Loss and Benefit Caused by a Diesel Engine

From the Perspective of Human Health

Feri Afrinaldi, Hong-Chao Zhang, Zhi-Chao Liu, and Annette Hernandez

Keywords:

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Summary

This article presents a model that quantifies the health loss and benefit triggered by the life cycle of a diesel engine. The health loss and benefit are expressed in the form of disability-adjusted life years (DALY), a metric used by the World Health Organization to conduct health impact assessments. In order to quantify the health loss, life cycle assessment methodology is applied. To estimate the health benefit, the relationship between DALY per capita and gross domestic product (GDP) per capita is modeled. The change in GDP per capita, resulting from the change in the level of employee compensation caused by the life cycle of the diesel engine, is used to estimate the change in the level of DALY per capita. An economic input-output model is applied to estimate the amount of employee compensation required over the life cycle of the diesel engine. This study concludes that the health benefit achieved by the socioeconomic growth, triggered by the life cycle of the diesel engine, is higher than the health loss caused by the pollutions produced over the life cycle of the diesel engine. Furthermore, the results support findings in the literature that socioeconomic growth generates a higher health benefit in a lower-income country than in a higher-income country. This also might be one of the reasons for another statement found in the literature that developing countries put higher priorities on economic development.

Introduction

According to the U.S. Environmental Protection Agency (US EPA 2014a), the key greenhouse gases produced by humans are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. If the sources of these emissions are broken down according to the economic sectors, then the sources, at the global scale, are energy supply (26%), industry (19%), land use (17%), agriculture (14%), transportation (13%), commercial and residential buildings (8%), and waste and wastewater (3%) (US EPA 2014b). Among the sectors of industry, manufacturing industries have a significant contribution (Sutherland et al. 2008). Within the manufacturing sectors, automobile manufacturing, especially the diesel engine, has garnered more attention. There have been many studies aimed to assess the environmental impacts of the life cycle of a diesel engine.

Li and colleagues (2013) assessed the environmental impacts of a diesel engine manufactured in China using the life cycle assessment (LCA) methodology. The impact categories considered in their study were global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP). This study found that the use phase of the diesel engine has the highest contribution to the total environmental impacts. Jiang and colleagues (2014) used an input-output (I-O) approach to assess pollutants produced by the life cycle of a diesel engine. This study estimated the quantity of CO_2, sulfur dioxide (SO_2), N_2O, CH_4, and dust produced over the life cycle of a diesel engine. Jiang and colleagues (2014) also concluded that the

Address correspondence to: Feri Afrinaldi, Department of Industrial Engineering, Andalas University, Limau Manis, Padang, 25163, Indonesia. *Email:* feri_afrinaldi@ft.unand.ac.id

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use phase of the diesel engine has the largest impact on the environment. Sutherland and colleagues (2008) assessed the benefit that can be gained, in the form of energy intensity, from the remanufacturing process of a diesel engine. The researchers found that the remanufacturing processes can produce a 90% energy savings. A study comparing the environmental impacts of the manufacturing and remanufacturing processes of a diesel engine can be found in Dias and colleagues (2013). They observed that the remanufacturing process can result in 74%, 23%, 71%, and 39.83% savings on the emission of CO_2, carbon monoxide (CO), SO_2, and energy consumption, respectively. Liu and colleagues (2014) also compared the environmental impacts of a newly manufactured diesel engine and a remanufactured diesel engine. The study indicated that diesel engine remanufacturing can reduce GWP, ozone layer depletion potential, EP, POCP, AP, and abiotic depletion potential up to 67%, 97%, 79%, 32%, 32%, and 25%, respectively. However, this study excluded the environmental impacts caused by the new components used to replace the faulty components of the diesel engine that has reached the end of its life.

Most studies have focused on the environmental impacts triggered by the life cycle of a diesel engine. However, according to Norris (2006), in addition to causing pollution, the life cycle of a product also changes the levels of employment, wages, and taxes paid. These may reduce the level of poverty and increase government spending on public services. As a result, it may change the level of morbidity (Norris 2006). Norris (2006) also modeled the relationship between the change in gross national product (GNP) and the change in mean life expectancy. The model indicated that there is a positive exponential relationship.

This study aims to compare the human health loss and benefit caused by the life cycle of a diesel engine. To quantify the health loss, LCA methodology is applied. For the health benefit, this research focuses on the effect of the change in the level of employee compensation to the health outcome of the society. It is assumed that the workers will use their wages to increase their quality of life. This will result in a lower frequency of illness and premature death. The frequency of illness and premature death is measured using disability-adjusted life years (DALY), a metric used by the World Health Organization (WHO) to conduct health impact assessments.

Method

Disability-Adjusted Life Years Loss

The DALY loss is calculated by applying the LCA characterization method. The total DALY loss, denoted as $\Delta DALY_{\text{Loss}}(s)$, is given by equation (1), where s denotes the distance traveled by the engine. $\Delta DALY_{\text{Loss}}(s)$ is defined as the sum of DALY loss during the production phase $\Delta DALY_{\text{Loss}}^{\text{Prod}}$, the use phase $\Delta DALY_{\text{Loss}}^{\text{Use}}(s)$, and the end-of-life (EoL) phase $\Delta DALY_{\text{Loss}}^{\text{EoL}}$. $\Delta DALY_{\text{Loss}}^{\text{Prod}}$ and $\Delta DALY_{\text{Loss}}^{\text{EoL}}$ are not a function of s and are given by equations (2) and (3).

$$\Delta DALY_{\text{Loss}}(s) = \Delta DALY_{\text{Loss}}^{\text{Prod}} + \Delta DALY_{\text{Loss}}^{\text{Use}}(s) + \Delta DALY_{\text{Loss}}^{\text{EoL}} \quad (1)$$

$$\Delta DALY_{\text{Loss}}^{\text{Prod}} = \sum_{i=1}^{n} Load_i \; daly_i \quad (2)$$

$$\Delta DALY_{\text{Loss}}^{\text{EoL}} = \sum_{k=1}^{q} Load_k \; daly_k \quad (3)$$

where:

i = the ith environmental intervention during the production phase of a diesel engine

k = the kth environmental intervention during the EoL phase of a diesel engine

$Load_i$, $Load_k$ = quantity of environmental interventions type i and k (kilograms; kg)

$daly_i$, $daly_k$ = damage factors for environmental intervention types i and k (DALY/kg)

DALY loss during the use phase is the product of $Load_j(s)$ and the characterization factor for environmental intervention type j, $daly_j$ (DALY/kg), as shown in equation (4). The quantity of environmental intervention during the use phase $Load_j(s)$ is influenced by the distance traveled by the engine s, fuel efficiency η (kilometers per liter; km/L), and the emission factor of constituent type j, ef_j (kg/L) and is given by equation (5).

