1+3.1)	879	4,587	99,408	88	-	-
	Substructure (1.2+2.2+3.2)	9,488	5,368	709,332	-	1,081	33
	Total	10,367	9,955	808,739	88	1,081	33

TABLE III
INPUT AND OUTPUT PER FUNCTIONAL UNIT OF THE LIFE CYCLE ASSESSMENT BY PHASE OF THE EXPRESSWAY

Item	Inventory	Unit	Phase Construction	Service	Rehabilitative	Disposal
1	Material					
1.1	Concrete	Tons	209,377			Except pilling, all input mass were treated as waste in disposal phase.
1.2	Formwork (thick 2.3 mm)	Tons	1,269			
1.3	Reinforcements	Tons	6,294			
1.4	Steel (street lighting column)	Tons	7			
1.5	Galvanize coating	m2	204			
1.6	Gravel	Tons			18,161	
1.7	Bituminous	Tons			6,410	
1.8	Tap water	m3	27,637,794			
2	Energy					
2.1	Fuel Consumption (diesel)	MJ	1,093,732,508*		8,576,644*	5,352,370*
		l	30,046,936		23,562	147,040
2.2	Gasoline	Tons		102,953**		
2.3	Lubricating oil	l	1,391,405		4,039	9,503
3.0	Electricity	kWh		1,423,500***		231,851
4.0	Emission to air					
4.1	HC	kg		298		
4.2	Nox	kg		372		
4.3	CO	kg		10,628		
4.4	CO2	kg		333,565		
5	Solid Waste					
5.1	Existing Asphaltic concrete	m3			54,868,064	2,386
5.2	Existing concrete	Tons				39,739
6	Transportation					
6.1	30-t Truck	tkm	26,693,188			
6.2	10-t Truck	tkm			197,753,503	
6.3	10-t Truck	tkm				1,135,442

Remarks:
1) *Exclude transportation of material to construction site and assume all heavy machinery during the construction phase is fuelled by diesel.
2) **Assume a fuel density of 1.333 E+10 l/ton and a freeway traffic condition to determine the fuel consumption and emission to air using the driving cycle method.
3) ***Electricity for the street lighting system in the service phase.

In the service phase, the average daily traffic volume is 73,336 trips (1-way, 3 lanes). The average speed on the expressway is 70 kph (maximum speed 90 kph) with an average acceleration of 0.05 mpss (S.D. = 0.16). The driving condition is that of stop-and-go at the merging areas of entrance and exit ramps. Fig. 3 illustrates the free flow driving condition with varying velocity.

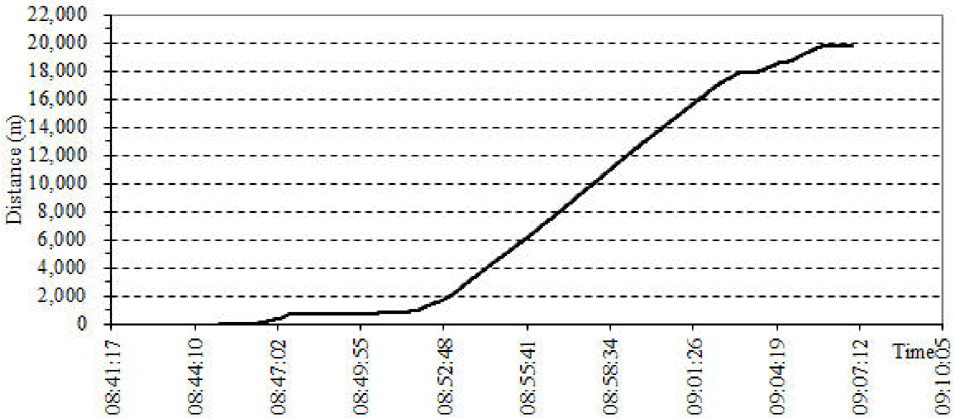


Fig. 3 Example for Distance Trajectory (Outbound)

A. Normalized Environmental Impacts

As presented in Table IV, the average normalized environmental impacts of the expressway for the construction, service, rehabilitation, demolition and disposal phases and transportation are 81.46, 11.97, 3.72, 0.33 and 2.52%, respectively. ADP is mostly attributable to the fuel consumption (gasoline) and emission from the engine combustion in the service phase. On the other hand, the fuel consumption (diesel) and emission from heavy machinery in the construction phase are largely responsible for EUP, GWP, ODP, HUP, FWAP, MAEP, and POP. The steel reinforcement production in the construction phase contributes the most to TEP.

