The International Journal of Life Cycle Assessment (2019) 24:753–766
https://doi.org/10.1007/s11367-018-1480-6

ROADWAYS AND INFRASTRUCTURE

Environmental and economic impact of using new-generation wide-base tires

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Received: 4 January 2018 / Accepted: 30 April 2018 / Published online: 15 May 2018

Abstract

Purpose New-generation wide-base tire (NG-WBT) is known for improving fuel economy and at the same time for potentially causing a greater damage to pavement. No study has been conducted to evaluate the net environmental saving of the combined system of pavements and NG-WBT. This study adopted a holistic approach (life cycle assessment [LCA] and life cycle costing [LCC]) to quantitatively evaluate the environmental and economic impact of using NG-WBT.

Methods The net effect of different levels of market penetration of NG-WBT on energy consumption, global warming potential (GWP), and cost based on the fatigue cracking and rutting performance of two different asphalt concrete (AC) pavement structures was evaluated. The performance of pavements was determined based on pavement design lives; pavement surface characteristics, and pavement critical strain responses obtained from the artificial neural network (ANN) based on finite element (FE) simulations were used to calculate design lives of pavements. Based on the calculated design lives, life cycle inventory (LCI) and cost databases, and rolling resistance (RR) models previously developed by the University of Illinois at Urbana-Champaign (UIUC) were used to calculate the environmental and economic impact of the combined system.

Results and discussion The fuel economy improvement using NG-WBT is 1.5% per axle. Scenario-based case studies were conducted. Considering 0% NG-WBT market penetration (or 100% standard dual tire assembly [DTA]) as a baseline, scenario 1 assumed the same fatigue and rutting potential between NG-WBT and DTA; therefore, the only difference came from fuel economy improvement of using NG-WBT. In scenario 2, pavement fatigue cracking potential determined the pavement design life; both thick and thin AC overlay sections experienced positive net environmental savings, but mixed net economic savings. In scenario 3, pavement rutting potential determined the pavement design life; the thick AC overlay section experienced positive net environmental savings, but mixed net economic savings. The thin section experienced negative net environmental and economic savings.

Conclusions The outcomes of scenario-based case studies indicated that NG-WBT can result in significant savings in life cycle energy consumption and cost, and GWP; however, these benefits were sensitive to the method used to determine the pavement performance; especially, a small change in pavement strain can result in significant change in pavement life. In addition, the effect of fuel price/economy improvement, discount rate, and International Roughness Index (IRI) threshold values was studied in the sensitivity analyses.

Keywords Fuel consumption · Infrastructure · Life cycle costing · Pavement · Roadway · Roughness · Wide-base tire · Tire

Abbreviations

AC	Asphalt concrete
AI	Asphalt Institute
ANN	Artificial neural network
DTA	Dual tire assembly
EI	Ecoinvent
FE	Finite element
GHG	Greenhouse gas
GWP	Global warming potential
IRI	International roughness index
LCC	Life cycle costing

Responsible editor: Omer Tatari

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LCI	Life cycle inventory
MPD	Mean profile depth
NG-WBT	New-generation wide-base tire
RAP	Reclaimed asphalt pavement
RR	Rolling resistance
UIUC	University of Illinois at Urbana-Champaign

1 Introduction

Despite its introduction in 1908, the early wide-base tire was not used in truck transportation because of several drawbacks associated with it, such as an uncomfortable ride and a greater risk of impact damage to the tire. After more than two decades of research by tire and pavement industries, a new-generation wide-base tire (NG-WBT) was introduced (Al-Qadi et al. (2004)). The introduction of the NG-WBT in the late 2000s, however, delivered superior vehicle stability, reduced vehicle weight and repair costs, and improved handling and fuel economy over standard dual-tire assembly (DTA) (North American Council for Freight Efficiency 2010). A study showed that using wide-base tires causes greater damage to pavement compared with standard DTA (Bonaquist 1992). Promoters of NG-WBT claim that NG-WBT induces less damage to pavement compared with early wide-base tires, and that they improve safety and environmental and economic characteristics (North American Council for Freight Efficiency 2010).

This study evaluates these claims by conducting life cycle assessment (LCA) and life cycle costing (LCC) which help balance the burden of increased pavement damage with the benefits to vehicles from using NG-WBT. Scenario-based case studies investigating the result of these benefits and burdens are presented.

2 Background

A number of studies evaluated existing pavement LCA and models, including studies by Santero et al. (2011), Kendall (2007), Zhang et al. (2010), Mukherjee and Cass (2012), and Wang et al. (2012a). Yang et al. (2015) and Golestani et al. (2017) studied the environmental and economic impact of using recycling materials in asphalt concrete (AC) mixtures. A framework and a guideline for pavement LCA were developed by the University of California Pavement Research Center (UCPRC) (Harvey et al. 2011). Some LCA studies estimated the emissions and/or energy consumption in the use stage. Santero (2009) estimated CO_2 emissions caused by rolling resistance based on the vehicle mile traveled and vehicle fuel economy. Yu and Lu (2012) computed energy consumption and greenhouse gas (GHG) emission from rolling resistance using a fuel consumption factor. Wang et al., 2012bevaluated the impact of pavement surface characteristics, vehicle type, traffic conditions on rolling resistance, vehicle fuel consumption, and GHG emission during the use stage of pavement LCA. Trupia et al. (2017) studied the contribution of rolling resistance in pavement LCA and found traffic growth and fuel efficiency have a limited impact in the use stage. The modeling of NG-WBT and the corresponding response in pavements were studied in Hernandez and Al-Qadi (2016), Hernandez et al. (2016), and Gungor et al. (2016).

A number of research evaluated the effect of wide-base tires on vehicle fuel consumption. Genivar (now rebranded WSP global) conducted a study in 2005 (GENIVAR Consulting Group 2005) to evaluate the costs and benefits of proposed amendments to Québec's Vehicle Load and Size Limits Regulations. The economic analysis included the direct costs (i.e., damage to pavement), direct benefits (i.e., reduced operating costs by the trucking industry), indirect costs (i.e., higher cost of purchasing and retreading NG-WBT), and indirect benefits (i.e., a reduced fuel consumption and vehicle emissions related cost). According to Genivar, Michelin's super single tires reduce vehicle rolling resistance by 12%, which is equivalent to fuel saving of 4%. The study also reported that six of the seven Québec trucking firms observed reductions in fuel consumption ranging from 3.5 to 12%.