Substituting equation (5) into equation (4) results in an equation for $\Delta DALY_{\text{Loss}}^{\text{Use}}(s)$, as shown in equation (6).

$$\Delta DALY_{\text{Loss}}^{\text{Use}}(s) = \sum_{j=1}^{m} Load_j(s) \; daly_j \quad (4)$$

$$Load_j(s) = \frac{s}{\eta} \, ef_j \quad (5)$$

$$\Delta DALY_{\text{Loss}}^{\text{Use}}(s) = \frac{s}{\eta} \sum_{j=1}^{m} ef_j \; daly_j \quad (6)$$

Disability-Adjusted Life Years Benefit

In this study, the DALY benefit is calculated based on the model found in Norris (2006). Norris (2006) quantified the effect of economic growth caused by the life cycle of a product on human health. However, there are several factors that affect economic growth (increase in GDP), such as compensation of employees, rents, profits, net interest, indirect taxes, and depreciation (Tucker 2012). Not all of the aforementioned factors have a direct relationship to the life cycle of a product, which is based on the relationship between the factor and the functional unit of the product being studied. In contrast to the other factors, the value added in the form of employee compensation is easier to link with the functional unit of a product because it has a directly proportional relationship with the life cycle of a

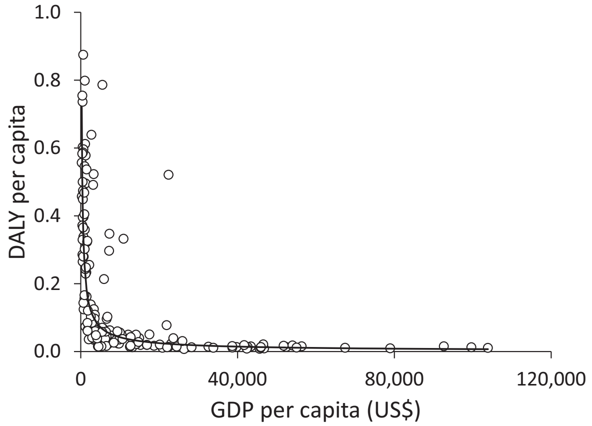

Figure 1 DALY per capita versus GDP per capita. Each point in this chart represents a country. DALY = disability-adjusted life years; GDP = gross domestic product.

product. A change in the value of functional unit of the product is proportional to the change in the amount of value added in the form of employee compensation.

The method presented in this article focuses on the effect of value added in the form of employee compensation, transferred to a diesel engine (during its life cycle), to human health. Given that the economic growth is usually measured as an increase in GDP, the first step is to model the relationship between DALY and GDP. Based on the data published by World Bank (2014a) and WHO (2014), the relationship between DALY per capita, *DALYPC*, and GDP per capita, *GDPPC*(US$ per capita), is presented in figure 1.

From the figure, it can be seen that the relationship between *DALYPC* and *GDPPC* can be modeled as follows, equation (7).

$$DALYPC = \gamma\, GDPPC^{-\theta} \tag{7}$$

In order to calculate the rate of change of DALY per capita when GDP per capita changes, the first derivative of *DALYPC* with respect to *GDPPC* is derived and it is given by equation (8).

$$\frac{dDALYPC}{dGDPPC} = -\gamma\,\theta\, GDPPC^{-(\theta+1)} \tag{8}$$

The change in *GDPPC*, $\Delta GDPPC$, as a result of value added in the form of employee compensation transferred to the diesel engine, denoted as *V*, in US$, is given by $\Delta GDPPC = V/Pop$, where *Pop* denotes population (people). Furthermore, when the assessment is done for a single engine, then it is most likely that $V/Pop \rightarrow 0$. Therefore, it is reasonable to estimate $\Delta DALYPC/\Delta GDPPC$ as the following, equation (9).

$$\frac{\Delta DALYPC}{\Delta GDPPC} \cong -\gamma\,\theta\, GDPPC^{-(\theta+1)} \tag{9}$$

Multiplying equation (9) with $\Delta GDPPC = V/Pop$ results in the benefit gained from the socioeconomic growth triggered by the life cycle of the diesel engine, equation (10). It has a negative sign and is called $\Delta DALYPC_{Benefit}$ because value added in the form of employee compensation will reduce the level of DALY per capita.

$$\Delta DALYPC_{\text{Benefit}} = -\gamma\,\theta\,\frac{V}{Pop} GDPPC^{-(\theta+1)} \tag{10}$$

Multiplying equation (10) with *Pop* will result in total DALY benefit ($\Delta DALY_{\text{Benefit}}$), equation (11).

$$\Delta DALY_{\text{Benefit}} = -\gamma\,\theta\, V\, GDPPC^{-(\theta+1)} \tag{11}$$

During the production and EoL phase of the diesel engine, *V* is not a function of the distance traveled by the engine, *s*. It is determined by the total of economic activities required to produce and process the engine when it reaches its EoL. However, *V* is a function of *s* during the use phase because a longer distance traveled by the engine means a higher demand for diesel fuel production and distribution. This also implies a higher cost for maintenance and insurance. Consequently, a higher amount of employee compensation is required.