TABLE IV
NORMALIZED POTENTIAL ENVIRONMENTAL IMPACTS BY IMPACT CATEGORY OF EACH INDIVIDUAL PHASE OF THE EXPRESSWAY LIFE CYCLE IN THAILAND

Impact category	Environmental impact (Normalized base on CML Baseline 2000)	% impact C	S	R	D	T
ADP	3.17034E-05	41.05	54.13	3.09	0.14	1.60
ACP	4.10833E-06	76.40	14.73	3.08	0.35	5.44
EUP	1.69087E-06	82.73	7.24	2.14	0.40	7.51
GWP	5.57607E-06	62.57	30.03	1.50	0.31	5.59
ODP	1.24252E-07	97.36	0.00	2.14	0.50	0.00
HUP	5.8241E-07	90.46	0.46	6.94	0.43	1.71
FWAP	4.88654E-06	97.28	0.00	2.41	0.30	0.02
MADP	3.3141E-05	92.78	0.00	6.79	0.40	0.03
TEP	1.13825E-06	95.26	0.00	4.49	0.20	0.04
POP	4.61825E-07	78.76	13.08	4.61	0.32	3.23
average		81.46	11.97	3.72	0.33	2.52

Note: C = construction phase, S = service phase, R = rehabilitation and D = demolition and disposal phase

B. Comparison with Previous Research Studies

In comparison with previous research studies with the same functional unit on the basis of carbon footprint, the total carbon footprint of the expressway of this research work is equivalent to 245,639 tons CO2-eq, of which 153,690; 73,773; 3,693, 775 and 13,728 tons CO2-eq are attributable to the construction, service, rehabilitation, demolition and disposal phases and transportation, respectively. In Table V, the carbon footprints of five phases of the expressway are presented in comparison with those of the construction and service phases of a highway in the U.S. and that of the construction phase of a highway in the East Asia and Pacific region.

TABLE V
COMPARISONS OF CARBON FOOTPRINTS BETWEEN THE EXPRESSWAY UNDER STUDY AND THOSE OF THE HIGHWAY PROJECTS

Country	Carbon Emission
This study (Thailand) [a]	245,639
This study (Thailand) [b]	29,091
UNITED STATES [c]	165,000
UNITED STATES [d]	2,250
East Asia and Pacific [e]	74,397

The functional unit is CO_2 tons/km/50 year life time/3 lanes.
Remarks:
[a]Only the construction phase of the expressway.
[b]Only the service phase of the expressway.
[c]Only the construction phase of a highway [19].
[d]Only the service phase of a highway [19].
[e]Only the construction phase of a highway [20].

C. Sensitivity Analysis Result

In the service phase, gasoline consumption has the most impact ADP, accounting for 54.1% of all the impact categories of this phase. When gasoline consumption was varied between +25%, +15%, -15% and -25% the effects on ADP were +11.92%, +7.51%, -8.84%, and -15.65%, respectively. Certain technologies that alter driving behaviors should be adopted to minimize the stop-and-go instances and thus reduce the environmental impacts, or motorists could be persuaded to avoid travel during rush hours and thereby save fuel by approximately 32.7% [21].

In the construction phase, air pollution from the combustion of heavy machinery has the most effects on ACP, EUP, GWP, ODP, HUP, FWAP, MAEP, and POP, accounting for 76.4%, 82.7%, 63.57%, 97.4%, 90.5%, 97.3%, 92.8%, and 98.8% throughout the expressway's life cycle, respectively. Fig. 4 shows the effects on the 10 impact categories throughout the life cycle of the expressway when air pollution from heavy machinery was varied between +25%, +15%, -15% and -25%.