A 2010 report by North American Council for Freight Efficiency (North American Council for Freight Efficiency (NACFE), 2010) states that the use of wide-base tires brings fuel savings of 3 to 6% depending on the adoption at the tractor and trailer wheel positions. Ponniah et al. (2010), after a thorough review of past studies (GENIVAR Consulting Group 2005; Markstaller et al., 2000; US Environmental Protection Agency 2004; Weber 2002; Michelin X-One Brochure 2009; Al-Qadi and Elseifi (2007), adopted a 1.5% fuel savings per axle. A study by Franzese et al. (2010) investigated the change in fuel consumption of Class 8 combination trucks equipped with wide-base tires. It was found that when either the truck or the trailer was equipped with wide-base tires, the improvement was 6%, and when both were equipped with wide-base tires, the improvement reached 9%. The final reduction adopted in the study was 1.5% per axle because of its reasonable representativeness of various sources, and flexibility to account for axles equipped with NG-WBT.

These studies focused on the direct fuel consumption savings from using the NG-WBT only during the use stage. However, a more holistic life cycle perspective is needed to understand the impact of NG-WBT. Hence, the following need to be addressed:

- A holistic study comparing the environmental and economic impacts of NG-WBT to standard DTA using LCA and LCC;

- A mechanistic approach to evaluate the impact of NG-WBT;
- Impact of various market penetrations of NG-WBT on environment and economy; and
- Sensitivity analyses on fuel price, discount rate, fuel economy improvement, and International Roughness Index (IRI) threshold values on economy.

The subsequent section discusses the objective and methodology of this study, followed by scenario-based case studies and sensitivity analyses.

3 Objective of the study

To address the aforementioned gap in knowledge with respect to the impact of NG-WBT, the objective of this paper is to provide a methodology to evaluate the energy consumption, global warming potential (GWP) based on GHGs, and cost during the pavement life cycle with an emphasis on the impact of NG-WBT on asphalt concrete (AC) overlay design life and fuel economy. In this paper, energy consumption refers to the primary energy and secondary energy consumed in material production and equipment operation, excluding the feedstock energy of asphalt binder used in overlay construction. In the use stage, the embodied energy of fuel is referred to as energy. The intended audience includes state and local transportation agencies, trucking industry, and tire manufacturers. In addition, the result of the study may be of interest to the pavement industry and academic scholars specialized in transportation. The result of this comparative LCA study will be disclosed to the public.

4 Methodology

Evaluating the effect of NG-WBT in pavement LCA is not simple because there are numerous variables affecting the result. This study focuses only on few parameters that can significantly affect the analysis. The selected parameters are two asphalt concrete (AC) pavement structures, two different levels of truck traffic, and five levels of market penetration of NG-WBT. This section will address the scope of the study based on ISO 14044:2006 (International Organization for Standardization (ISO), 2006). Modeling of each pavement life cycle, progression equations of the pavement surface, and transfer functions for fatigue cracking and rutting for pavement design life calculation are discussed. Figure 1 shows the overall procedure of environmental and economic assessments of NG-WBT performed in the paper.

4.1 Scope of the study

The product system in the study includes an AC overlay construction (including milling, a new AC overlay, and the impact of interaction between vehicle and pavement due to NG-WBT). An AC overlay is a rehabilitation activity conducted during pavement life cycle to resist traffic and other environmental conditions as a functional roadway for automobiles during its design life. Detailed information about the two pavement sections and other conditions is summarized in Table 1. The cross-sections of two pavement structures are presented in Fig. 2. This study only considers the surface AC overlay; pavement structure below the surface overlay (same for both structures) is out of scope. The scope of the study covers material, construction, and use stages as illustrated in Fig. 3.

The production and transportation of pavement materials and equipment usage during construction activities including milling and removing existing AC pavement as well as placing a new AC overlay are considered. Also considered in the study is the hauling of milled existing AC pavement away from the site. The LCA of tires is not included in the study due to data unavailability.

The indicators selected in the study are energy consumption, GWP, and cost during the specified pavement life cycle stages because these are widely used indicators by government agencies, industry, and public. Environmental Protection Agency's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1 was used for impact characterization as the study was conducted in the USA. Instead of keeping a common analysis period, the study annualizes the total environmental and economic impacts during relevant life cycle stages, assuming that the rehabilitation will be repeated when they reach their design lives. The annualization of results allows for a comparison among cases with different pavement design lives. The results of economic savings were annualized in present worth value with a discount rate of 3%.

The functional unit of this study is two-mile AC pavement with two lanes in one direction with the annualized analysis period. Additional pavement damage caused by NG-WBT was estimated based on rutting and fatigue cracking potential of the pavement. Details about modeling of each pavement life cycle are discussed in the following section.

4.2 Pavement life cycle modeling

4.2.1 Material stage

The materials used in an AC overlay construction are asphalt binder, aggregate, mineral fillers, and reclaimed asphalt pavement (RAP). The operation of asphalt plant and material hauling were also considered. The life cycle inventory (LCI)

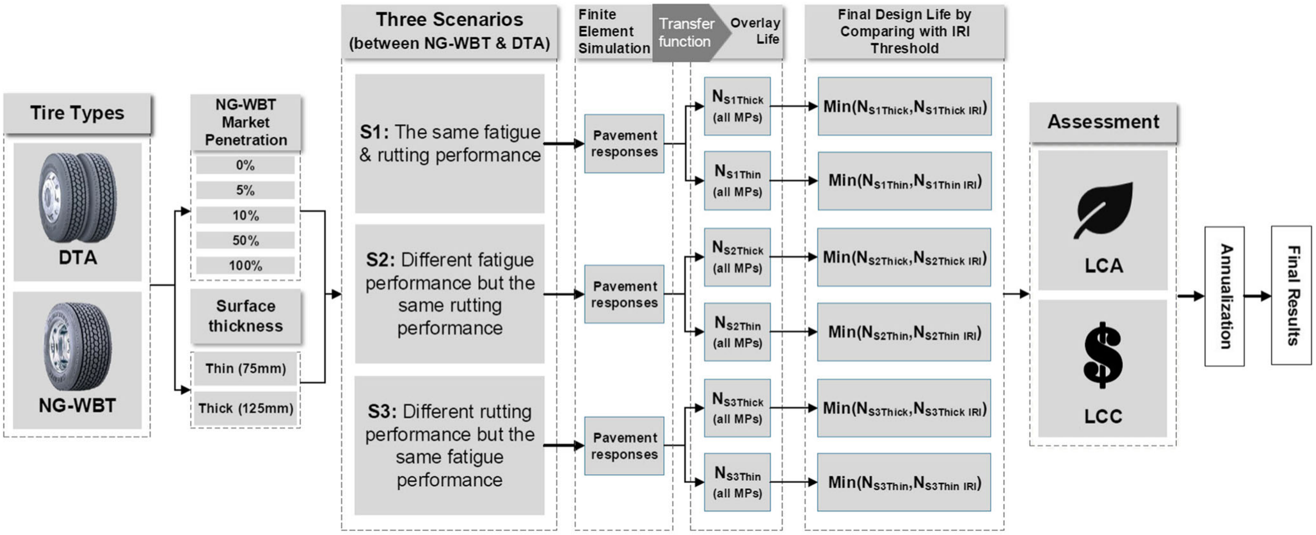


Fig. 1 Overall procedure of environmental and economic assessment of NG-WBT for scenario-based case studies

and cost databases previously developed (Kang 2013; Kang et al. 2014; Ozer et al. 2017) and modified with default US-Ecoinvent (US-EI) 2.2 unit processes (EarthShift 2013) to reflect general conditions of North America were used to calculate the energy consumption, GWP, and cost associated with the production and transportation of pavement materials.