Now, let us define that the value added in the form of employee compensation for the production phase is V_{Prod}, for the EoL phase is V_{EoL}, and for the use phase is $V_{\text{Use}} = V(s)$. Equation (11) is expanded as the following, equation (12).

$$\begin{aligned}\Delta DALY_{\text{Benefit}}(s) = &-\gamma\,\theta\, V_{\text{Prod}}\, GDPPC^{-(\theta+1)}\\ &-\gamma\,\theta\, V(s)\, GDPPC^{-(\theta+1)}\\ &-\gamma\,\theta\, V_{\text{EoL}}\, GDPPC^{-(\theta+1)}\end{aligned} \tag{12}$$

The next task is to quantify V_{Prod}, $V(s)$, and V_{EoL}. An economic I-O (EIO) model found in Leontief (1986) is applied to calculate $V(s)$.

Based on Leontief (1986), in the state of equilibrium, the relationship between the level of outputs of the industries, $x_1(s)$, $x_2(s)$, $\cdots$, $x_n(s)$, and the final demand, $y_1(s)$, $y_2(s)$, $\cdots$, $y_n(s)$, is given by equation (13). x_i and y_i are in US$.

$$\mathbf{x}(s) = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}(s) \tag{13}$$

where:

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n}\\ a_{21} & a_{22} & \cdots & a_{2n}\\ \cdots & \cdots & \cdots & \cdots\\ a_{n1} & a_{n2} & \cdots & a_{nn}\end{pmatrix}$$

$$\mathbf{y}(s) = \begin{pmatrix} y_1(s)\\ y_2(s)\\ \vdots\\ y_n(s)\end{pmatrix}$$

Matrix **A** is called the structural matrix of the economy and its element a_{ij}, is known as the input coefficient (Leontief 1986). This matrix is constructed based on the I-O table of the economy being studied.

In equation (13), x_i and y_i are expressed as a function of distance, *s*. $x_i(s)$ means the level of outputs that must be provided by industry *i* so that consumers can use the diesel engine for the distance *s*. These industries include those that produce and distribute diesel fuel as well as maintenance and insurance companies. $y_i(s)$ denotes the final demand required by industry i, such as the amount of diesel fuel, in US$, required to operate the diesel engine for the distance s. $y_i(s) > 0$ if industry i is related to the activities supporting the use of the diesel engine, otherwise $y_i = 0$.

Following Leontief (1986), $(\mathbf{I}-\mathbf{A})^{-1}$in equation (13) is denoted as follows:

$$(\mathbf{I}-\mathbf{A})^{-1} = \begin{pmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{pmatrix}$$

Now equation (13) can be rewritten as the following, equation (14).

$$\begin{array}{lcl} x_1(s) & = & A_{11}y_1(s) + A_{12}y_2(s) + \cdots + A_{1n}y_n(s) \\ x_2(s) & = & A_{21}y_1(s) + A_{22}y_2(s) + \cdots + A_{2n}y_n(s) \\ \cdots & \cdots & \cdots \\ x_n(s) & = & A_{n1}y_1(s) + A_{n2}y_2(s) + \cdots + A_{nn}y_n(s) \end{array} \quad (14)$$

According to Chiang and Wainwright (2004), the portion of input required by industry j from the primary sectors of the economy (labor, public services, and capital) in order to meet the final demand is given by a_{0j}.

$$a_{0j} = \left(1 - \sum_{i=1}^{n} a_{ij}\right)$$

If ρ_i denotes the ratio of value added in the form of employee compensation to the total primary input required by sector i, then the portion of value added in the form of employee compensation needed by industry i is given by μ_i, equation (15).

$$\mu_i = \rho_i \, a_{0j} \quad (15)$$

Multiplying μ_i and $x_i(s)$ results in the value added in the form of employee compensation required by industry i, $V_i(s)$, equation (16).

$$\begin{array}{lcl} V_1(s) & = & \mu_1 x_1(s) = \mu_1\left[A_{11}y_1(s) + A_{12}y_2(s) + \cdots + A_{1n}y_n(s)\right] \\ V_2(s) & = & \mu_2 x_2(s) = \mu_2\left[A_{21}y_1(s) + A_{22}y_2(s) + \cdots + A_{2n}y_n(s)\right] \\ \cdots & \cdots & \cdots \\ V_n(s) & = & \mu_n x_n(s) = \mu_n\left[A_{n1}y_1(s) + A_{n2}y_2(s) + \cdots + A_{nn}y_n(s)\right] \end{array} \quad (16)$$

Total value added in the form of employee compensation, $V(s)$, is given by equation (17).

$$V(s) = \sum_{i=1}^{n} V_i(s) = \sum_{i=1}^{n}\sum_{j=1}^{n} \mu_i \, A_{ij} \, y_j(s) \quad (17)$$

Furthermore, it is easy to find that, if sector j is related to diesel fuel production and distribution, the amount of $y_j(s)$is influenced by the price of the diesel fuel, P (US$/liter), the fuel efficiency of the diesel engine, η (km/liter), and the distance traveled by the engine, s (km). Therefore $y_j(s)$ is given by equation (18).

$$y_j(s) = \frac{s}{\eta}P \quad \text{(if sector } j \text{ is related to diesel fuel production and distribution)} \quad (18)$$

Based on equation (17), V_{Prod} and V_{EoL} are formulated. It is known that V_{Prod} and V_{EoL} are not influenced by s, as shown in equations (19) and (20).

$$V_{\text{Prod}} = \sum_{i=1}^{n}\sum_{j=1}^{n} \mu_i A_{ij} d_j \quad (19)$$

$$V_{\text{EoL}} = \sum_{i=1}^{n}\sum_{j=1}^{n} \mu_i A_{ij} b_j \quad (20)$$

d_j is the final demand, in US$, to produce the diesel engine, from material production to assembly. Therefore, $d_j > 0$, if sector j is related to diesel engine manufacturing, otherwise $d_j = 0$. Similarly, b_j is the final demand, in US$, to process the diesel engine when it reaches its EoL, in US$, $b_j > 0$, if sector j is related to the EoL treatment of the diesel engine, otherwise $b_j = 0$. Because of lack of data, the value added in the form of employee compensation required by industries related to the maintenance and insurance activities of the diesel engine is not considered.