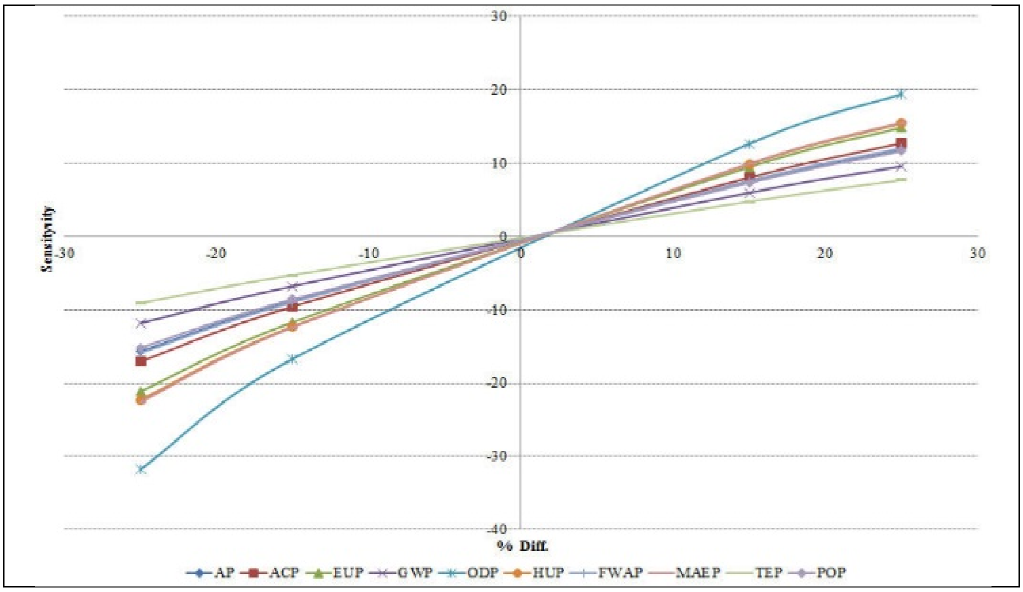
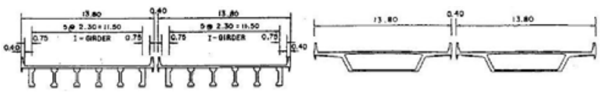


Fig. 4 Sensitivity of AP, ACP, EUP, GWP, ODP, HUP, FWAP, MAEP, TEP and POP

The air pollutants from heavy machinery combustion can be lowered by decreasing the weight or quantity of raw materials (refer to (2)). With the superstructure technology, the raw material requirement could be reduced by 25% by replacing precast I-girders with precast segmental box-girders, as shown in Fig. 5. Thus, by inference from the slopes in Fig. 4, the effects on the environment of the most influencing impact categories in the construction phase could also be reduced by 25%.



(a) Precast I-girder (b) Precast Segmental Box Girder

Fig. 5 Comparison between I-Girder andBox Girder superstructures

In the rehabilitation phase, routine maintenance should be instituted whereby the surface pavements are constantly monitored and repairs are instantaneously performed to increase the rolling resistance and thus reduce the fuel consumption by about 7% [12].

In the demolition and disposal phase, the maximum TEP, which is influenced by the proportion of steel beam in reinforced concrete, is 95.3%. When the quantity of steel was varied from the original quantity by +25%, +15%, -15% and -25%, the effects on TEP were +7.69%, +4.76%, -5.26% and -9.08%, respectively. In practice, the use of recycle materials in the steel beam production helps reduce the demand for virgin materials by approximately 12.1-54.6% [22].

IV. Conclusion

The environmental impacts of an expressway are influenced by the following factors: First, the suitability of traffic design to traffic volume since the traffic design significantly affects the energy consumption and emission in the service phase and dictates the proper project size [23]. Second, the superstructure height because the higher the superstructure, the more complex the construction techniques, then the more the equipment required, and thus the lengthier the construction sequence [24]. Finally, the expressway location since the farther the distance, the more the energy and resources are required to transport the construction materials and equipment [24], which in turn affects the productivity on site [25]. Most importantly, the findings of this research work could be adopted as a benchmark against which the environmental impacts of future projects of similar nature can be measured.