4.2.2 Construction stage

The environmental impacts and cost from the construction stage include fuel use and emissions resulted from both construction equipment and construction-related traffic. This study assumed that construction occurs during 9-h nighttime closures, so a minimal impact from construction induced traffic delay was assumed. The information on productivity and fuel consumption of construction equipment for relevant construction activities for AC overlay was obtained from University of Illinois at Urbana-Champaign's (UIUC) pavement pay-item database (Ozer et al. 2017). Environmental Protection Agency (EPA)'s Motor Vehicle Emissions Simulator (MOVES) (Motor Vehicle Emissions Simulator (MOVES) 2016a Model 2016) was used to obtain emission factors of construction equipment. Environmental impacts associated with diesel combustion by equipment were obtained from US-EI 2.2 (EarthShift 2013).

The construction data flow begins with the design. The design pavement structure is related to a given set of construction, maintenance, and rehabilitation tasks grouped together based on the construction plan. Each task has a productivity rate indicating how fast the task can be done, and a set of default equipment is assigned to each task. The task productivity is related to the individual equipment fuel consumption to calculate the fuel usage for the task. Based on the fuel used by each piece of equipment, emissions and environmental impacts are computed. Construction tasks used in the study include pavement milling, removing, brooming, paving, and hauling (Kang et al. 2018). Cost information associated with these tasks was obtained from the UIUC pay item database

Table 1 Information on two asphalt concrete (AC) pavement sections

Case study	Thick AC surface (671HC)	Thin AC surface (670HC)
County	Nevada	Los Angeles
Route	I-80 Westbound	SR-213 Westbound
Surface	Asphalt Concrete	Asphalt Concrete
Section length	3129 m (2 miles)	3129 m (2 miles)
Number of lanes (One-way)	2	2
Lane width	3.66 m (12 ft)	3.66 m (12 ft)
AADT (One-way)	13,500	15,750
Truck percentage	19%	2%
Construction type	Mill and AC overlay	Mill and AC overlay
AC layer thickness	125 mm (4.9 in)	75 mm (3.0 in)
Tire types analyzed	Standard DTA and four levels of market penetration of NG-WBT	Standard DTA and four levels of market penetration of NG-WBT

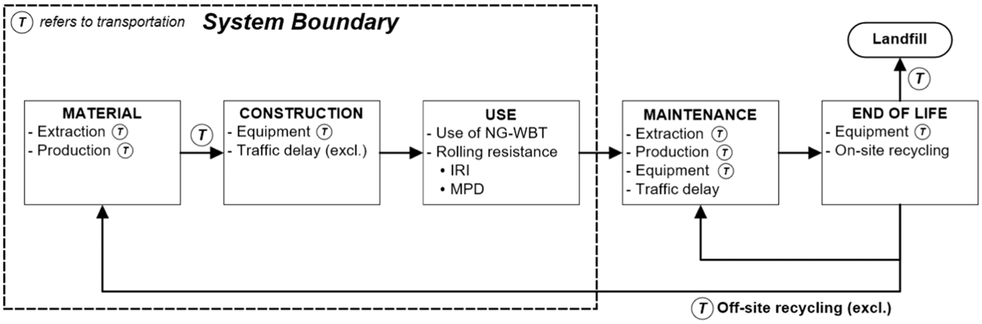


Fig. 2 Pavement life cycle stages and system boundary of the study

(Kang 2013; Kang et al. 2014; Ozer et al. 2017) and compared with various sources (California Department of Transportation 2011; Brock and Richmond 2006; Davis et al. 2017) for validation. Data sources used for construction stage are summarized in Table 2.

4.2.3 Use stage

According to Harvey et al. (2011), the use stage considers negative impacts (i.e., additional fuel consumption, emissions, damage to vehicles, and tire wear) from deterioration of the pavement, the heat island effect, albedo, and carbonation of concrete pavements. This paper focused on the additional burden from an increased rolling resistance caused by deteriorated pavement as its impact is dominating on all pavement life cycle stages as well as within the use stage (Santero 2009; Wang et al., 2012a). For use stage modeling, the time progression of pavement surface characteristics (International Roughness Index [IRI] and Mean Profile Depth [MPD]) under DTA on a road segment was generated from pavement performance model based on a pavement condition survey by UCPRC. Based on different market penetration of NG-WBT and design lives of AC overlay, separate overlay surface progression models were developed for NG-WBT. Based on UIUC's rolling resistance model and literature (Ziyadi et al. 2018; Chatti and Zaabar 2012; Kerali, 2002), the impact of surface characteristics on vehicle fuel consumption were quantified, and these values were used to update the relevant parameters in the vehicle emission model (Motor Vehicle Emissions Simulator (MOVES) 2016a Model (2016). A detailed rolling resistance model development procedure is discussed elsewhere (Ziyadi et al. 2018).

Since there is no existing model for IRI performance under NG-WBT, this paper developed three scenarios for evaluating the potential impacts from NG-WBT on pavement IRI. In addition, the relationship among pavement surface characteristics, rolling resistance, and vehicle fuel consumption for vehicles equipped with NG-WBT is not developed to date; therefore, this study adopted an average fuel economy improvement of 1.5% per axle as previously mentioned. The results of