Breakeven Analysis

It can be seen that equation (1) is a linear model. Because the economic I-O model is a linear model, then equation (12) is also linear in terms of s. If equations (1) and (12) are plotted, figure 2 will be produced. Note that the value of $\Delta DALY_{\text{Benefit}}$ plotted in figure 2 is the absolute value. In figure 2, (s*, $\Delta DALY$*) is the breakeven point.

The slopes of $\Delta DALY_{\text{Loss}}$ and $\Delta DALY_{\text{Benefit}}$ are given by equations (21) and (22).

$$\frac{d\left[\Delta DALY_{\text{Loss}}(s)\right]}{ds} = \frac{1}{\eta}\sum_{j=1}^{m} ef_j \, daly_j \quad (21)$$

$$\frac{d\left[\Delta DALY_{\text{Benefit}}(s)\right]}{ds} = -\theta\,\gamma\,\frac{dV(s)}{ds} GDPPC^{-(\theta+1)} \quad (22)$$

$dV(s)/ds$ is given by equation (23).

$$\frac{dV(s)}{ds} = \sum_{i=1}^{n}\sum_{j=1}^{n} \mu_i \, A_{ij} \frac{dy_j(s)}{ds} \quad (23)$$

$\frac{dy_j(s)}{ds}$ is presented in equation (24).

$$\frac{dy_j(s)}{ds} = \begin{cases} \frac{P}{\eta} & (j \text{ related to diesel fuel production and distribution}) \\ 0 & (\text{otherwise}) \end{cases} \quad (24)$$

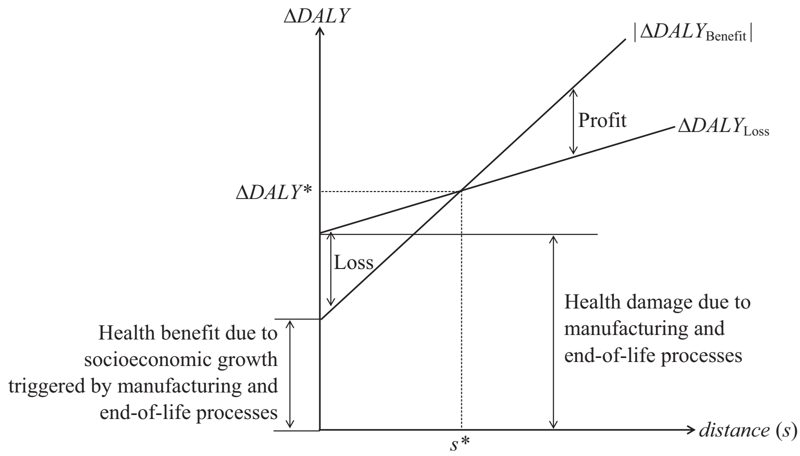

Figure 2 ΔDALY benefit–loss breakeven chart. DALY = disability-adjusted life years.

Table 1 Material composition

Part name	*Quantity per engine*	*Material*	*Mass (kg)*	*Total (kg)*
Cylinder block	1	Cast iron	260.00	260.00
Cylinder head	6	Cast iron	15.60	93.60
Fly wheel housing	1	Cast iron	43.65	43.65
Gear box	1	Cast iron	22.10	22.10
Connection rod	6	Steel	3.52	21.12
Crankshaft	1	Steel	103.00	103.00
Fly wheel	1	Steel	30.60	30.60
Other components		Aluminum		45.30
Other components		Cast iron		163.18
Other components		Steel		45.96
Other components		Steel alloy		36.07
Other components		Rubber		5.44
			Total	**870.02**

Note: kg = kilograms.

Results and Discussion

In this section, the applicability of the above methods is discussed through a case study. The damage to human health, measured in DALY, caused by the life cycle of a diesel engine is assessed.

Product System Boundary and Life Cycle Inventory

The diesel engine under consideration is manufactured in China and sold in the domestic market of China, Southeast Asian countries, such as Indonesia and Malaysia, and African countries. It is a six-cylinder, in-line, water-cooled, and turbocharged engine. Table 1 presents the diesel engine's material composition.

The life cycle of the diesel engine is illustrated in figure 3. The figure shows the flow of the materials beginning with material production, proceeding through manufacturing and ending with EoL treatment. Based on data availability, the assumptions made in this study are the following:

a) Steel alloy is modeled as steel.
b) Based on the relatively small percentage and lack of data to model the production processes, components made of rubber are not considered.
c) Scrap, lubrication oil, coating materials and painting are not considered.
d) Material transportation, maintenance and insurance activities, and end-of-life treatment are not considered due to the lack of data.

For the use phase, it is assumed that the fuel efficiency (η) of the engines is 4 km/L and total distance traveled over the life of the engines is 300,000 km (Li et al. 2013). Moreover, because of the lack of data to model the relationship between the weight of the vehicle and fuel consumption, it is assumed that the fuel consumed by the vehicle during the use phase is entirely charged to the engine. To compute resources consumed and emissions produced during diesel fuel refining and combustion, data published by the US EPA (2014c) and Sheehan and colleagues (1998) are utilized.

ΔDALY Loss and ΔDALY Benefit

In calculating ΔDALY loss and ΔDALY benefit, this study considers two scenarios:

a. Scenario 1
   - Production (material production, manufacturing, and assembly) occurs in China.
   - Use (driving) and diesel fuel refining process occur in China.

b. Scenario 2
   - Production (material production, manufacturing, and assembly) occurs in China.
   - Use (driving) and diesel fuel refining occur in Indonesia.