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REFERENCES

[1] K. Junkeaw, Advanced Environmental Impact Assessment. Bangkok: Kasetsart University, 2011.
[2] C. J. Kibert, et al., Construction ecology Nature as the basis for green buildings. London: Spon press, 2002.
[3] SETEC, "Guidelines for Life-Cycle Assessment: A "Code of Practice," workshop proceedings," ed. Florida Society of Environmental Toxicology and Chemistry: Pensacola, 1993.
[4] A. Azapagic and R. Clift, "Life cycle assessment and multiobjective optimization," Jounal of Cleaner Production, vol. 7, pp. 137-143, 1999.
[5] G. Rebitzera, et al., "Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications," Environment International, vol. 30, 2004.
[6] ISO, Environmental management-Life cycle assessment-Goal and scope definition and inventory analysis. ed. Geneva: International Organization for Standardization, 1998.
[7] X. Li, et al., "An LCA-based environmental impact assessment model for construction processes," Building and Environment, vol. 45, pp. 766-775, 2010.
[8] W. Pintapun, "Comparision of Concrete pavement and asphalt concrete pavement for highway design in Thailand," Master of Engineering, Major field Civil Engineering, Department of Civil Engineering, Kasetsart Bangkok, Thailand, 2002.
[9] S. Panwai, et al., "Development of SIDRA-TRIP Integrated GPS Model to Evaluate Fuel Consumption/Emission on Expressway and Alternative Road," ed. Busan: 17th ITS World Congress, Busan, 2010: Proceedings 2010.
[10] R. Chowdhury, et al., "A life cycle base environmental impacts assessment of construction materials use in road construction," Resource conservation & Recycling, vol. 54, pp. 250-255, 2010.
[11] Clifford J. Schexnayder and Richard E. Mayo, Construction Management Fundamentals: McGraw Hill, 2004.
[12] N.D. Lea International LTD, "Modeling road deterioration and maintenance effects in HDM-IV. Final Report," Vancouve Canada1992.
[13] National Research Council, "Modeling Mobile-Source Emission," 2000.
[14] AEC, "Final report on feasibility study environment impact assessment and route alignment study of Ekamai-Ramindra Expressway project," Asian Engineering Consultant, Bangkok Thailand1988.
[15] R. Akcelik, et al., "Calibrating Fuel Consumption and Emission Model for Modern Vehicles," Paper presented at the IPENZ Transportation Group Conference, Rotorua, New Zealand., 2012.
[16] ETH-ESU 96, "Öko-inventare von Energiesystemen," ESUGroup Öko-inventare von Energiesystemen1996.
[17] LCA.Lab National Metal and Materials Technology Center, "Thai National Life cycle Inventory Database," National Science and Technology Development Agency, Ed., ed. Thailand, 2005.
[18] D. P. Bowyer, et al., "Guide to Fuel Construction Analysis for Urban Trafic Management," ARRB Transport Rearch Ltd, Vermont South, Australia.1985.
[19] Asain Development Bank, "Reducing Carbon Emission from Transport Project," Asain Development Bank2010.
[20] The world bank, "Greenhouse Gas Emission Mitigation in Road Construction and Rshabilitation," The world bank,2010.
[21] S. Panwai, et al., "Comparative Evaluation of Power-Based Environmental Emissions Models," IEEE (ITSC2006), vol. 9, pp. 1251-1256, 2006.
[22] K. a. D. Aravind, A., "Pavement design with central plant hot-mix recycled asphalt mixes," Construction and Building Materials, vol. 21, pp. 928-936 2007.
[23] Y. Huang, et al., "Measuring the carbon footprint of road construction using CHANGER," International Journal of Pavement Engineering, vol. iFirst, pp. 1-10, 2012.
[24] S. R. Sanders, et al., "Preliminary Estimating Models for Infrastructure Projects," Journal of Cost Engineering, vol. 34, pp. 7-13, 1992.
[25] M. T. Callahan, et al., Construction Project Scheduling. New York: McGraw-Hill, 1992.