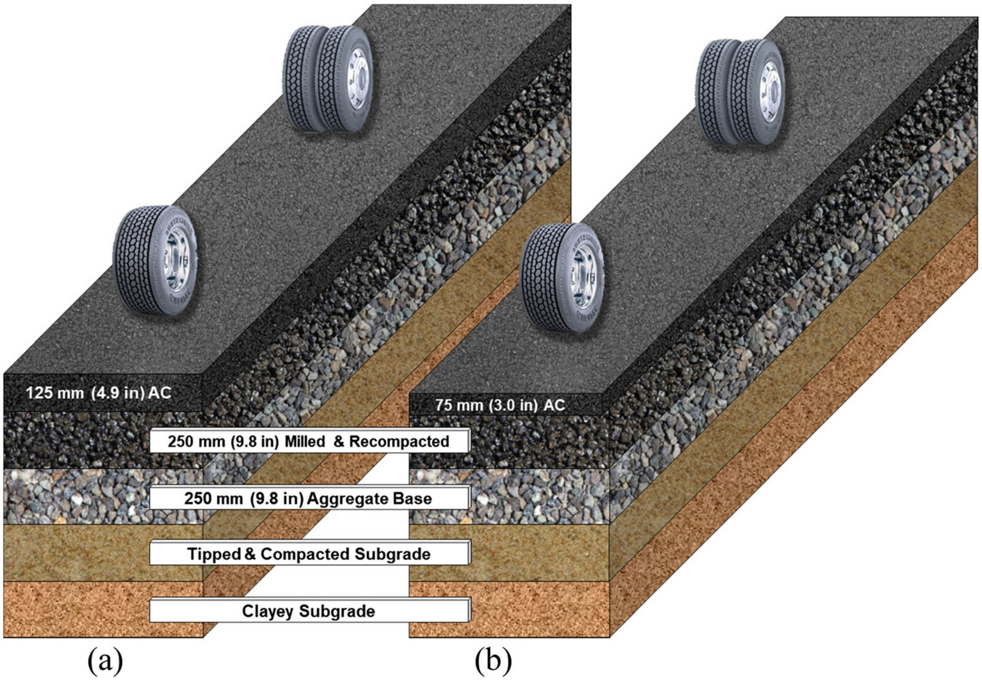


Fig. 3 Cross-sections of two asphalt concrete (AC) pavement structures **a** 671HC (thick [125 mm] AC overlay) and **b** 670 HC (thin [75 mm] AC overlay)

Table 2 Data sources used for modeling construction stage impact database

Data sources	Purpose
Ozer et al. (*2017*)	Pay item database for on-site equipment fuel consumption and productivity
EarthShift (*2013*)	Emission factors and environmental impacts from equipment fuel combustion and upstream fuel production
EPA MOVES (*2016*)	Construction equipment emissions factors from simulations

economic savings were calculated from the computed energy savings in the use stage using higher heating value conversion factors from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) (Greenhouse gases, regulated emissions, and energy use in transportation (GREET) (rev2), 2012). The amount of fuel saving in the use stage was then multiplied by the unit price of diesel in 2012 ($1.05 per liter or $3.97 per gal) to compute the monetary saving. The effect of diesel price and NG-WBT fuel economy improvement on the overall environmental and economic savings was also studied using sensitivity analyses in Section 6.4.

4.2.4 Performance models for IRI and MPD

The IRI and MPD progression models for AC overlays were taken from studies by Tseng (2012) and Lu et al. (2009), respectively. The first 7 years of IRI and MPD progressions for both 671HC and 670HC overlay sections are illustrated in Figs. 4 and 5, respectively.

4.2.5 Transfer functions

As mentioned in the scope of the study, this paper considered three failure criteria (fatigue cracking, rutting, and IRI) to determine the design lives of pavement as a result of different levels of market penetration of NG-WBT. Transfer functions from the Asphalt Institute (AI) were used to compute the number of repetition for each failure criteria. The Mechanistic Empirical Pavement Design Guide transfer functions are used primarily for fatigue cracking progression (Kang and Adams 2007), so the AI transfer functions were used to determine the number of repetitions to failure in this study. The stiffness value of thick and thin AC surface courses was 2600 MPa (377 ksi). Equations (1) and (2) show the AI transfer function for bottom-up fatigue cracking, and eq. (3) shows the AI transfer function for rutting:

$$N_f = 0.0795 \times C\varepsilon_t^{-3.291} \left| E^* \right|^{-0.854} \tag{1}$$

$$C = 10^{4.84\left(\frac{V_b}{V_a+V_b}-0.69\right)} \tag{2}$$

where

N_f	is the maximum allowed repetition;
C	is the correction factor;
V_a	is the volume of asphalt in the mix;
V_b	is the volume of air in the mix;
ε_t	is the tensile strain; and
E^*	is the stiffness (dynamic modulus) of asphalt in units of psi.

$$N_d = 1.365 \times 10^{-9} (\varepsilon_c)^{-4.447} \tag{3}$$

where

N_d	is the maximum number of axle loads to the rut depth failure criteria (1.3-cm [0.5-in] rut depth)
ε_c	is the vertical compressive strain on top of the subgrade.

5 Case studies

The scope of the study includes two case studies based on two AC pavement structures (671HC and 670HC), as illustrated in Fig. 3. From here on, 671HC and 670HC will be referred to as thick and thin sections, respectively. Each case study considers AC overlay construction in 2012 with the same thickness as the AC layer in the original pavement. As mentioned in the scope of the study, the results in the case studies were annualized to enable comparison among cases with inconsistent pavement design lives. Setting DTA as the baseline (0% market penetration of NG-WBT), four different levels of NG-WBT market penetrations (5, 10, 50, and 100%) were considered. As the IRI progression model for NG-WBT is not developed to date, the following three scenarios were assumed:

Fig. 4 IRI and MPD progression of 671HC (thick) section

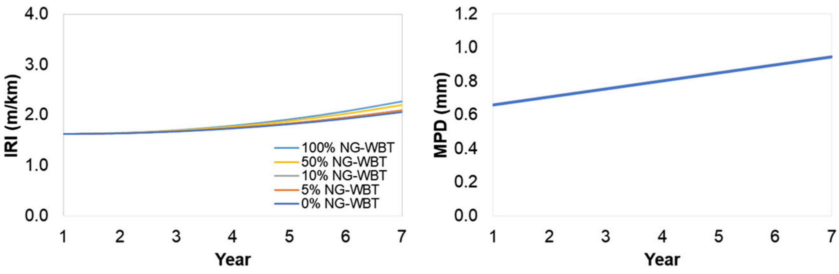
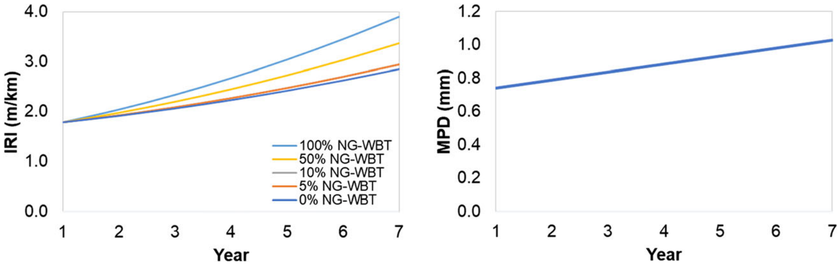