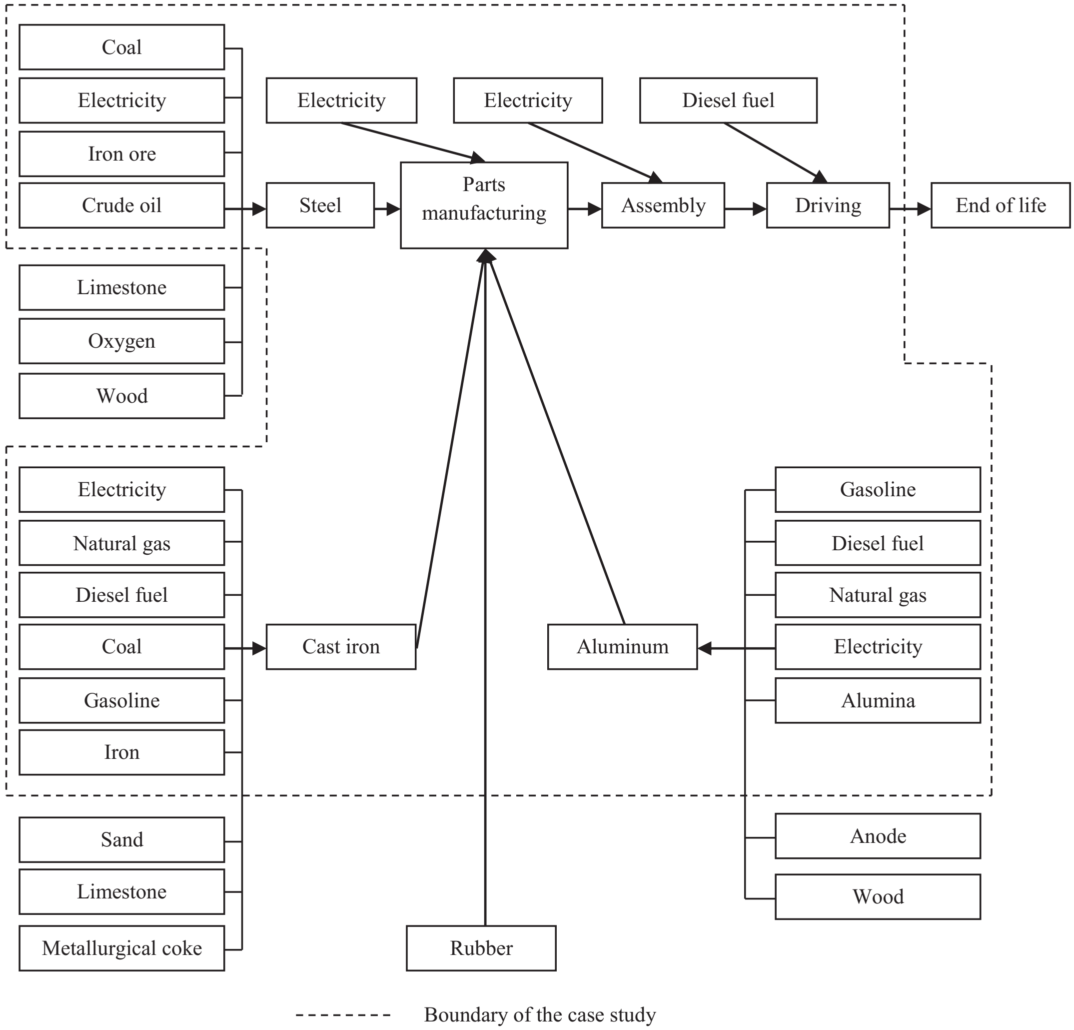

Figure 3 Simplified life cycle of a diesel engine.

To calculate ΔDALY loss, the damage factor, *daly*, is obtained from Eco-Indicator 99 (Goedkoop and Spriensma 2001). All substances, such as cadmium, chromium, CO_2, CO, SO_2, and so on, that have impacts on DALY are considered. In order to illustrate how the calculation is done, CO_2 released into the atmosphere during the use phase is used as an example. According to the US EPA (2014c), if 1 gallon of diesel fuel is burned, then 10.210 kg of CO_2 will be released to the air ($ef_{CO_2} = 10.210$ kg CO_2). Further, according to Goedkoop and Spriensma (2001), CO_2 released to the air has a damage factor ($daly_{CO_2}$) of 2.1×10^{-7} DALY/kg. Therefore, by using equation (6):

$$\Delta DALY^{\mathrm{Use}}_{\mathrm{Loss}} \text{ due to } \mathrm{CO_2} = \left(\begin{array}{l} \frac{300{,}000\,\mathrm{km}}{4\,\mathrm{km/liter}} \times 10.210\,\mathrm{kgCO_2/gal.} \\ \times 0.264\,\mathrm{gal./liter} \times 2.1 \times 10^{-7}\mathrm{DALY/kgCO_2} \end{array} \right) = 0.042\,\mathrm{DALY}.$$

The aggregated ΔDALY loss for each scenario is presented in figure 4. From the figures, it can be seen that ΔDALY loss for each scenario is exactly the same. This is because the parameters used to calculate ΔDALY loss for each scenario are also exactly the same.

The first step to estimate ΔDALY benefit is to estimate the inputs required, in US$, over the life cycle of the diesel engine (see table 2). The values of the input required, for material production, manufacturing, and assembly, are based on the information provided by the manufacturer. For diesel fuel production and distribution, the values are estimated based on the price of diesel fuel in China and Indonesia. For example, in 2013 the average price of diesel fuel in Indonesia was US$0.55 /L (Tempo 2013). Therefore, by using equation (18), for 300,000 km of driving and 4 km/L fuel efficiency, US$41,250 is needed in Indonesia.