Fig. 5 IRI and MPD progression of 670HC (thin) section



- Scenario I: DTA and NG-WBT have the same impact on fatigue cracking and rutting potential (indicated by IRI), thus pavement sections exposed to DTA or NG-WBT have the same design lives and therefore the only difference comes from the fuel economy improvement by NG-WBT.
- Scenario II: DTA and NG-WBT have different fatigue cracking potential, but the same rutting potential. Different market penetrations of NG-WBT have different maximum number of repetitions and pavement design lives are calculated using Miner's rule.
- Scenario III: DTA and NG-WBT have the same impacts on pavement's fatigue cracking potential, but different impacts on the pavement's roughness performance. The rutting performance model was used as an approximate indicator for roughness performance. The difference in IRI performance between DTA and NG-WBT was considered proportionate to the difference in their respective rutting
- Life based on the models presented in Von Quintus et al. (2001). The annual IRI value under NG-WBT was calculated using eq. (4).

$$\Delta IRI_{NG-WBT \text{ between Year } j \text{ and } i} = \Delta IRI_{DTA \text{ between Year } j \text{ and } i} \times \frac{\text{Rutting life with } DTA}{\text{Rutting life with } NG-WBT} \quad (4)$$

where

$\Delta IRI_{NG-WBT \text{ between Year } j \text{ and } 1}$	increase of IRI value between Year j and Year i under NG-WBT, in m/km;
$\Delta IRI_{DTA \text{ between Year } j \text{ and } 1}$	increase of IRI value between Year j and Year i under DTA, in m/km;
Rutting life of *DTA*	pavement design life in years under DTA calculated based on the rutting model shown in eq. [3]; and
Rutting life of *NG−WBT*	pavement design life in years under NG-WBT calculated based on the rutting model shown in Eq. [3].

In any scenario, the overlay rehabilitation was triggered if the IRI value exceeded 170 in/mi. Maximum tensile strain and compressive strain in thin and thick sections (Fig. 3) were predicted using a previously developed artificial neural network (ANN) model based on finite element (FE) simulations (Ziyadi and Al-Qadi 2017) and fed into the distress models shown in Eqs. (1), (2), and (3). The maximum tensile strain values were obtained under 80-kN (18-kip) axle load, temperature of 20 °C (68 °F), and tire pressure of 689 kPa (100 psi). The maximum number of repetition and the design life for each scenario are presented in Tables 3 and 4, respectively.

6 Results and discussion

The environmental and economic impacts of each scenario in the following section are normalized by the predefined functional unit, project-year.

6.1 Scenario 1: same fatigue and rutting potential between DTA and NG-WBT

As the only difference between DTA and NG-WBT is the fuel economy improvement, reduction of GWP, energy saving, and economic saving against the baseline (0% NG-WBT market penetration) were observed. The results are summarized in Fig. 6. The impact of rolling resistance due to IRI and MPD is referred to as *RR* throughout Section 6.

6.2 Scenario 2: fatigue potential determines the pavement design life

In this scenario, the pavement life is determined by fatigue cracking performance. NG-WBT introduces a higher tensile strain at the bottom of the AC layer causing a reduced pavement design life. This also means the higher the market penetration of NG-WBT, the greater the predicted reduction in pavement design life. The results of scenario 2 are summarized in Fig. 7.

The results show that the damage to pavement from NG-WBT imposed a very significant impact on the material production and construction stages. When this impact was included in the analysis, various consequences were observed for the thin and thick sections. For the thick section, net savings in energy consumption and GWP were positive for all market penetration of NG-WBT. However, the net economic saving

Table 3 Maximum tensile and compressive strains for cases 670HC and 671HC

Tire type	Distress type	Location and type of strain	Case 670HC (thin overlay)	Case 671HC (thick overlay)
DTA	Fatigue cracking	Max tensile strain on the bottom of AC (microstrain)	282.29	178.38
		Max allowed repetitions	617,891	4,572,714
	Rutting	Max compressive strain on the top of subgrade (microstrain)	529.53	339.34
		Max allowed repetitions	634,271	4,650,284
NG-WBT	Fatigue cracking	Max tensile strain on the bottom of AC (microstrain)	355.52	211.38
		Max allowed repetitions	289,239	2,615,586
	Rutting	Max compressive strain on the top of subgrade (microstrain)	615.86	375.61
		Max allowed repetitions	322,568	2,951,443

Table 4 Annual damage and design life for (a) scenarios 1, (b) 2, and (c) 3

Pavement section	Market penetration of NG-WBT	Annual damage	Design life (year)	IRI trigger life (year)
(a)				
671HC (thick overlay)	0% (or 100% dual tire, i.e., baseline)	0.0909	12	11
	5%	0.0909	12	11
	10%	0.0909	12	11
	50%	0.0909	12	11
	100%	0.0909	12	11
670HC (thin overlay)	0% (or 100% dual tire, i.e., baseline)	0.0915	11	7
	5%	0.0915	11	7
	10%	0.0915	11	7
	50%	0.0915	11	7
	100%	0.0915	11	7
Pavement section	Market penetration of NG-WBT	Annual damage	Design life (year)	IRI trigger life (year)
(b)				
671HC (thick overlay)	0% (or 100% dual tire, i.e., baseline)	0.0909	12	11
	5%	0.0943	11	11
	10%	0.0977	11	11
	50%	0.1248	9	11
	100%	0.1588	7	11
670HC (thin overlay)	0% (or 100% dual tire, i.e., baseline)	0.0915	11	7
	5%	0.0968	11	7
	10%	0.1020	10	7
	50%	0.1436	7	7
	100%	0.1956	6	7
(c)				
671HC (thick overlay)	0% (or 100% dual tire, i.e., baseline)	0.0893	12	11
	5%	0.0919	11	11
	10%	0.0945	11	11
	50%	0.1151	9	10
	100%	0.1408	8	10
670HC (thin overlay)	0% (or 100% dual tire, i.e., baseline)	0.0892	12	7
	5%	0.0935	11	7
	10%	0.0978	11	7
	50%	0.1323	8	6
	100%	0.1754	6	5

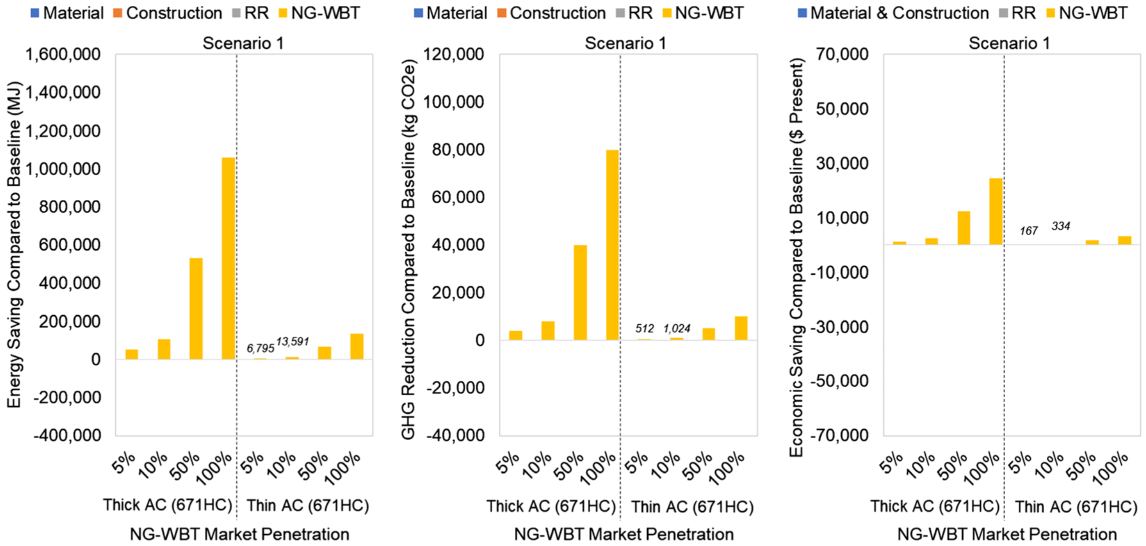


Fig. 6 Scenario 1 results for case 671HC (thick) and case 670HC (thin)

for any market penetration was slightly negative as the value of calorific or energy value divided by the unit cost of fuel is very high compared with that of pavement materials. Similarly, for the thin section, net savings in energy consumption and GWP were positive for all market penetration but economic savings were negative at 100% market penetration because of a reduced overlay service life and a low truck percent.

6.3 Scenario 3: rutting potential determines the pavement design life

This part of the study used rutting life to estimate the IRI performance under NG-WBT. The use stage (RR and NG-WBT) results of scenario 3 for the thick and thin cases were contrasting as seen in Fig. 8. For the thick case, savings in energy and GWP from fuel economy improvement were greater than burdens from rolling resistance (due to IRI and MPD) so net savings in energy and GWP in the use stage were positive at all market penetrations. Net economic savings were slightly negative because the value of calorific or energy value divided by the unit cost of fuel is very high compared with that of pavement materials. The thin AC section experienced negative net savings in energy, GWP, and cost at all market penetrations in the use stage because roughness-induced burdens were greater than savings from fuel economy improvement due to significantly faster IRI progression. For both cases, reduced overlay service lives resulted in additional burdens in material and construction stages.

The percent changes in net environmental savings in scenarios 2 and 3 with respect to Scenario 1 (baseline) are presented in Table 5.

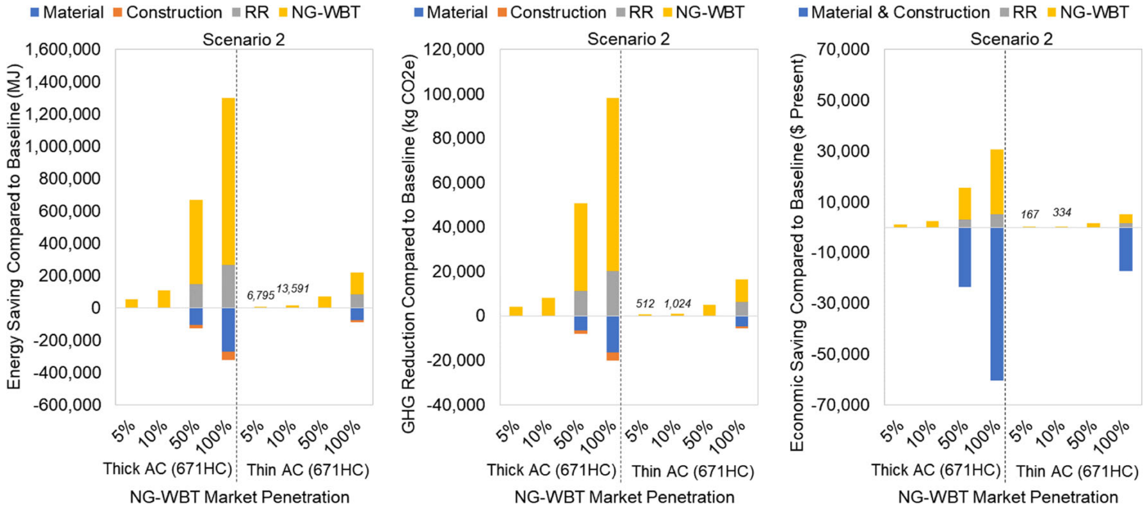


Fig. 7 Scenario 2 results for case 671HC (thick) and case 670HC (thin)

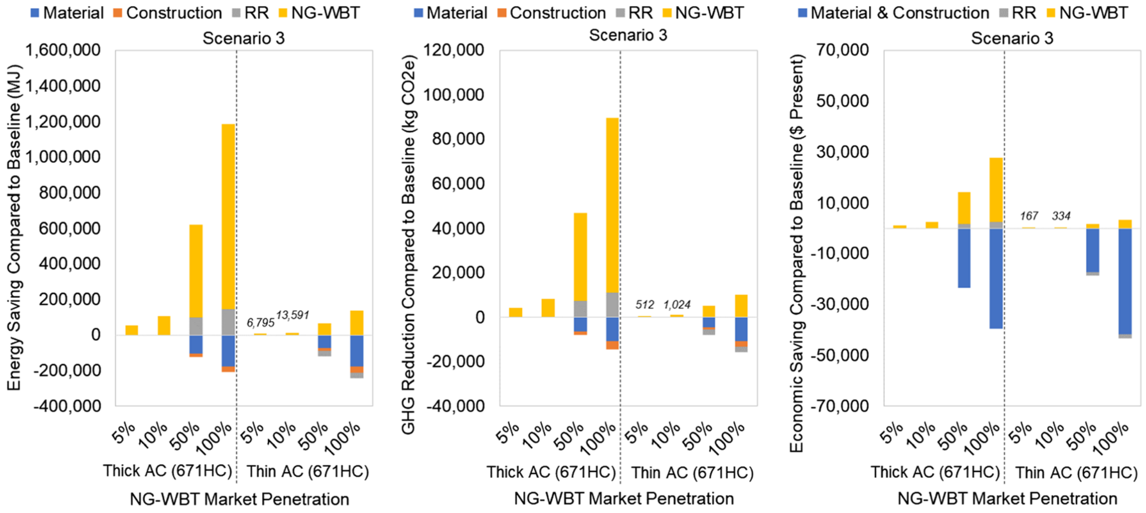


Fig. 8 Scenario 3 results for case 671HC (thick) and case 670HC (thin)

6.4 Sensitivity analysis

The following sensitivity analyses were conducted to study the effect of fuel price and discount rate, fuel economy improvement, IRI, and tensile strain:

- Analysis I: fuel price (from \$1.05 to \$0.79 per liter [\$3.97 to \$3.00 per gal]) and discount rate (from 3% to 7%)
- Analysis II: fuel economy improvement (from 1.5% to 2.5% per axle)
- Analysis III: IRI threshold values (from 2.69 m/km [170 in/mi] to 2.53 m/km [160 in/mi] or 2.84 m/km [180 in/mi])
- Analysis IV: maximum tensile strain on the bottom of AC (10 and 25% increases)

Considering the result of the case study in Section 6.1 to 6.3 (scenarios 1, 2, and 3) as the reference, their effects (analyses I, II, and III) on cost are shown in Fig. 9 through Fig. 12. Their effects on net environmental impacts are mostly positive as seen in case studies (Fig. 6 to Fig. 8); therefore, only the result of cost sensitivity analyses is presented hereafter.