To estimate value added in the form of employee compensation, a China economic input-output (EIO) table for the year of 2007 (42 sectors) (China Academic Journals Electronic Publishing House 2014) and an Indonesia EIO table for the year 2008 (15 sectors) (Asian Development Bank 2014) are used. Therefore, it is necessary to express the economic values of the input requirement in terms of 2007 US$ for the unit processes

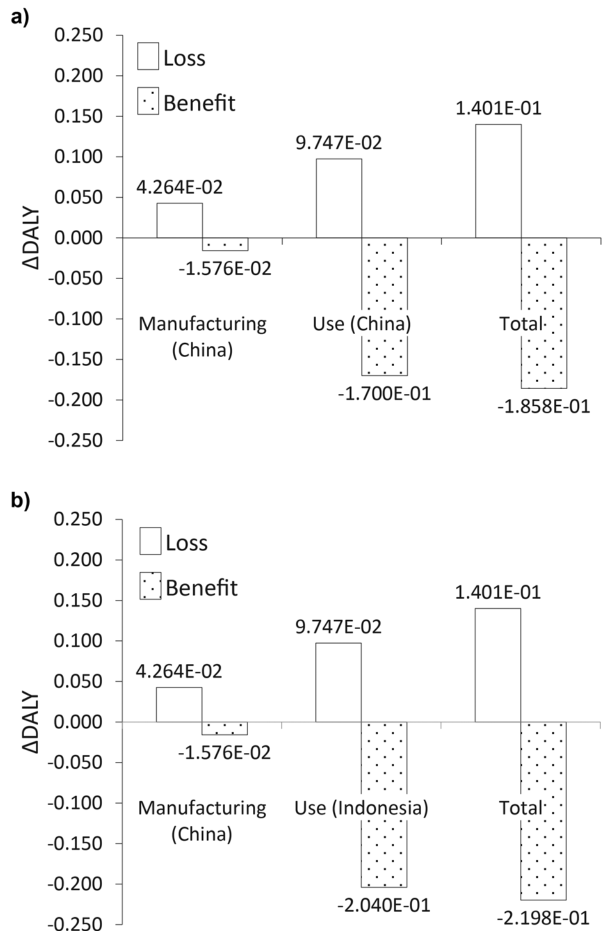

Figure 4 ΔDALY loss versus ΔDALY benefit: (a) scenario 1 and (b) scenario 2. DALY = disability-adjusted life years.

occurring in China and in terms of 2008 US$ for the unit process happening in Indonesia. This is done by using the GDP deflators of China and Indonesia. For example, according to World Bank (2014b), the GDP deflators of Indonesia in 2008 and 2013 were 237.64 and 327.90, respectively, so the input requirement for diesel fuel production and distribution in Indonesia, in terms of 2008 US$, is 237.64 / 327.90 × US$41,250 = US$29,895. In table 2, values without parentheses are in terms of 2013 US$, values within parentheses are in terms of 2007 US$, and value within braces are in terms of 2008 US$. Based on table 2, the final demand vectors, $\mathbf{y}(s)$and $\mathbf{d}$, are developed and presented by the following.

Scenario 1,

$$\mathbf{y}(s) = \left(0 \cdots 72,566.53 \cdots 0\right)^T,$$

$$\mathbf{d} = \left(0 \cdots 1,120.93 \cdots 5,039.98 \cdots 0\right)^T$$

Scenario 2,

$$\mathbf{y}(s) = \left(0\ 29,894.84\ 0 \cdots 0\right)^T,$$

$$\mathbf{d} = \left(0 \cdots 1,120.93 \cdots 5,039.98 \cdots 0\right)^T$$

For scenario 1, $y_{11}(s) = 72,566.53$, $d_{14} = 1,120.93$, $d_{24} = 5,039.98$, other elements of $\mathbf{y}(s)$ and $\mathbf{d}$ are zeros. For scenario 2, $y_2(s) = 29,894.84$, $d_{14} = 1,120.93$, $d_{24} = 5,039.98$, other elements of $\mathbf{y}(s)$ and $\mathbf{d}$ are zeros. For both scenarios, $s = 300{,}000$ km. Because the EoL treatment of the engines is excluded in this study, then $b_j = 0$ for all j. Using the EIO tables of China and Indonesia, $\mathbf{A}$ matrix for China and Indonesia is constructed. From the $\mathbf{A}$ matrices and the EIO tables of both countries, ρ_i, a_{0j}, and μ_i are calculated. Using equations (17) and (19), it is found that, in terms of 2013 US$, $V_{\text{Use}} = V(s) =$ US$26,532.88 and $V_{\text{Prod}} =$ US$2,459.88 for scenario 1; and $V_{\text{Use}} = V(s) =$ US$9,685.89 and $V_{\text{Prod}} =$ US$2,459.88 for scenario 2.

The next step is to estimate γ and θ, the parameters of equation (7). A regression analysis is applied to the plot presented in figure 1, and it is found that $\gamma = 50.65$, $\theta = 0.77$, $R^2 = 0.72$. According to World Bank (2014a), in 2013, China GDP per capita was US$6,807.43 and Indonesia GDP per capita was US$3,475.250. Using equation (12), ΔDALY benefit for each scenario is calculated and the results are presented in figure 4a and b.

From figure 4, it can be seen that the health benefit gained from socioeconomic growth in Indonesia is higher than that in China:

$$\left|\Delta DALY_{\text{Benefit}}^{\text{Use}}\ (\text{Indonesia})\right| > \left|\Delta DALY_{\text{Benefit}}^{\text{Use}}\ (\text{China})\right|.$$

This finding implies that the socioeconomic growth caused by the diesel engines' life cycle will have a higher benefit to the people living in a lower-income country (Indonesia) than for the people living in a higher-income country (China). This is in accordance with a statement found in Norris (2006, 101) stating that "economic growth is much more powerful at achieving health benefits when it occurs in the lower-income countries."

Breakeven Analysis of Health Loss and Benefit

Based on the above results, by using equations (21) and (22), it is obtained that:

$$\frac{d\left[\Delta DALY_{\text{Loss}}(s)\right]}{ds} = 3.249 \times 10^{-7}\ \text{DALY/km}$$

$$\frac{d\left[\Delta DALY_{\text{Benefit}}(s)\right]}{ds} = \begin{cases} -5.667 \times 10^{-7}\ \text{DALY/km} & (\text{Scenario 1}) \\ -6.8 \times 10^{-7}\ \text{DALY/km} & (\text{Scenario 2}) \end{cases}$$

Therefore, equations (1) and (12) are given by the following:

$$\Delta DALY_{\text{Loss}}(s) = 4.264 \times 10^{-2} + 3.249 \times 10^{-7} s \quad (\text{For both scenarios})$$

$$\Delta DALY_{\text{Benefit}}(s) = -1.576 \times 10^{-2} - 5.667 \times 10^{-7} s \quad (\text{Scenario 1})$$

$$\Delta DALY_{\text{Benefit}}(s) = -1.576 \times 10^{-2} - 6.8 \times 10^{-7} s \quad (\text{Scenario 2})$$

Table 2 Input requirements

	Scenario 1			Scenario 2		
Unit process	*Location*	*EIO sector*	*Price, 2013 US$ (2007 US$)*	*Location*	*EIO sector*	*Price, 2013 US$ (2007 US$) {2008 US$}*
Material production						
Aluminum production	China	Sector 14: Smelting and pressing of metals	108.85 (85.22)	China	Sector 14: Smelting and pressing of metals	108.85 (85.22)
Cast iron production	China	Sector 14: Smelting and pressing of metals	995.18 (779.11)	China	Sector 14: Smelting and pressing of metals	995.18 (779.11)
Steel production	China	Sector 14: Smelting and pressing of metals	305.84 (239.44)	China	Sector 14: Smelting and pressing of metals	305.84 (239.44)
Steel alloy production	China	Sector 14: Smelting and pressing of metals	21.91 (17.15)	China	Sector 14: Smelting and pressing of metals	21.91 (17.15)
Manufacturing and assembly						
Electricity	China	Sector 24: Production and distribution of electric power	6,437.64 (5,039.98)	China	Sector 24: Production and distribution of electric power	6,437.64 (5,039.98)
Use						
Diesel fuel production and distribution	China	Sector 11: Processing of petroleum, coking, processing of nuclear fuel	92,690.40 (72,566.53)	Indonesia	Sector 2: Products of mining and quarrying	41,250.00 {29,894.84}

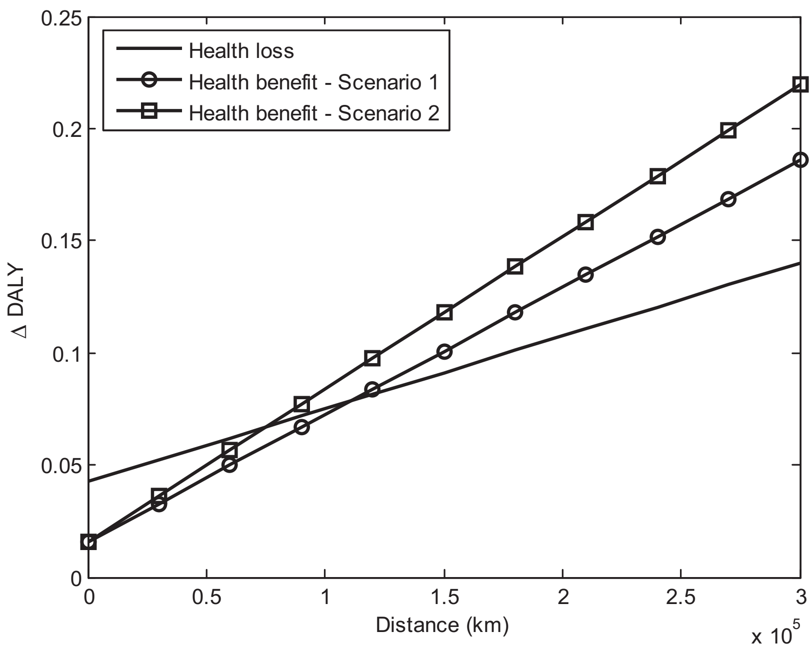

Figure 5 ΔDALY benefit–loss breakeven chart of the diesel engine.

$\Delta DALY_{Loss}(s)$ and $|\Delta DALY_{Benefit}(s)|$ are plotted in figure 5. Solving the above equations (the absolute value of $\Delta DALY_{Benefit}(s)$ is used) the following results are obtained:

$$s^*_{Scenario\,1} = 111{,}166\,km$$

$$s^*_{Scenario\,2} = 75{,}697\,km$$

It is concluded that, for scenario 1 (produce and use is in China), the breakeven distance is 111,166 km. For scenario 2 (produce in China and use in Indonesia), the breakeven point is reached when the engine is driven for 75,697 km. Because $s^*_{\text{Scenario 2}} < s^*_{\text{Scenario 1}}$ then it confirms that the socioeconomic growth is more powerful in achieving health

Table 3 Statistics for the total ΔDALY benefit and ΔDALY loss

	Mean	*Standard deviation*	*Minimum*	*Maximum*
Scenario 1	0.183 (0.139)	0.011 (0.006)	0.165 (0.128)	0.202 (0.149)
Scenario 2	0.217 (0.139)	0.013 (0.006)	0.194 (0.128)	0.239 (0.149)

Note: DALY = disability-adjusted life years.

benefit in lower-income countries. The loss and profit regions for each scenario are the following:

- Scenario 1
  - Health loss region (km): $0 \le s < 111{,}166$
  - Health profit region (km): $s > 111{,}166$
- Scenario 2
  - Health loss region (km): $0 \le s < 75{,}697$
  - Health profit region (km): $s > 75{,}697$

Uncertainty Analysis

The objective of uncertainty analysis is to see the effect of uncertainty on life cycle inventory (LCI) data to ΔDALY loss and ΔDALY benefit triggered by the life cycle of the diesel engine. The analysis is carried out through a Monte Carlo simulation. The number of replications used in the Monte Carlo simulation is 100,000. These replications are statistically independent. They allow statistical data, such as mean, standard deviation, minimum value, and maximum, to be collected. For this purpose, a confidence level of 95% ($\alpha = 0.05$) is used.