Comparing with the reference, a reduction in the price of diesel fuel and an increased discount rate reduced the net cost saving in all cases (Fig. 9). An increase in fuel economy improved net GWP saving significantly in all scenarios; the thick section in scenario 3 experienced net positive economic savings at all NG-WBT market penetration as shown in Fig. 10. When the IRI threshold value is 2.53 m/km (160 in/mi), the thin section in scenario 3 experienced a reduction in the

Table 5 Percent change in net environmental savings compared to baseline (scenario 1)

Scenario #	NG-WBT market penetration (%)	Pavement structure	Change in net energy saving (%)	Change in net GHG reduction (%)
2	5	Thick	0.0	0.0
	10		0.0	0.0
	50		3.1	7.2
	100		− 7.6	− 2.5
	5	Thin	0.0	0.0
	10		0.0	0.0
	50		0.0	0.0
	100		− 4.3	− 7.3
3	5	Thick	− 2.4	− 2.5
	10		− 1.2	− 1.2
	50		− 9.6	− 9.7
	100		− 0.4	− 3.8
	5	Thin	− 20.1	− 20.5
	10		− 10.1	− 10.2
	50		− 175.0	− 154.5
	100		− 175.0	− 161.7

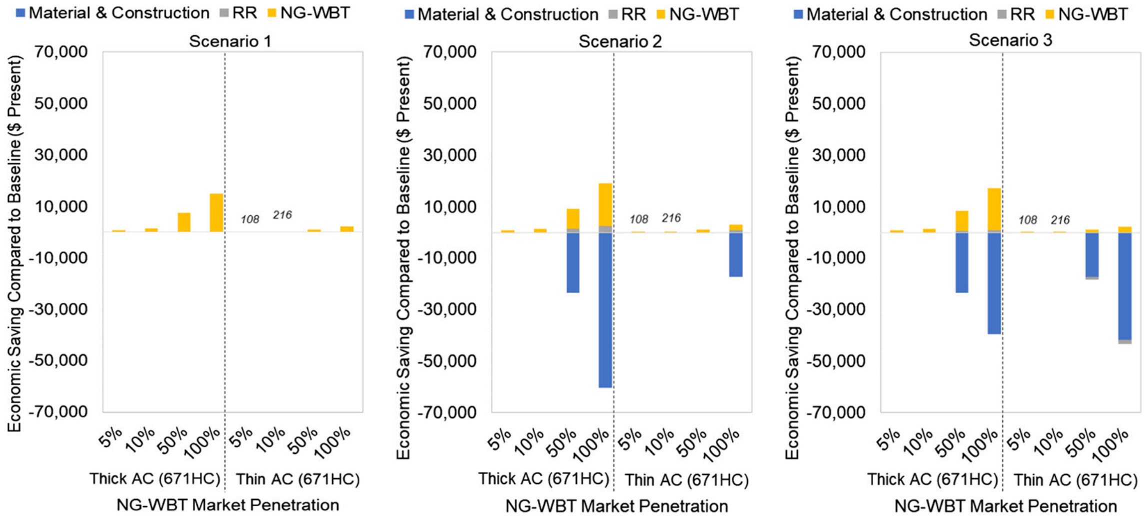


Fig. 9 The result of sensitivity analysis I on net cost saving

overlay design life at market penetration of 100%; therefore, the economic burden in material and construction stages increased (Fig. 11). When the IRI threshold value is 2.84 m/km (180 in/mi), an additional burden in material and construction stages was experienced (at 5, 10, 50, and 100% NG-WBT market penetration) because of an increased thick overlay design life in scenarios 2 and 3 at 0% market penetration (Fig. 12).

In addition, the analysis IV showed that 10 and 25% increases in maximum tensile strain (on the bottom of AC) decreased the thick overlay design life by at least 25 and 50%, respectively, negatively impacting the net environmental and economic savings at any NG-WBT market penetration.

7 Summary and conclusions

The net effect of using NG-WBT on energy consumption, GWP, and cost of two different AC overlay structures based on their fatigue cracking and rutting potential, and IRI progression were evaluated using LCA and LCC in this study. Maximum tensile and compressive strain values were obtained using a neural networks model developed based on FE simulations and were used to compute the design life of AC overlay using AI distress models. Considering a 1.5% fuel economy improvement per axle of NG-WBT, case studies with three possible scenarios were considered: (1) DTA and NG-WBT with the same fatigue cracking and rutting potential;