In this study, the source of uncertainty is the distance traveled by the engines. Uncertainties on the LCI data of the production phase are ignored because of lack of data. According to Huang and colleagues (2005), in 2004 the distance of 29,200 to 36,500 km/year was traveled by the trucks in China. Assuming that, on average, the distance of 300,000 km is traveled in 9 years by the engine, then in 9 years the engines travel 262,800 to 328,500 km. Because of lack of information, it is also assumed that this distance follows a uniform distribution,

$$s = Unif\,(262, 800, 328, 500)$$

Because there are no statistics found regarding the distance traveled by the trucks in Indonesia, it is assumed that $s = Unif$ (262,800, 328,500) also applies in Indonesia. The results of the uncertainty analysis are presented in table 3.

In table 3, the values within parentheses indicate ΔDALY loss and the values without parentheses indicate ΔDALY benefit. From table 3, it can be seen that the mean, minimum and maximum of ΔDALY benefit for scenario 2 are higher. The results from this research confirm that a higher health benefit is produced if the engine is used in a lower-income country. The above finding supports a statement found in Klöpffer (2003, 157) saying that “Industrialized countries tend to emphasize the environmental aspect (at least the green movements, the environmental agencies, and some companies as well), whereas developing countries give highest priority to economic development.”

Conclusions

This article has successfully quantified the health loss and benefit caused by the life cycle of a diesel engine. The health loss and benefit are expressed in terms of DALYs. The health loss is quantified by applying LCA methodology. Value added in the form of employee compensation transferred to the engine over its life cycle is used as the variable to quantify health benefits.

Health loss and benefit triggered by the life cycle of a diesel engine produced in China is quantified. Two scenarios are set for the use phase of the engine. Scenario 1, where the engine is used in China, and scenario 2, where the engine is used in Indonesia. This research shows that the health loss caused by the pollution over the life cycle of the diesel engine (0.14 DALY for both scenarios) is lower than the health benefit achieved by the economic growth triggered by the engine’s supply chain (0.186 DALY for scenario 1 and 0.22 for scenario 2). It is also found that the breakeven point is reached faster if the engine is used in Indonesia (111,166 km in China and 75,697 km in Indonesia).

The limitations of this research are as follows: A higher GDP per capita does not always lead to a higher health quality, as can be seen from the model expressing the relationship between GDP per capita and DALY per capita, equation (7). The performance of this model is good for gaining insights into the behavior of economies. However, the value of R^2 of this model is only 72%. Furthermore, other factors, such as taxes and public services, may also contribute to the level of DALY of the society. The problem is how to link those factors to product functional unit in order to conduct a life cycle–based assessment. Moreover, using DALY alone is not enough for decision and policy making because there are other aspects that need to be considered, such as energy consumption, abiotic depletion, global warming, ozone layer depletion, eco-toxicity, cost, and the social impacts.

Furthermore, the use of the EIO method may not give an accurate value of ΔDALY benefit. The reasons are the following. First, in the EIO model an industrial sector is comprised by several industries producing products of the same type. The outputs of those industries are aggregated to reflect the output of the sector. This leads to uncertainty and affects the accuracy of the value of ΔDALY benefit. Second, the EIO model explains the structure of the economy in the past. For example, the EIO tables of the U.S. economy for the years 2013, 2012, 2011, and so on, are available, but there are no data yet for the

EIO table of the U.S. economy for the current year. Therefore, the estimate on ΔDALY benefit may not reflect the current situation. Third, if a comparison is performed, how the industrial sectors are defined may also have influence on the comparison being conducted. For example, the approach used by the government of China and Indonesia in defining the industrial sectors could be different. This will also have an effect on the quality of the comparison being made.

However, the proposed model can still be used to estimate the loss and benefit caused by the life cycle of a product. It can assist stakeholders in assessing product life cycle sustainability, reducing the negative effect of a product to human health, and increasing social and economic benefits during the life cycle of a product. Moreover, the proposed model has the potential to be expanded so that the environmental, economic, and social impacts of a product can be integrated. This will allow for a comprehensive life cycle–based sustainability metric to be developed.

Furthermore, the model may be modified to address the effects of technology adoption to DALY benefit and loss. From the perspective of LCA, adopting a new technology for transportation might not always reduce DALY loss. This is the case for electric vehicle technology, a popular transport alternative. According to Hawkins and colleagues (2013), an electric vehicle is cleaner than an internal combustion vehicle during its use phase. However, according to Hawkins and colleagues (2013), if lignite, coal, or heavy oil combustion is used as the source of electricity to energize an electric vehicle, the total environmental impact over the life cycle of an electric vehicle is higher than the total environmental impact over the life cycle of an internal combustion vehicle. This would lead to a higher value of DALY loss. Furthermore, the adoption of more complex and better technology over the life cycle of a vehicle will also affect DALY benefit. In fact, this might reduce the level of DALY benefit because of reduced labor hours. However, if the adoption of better technology requires a higher technical capacity of the workers, it might increase the level of DALY benefit because a higher technical capacity associates with a higher level of employee compensation. To get a clearer picture of how technology adoption affects human health, a comparative study considering the effects of technology adoption to DALY benefit and loss is recommended for future research.

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About the Authors

Feri Afrinaldi was a Ph.D. student in industrial engineering at Texas Tech University, Lubbock, TX, USA, when this research was performed. He is currently a postdoctoral researcher in industrial engineering at Texas Tech University and is also a faculty member at the Department of Industrial Engineering, Andalas University, Padang, Indonesia. **Hong-Chao Zhang** is the interim chair and Derr Endowed Professor at the Department of Industrial Engineering, Texas Tech University. **Zhi-Chao Liu** is a Ph.D. student at the Institute of Sustainable Design and Manufacturing, Dalian University of Technology, Dalian, China. **Annette Hernandez** is an associate professor at the Department of Civil and Environmental Engineering, Texas Tech University.

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