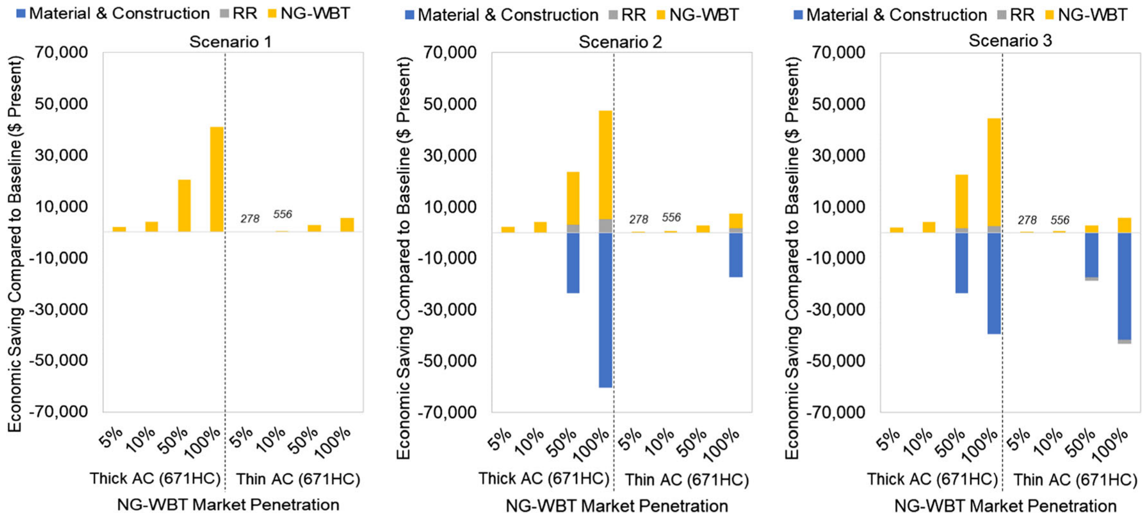


Fig. 10 The result of sensitivity analysis II on net cost saving

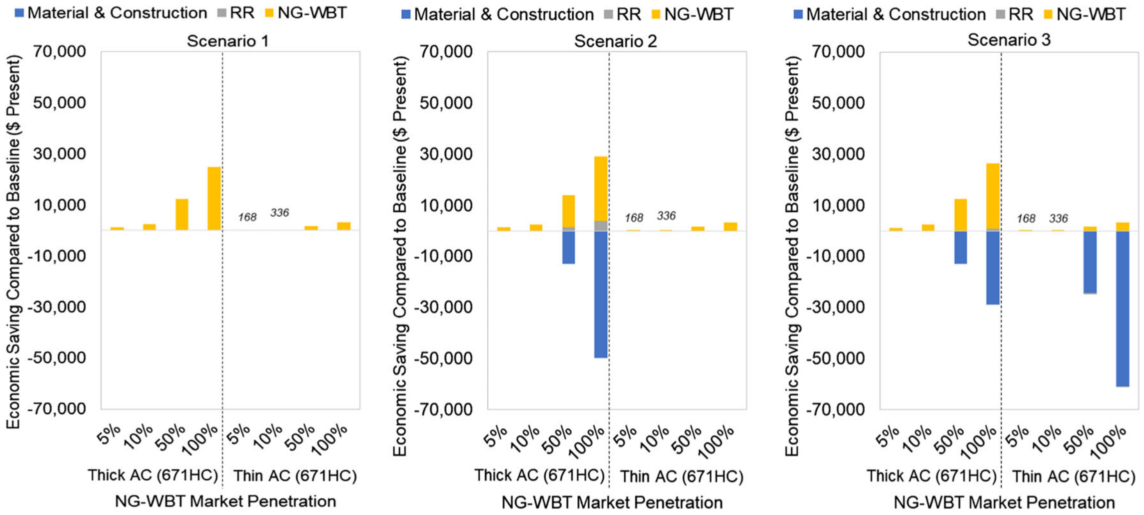


Fig. 11 The result of sensitivity analysis III on net cost saving for IRI threshold value of 2.53 m/km (160 in/mi)

(2) design lives determined by fatigue cracking potential; and (3) design lives determined by rutting potential.

From the case study, it is evident that NG-WBT can result in significant environmental and economic savings; in most cases, the net environmental savings were positive, but the net economic savings varied among cases. This was because the value of energy divided by the unit cost for fuel is much higher than that of pavement materials; fuel considers the embodied energy as its energy, but material considers the processing energy (with upstream) as its energy. This explains the reason for higher environmental savings compared with the economic savings in the study. In any scenario, the economic and environmental benefits were more prominent for the thick AC overlay (due to higher truck percent) at higher NG-WBT market penetration. However, it is difficult to generalize life cycle environmental and economic savings from NG-WBT because the results may vary depending on parameters such as pavement structural capacity, number of truck traffic, and pavement rehabilitation schedule. The economic savings may have been underestimated because only fuel cost was considered in the use stage for the economic assessment. In a future study, other potential cost savings from emissions, tire (maintenance), and truck weight reduction can be considered for a more comprehensive evaluation of the economic benefits of using NG-WBT.

In addition, it was seen in sensitivity analyses that a reduction in fuel price and an increase in discount rate resulted in the reduction in net economic saving; however, a higher fuel economy improvement increased economic savings in all scenarios. To sum up, this study evaluated the environmental and economic consequences of adopting a new tire technology for an important transportation infrastructure facility using LCA and LCC. Environmental and economic benefits were sensitive to the method used to determine the pavement performance; especially a small change in IRI threshold value or pavement response (i.e., strain and stress) can also result in significant change in pavement life as well as environmental and economic savings.

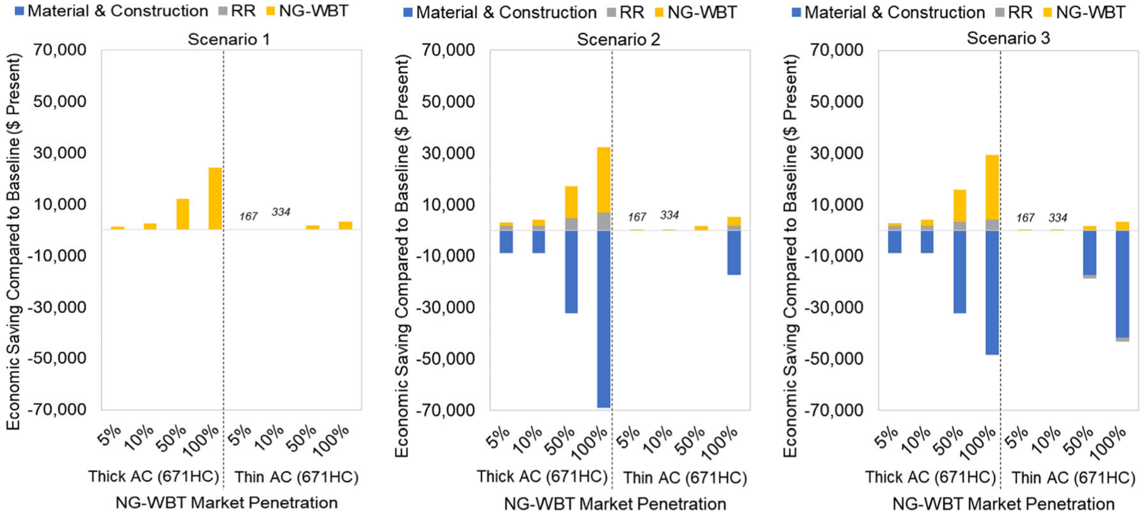


Fig. 12 The result of sensitivity analysis III on net cost saving for IRI threshold value of 2.84 m/km (180 in/mi)

Acknowledgements Authors are representatives of the Illinois Center for Transportation (ICT), and UCPRC.

Funding information This project is funded by the Federal Highway Administration (FHWA); inputs provided by Eric Weaver from the FHWA are greatly appreciated.

Disclaimer

The contents of this report reflect the view of authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view of policies of the FHWA, ICT, or UCPRC. This paper does not constitute a standard, specification, or regulations.

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