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Modeling fuel efficiency for heavy duty vehicles (HDVs) in India

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Abstract Transport sector accounts for almost 70% consumption of diesel in India. With increased dependency on road transportation for freight transport, there is a need to develop fuel-efficiency standards for the heavy duty vehicles (HDVs). This study models the fuel efficiency of the existing fleet of HDVs and compares it with the world's best practices. The model uses the technical details of the existing HDV fleet and the prescribed driving cycles to assess fuel efficiency. The results of the model are validated with the actual test results of fuel efficiency observed for HDVs in India. The model presents a fuel economy of 2.65 km/l for truck and bus model of given specification. The validated model is then used for evaluating the potential of different strategies to improve fuel efficiency. The models estimate a potential of about 36% improvement in the fuel efficiency in the HDVs in India through improvements in thermal efficiency, reduction in rolling resistance, and reduction in vehicle weight. The study provides a direction for the possible fuel efficiency improvements in HDV sector in India.

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Introduction

Transport sector is one of the major consumers of fossil fuels after industrial sector in India. It accounts for almost 70% of the total diesel consumption in India (MoPNG 2013). Road transportation accounts for 50% of freight and 90% of passenger movement in India (PC 2014). Correspondingly, a significant decline in the share of rail-based transport is observed in India in last few decades. This has eventually led to increased consumption of fuel as road transportation is considered to be less efficient than the rail-based movements. Considering the limited availability of fossil fuels in India, the geo-political variability, and environmental issues, there is an utmost need for improving the fuel efficiency of the heavy duty vehicle (HDV) fleet in India. It is therefore necessary to introduce fuel-efficiency standards and required technologies to curb the fuel consumption in heavy duty vehicles. The fuel efficiency standards for light duty vehicles have already been introduced in India in 2014; however, similar standards for HDV segment are yet to be considered and notified.

Due to the preference of road transportation for freight and passenger transportation, there is increased demand for trucks and buses on Indian roads. Growing infrastructure sector and demand for transportation of agriculture and industrial products have played a major role in the growth of HDV market in India. HDVs have a share of just 4–6% in the total number of registered

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vehicles in India, but are the biggest consumers of fossil fuel in the transport sector in India. Other than energy demands, the heavy duty vehicles are known to have the highest share in air pollutant emission loads from the road transportation sector in India (Goyal et al. 2013). Moreover, huge quantities of fuel, consumed in Indian HDV fleet, are of concern not only to India but to the international energy supplies.

Simulation models are widely used for reliable estimation of the fuel efficiency of HDVs. These models may offer strategic technical options to the regulators and OEM manufacturers for introducing HDV fuel efficiency standards and improving fuel efficiency in the Indian fleet. The modeling techniques drastically reduce the time and resources required for actual testing of vehicles for this purpose. There are a number of studies conducted in past to simulate the fuel efficiency of HDVs in different parts of the world. Mock et al. 2014 simulated and compared the fuel efficiencies using different HDV models. Goossens and Goodarzi 2013 used a predictive model (Maple Sim) for performance and fuel consumption prediction of a vehicle. Chaim et al. 2013; Song et al. 2013 also used different modeling techniques to estimate fuel economy for various categories of vehicles. Advanced models have been used in the USA and the EU to test HDV fuel efficiency and overall engine performance. VECTO, developed in Europe, and GEM, in the USA is currently being used by manufacturers and certification authorities in these countries (IEA-PCRA 2015a, b). These simulation software are currently being modified to accommodate more complex features of engine/vehicle during the test. Japan has also developed similar simulation software, which uses the engine/vehicle specifications as input parameters and takes predefined values of rolling resistance coefficient and aerodynamic coefficient (IEA-PCRA 2015c). While all these studies have shown the use of different models to simulate fuel efficiency of HDVs in various countries, there are no such studies in Indian context. This study presents a method to simulate fuel efficiency of heavy duty vehicles in Indian context. Considering that the Indian fleet, technical specifications of vehicles, road conditions, and driving cycles are different than the rest of the world, it becomes important to assess the fuel efficiencies in Indian context. The model is validated and then used for carrying out sensitivity analysis to assess the impact of various parameters on fuel efficiency. Finally, the potential of different options for fuel efficiency improvement in HDVs is evaluated.

Materials and methods

Study domain and scope

This study focuses on improvement of fuel efficiency in the HDV sector in India. There are in all 7.1 million trucks and 1.6 million buses registered in India till 2011 (PCRA 2013). The categorization of HDV sector in India is done on the basis of usage or gross combined mass (GCM). HDVs in India generally come in two GCM categories (7.5 T < GCM < 12 T and GCM > 12 T). The first category vehicles are termed as medium goods vehicle (MGV) and vehicles in second as heavy goods vehicle (HGV). HDVs are subjected to different uses in India. Table 1 includes the categories of HDV on basis of usage.

The fuel efficiency of vehicles in different categories varies with the usage pattern and technology. The manufacturers of HDVs conventionally use “carbon balance method” (Taubert and Majerczyk 2013) to assess the fuel consumption of their products. The method is

Table 1 HDV categorization on basis of usage

Category	Usage
Long haulage	Used for long hours of operation/long distances
Construction vehicles	Used on construction sites. These vehicles carry heavy weight and are designed for uneven surfaces.
Tipper	Used for urban transport purpose. These type of vehicles are sometimes used as garbage carriage.
Urban Transport/delivery cabs	Used for short haul purpose in cities. These vehicles are designed to carry lesser payload.
Urban transport buses	Used for commutation intra-city
Coaches	Used for commutation inter-city

affected by variation in load, ambient condition, road load simulation etc. and is cost and time intensive. To counter, this study proposes a mathematical model, which can serve as a base model for advanced level of simulation models in future. This model can reduce the complexity of testing the engines/vehicles on dynamometers and thus is an efficient way to reduce the cost involved in testing and development. Vehicle/engine specifications together with information on aerodynamics go as input to this model. The model can be tested for any driving cycle making this flexible and user friendly.

Methodology

The overall methodology followed in the study is presented in Fig. 1. A database of existing HDV fleet in India is prepared through primary surveys. A survey of different models of HDVs was conducted to understand their key characteristics in India. Based on the survey, heavy duty trucks and buses were classified into different weight and axle classes (Table 2). The survey also revealed important details about the engine types/technologies based on prevailing emission norms in Indian HDV sector. This study has used the survey results as an input to mathematical model, described in the next sections of this paper.

In this study, two HDV configurations (haulage truck and bus) have been used to assess the fuel efficiency. Table 2 shows the base vehicle configurations used for the analysis. The base vehicle configurations are fed into the fuel efficiency model.

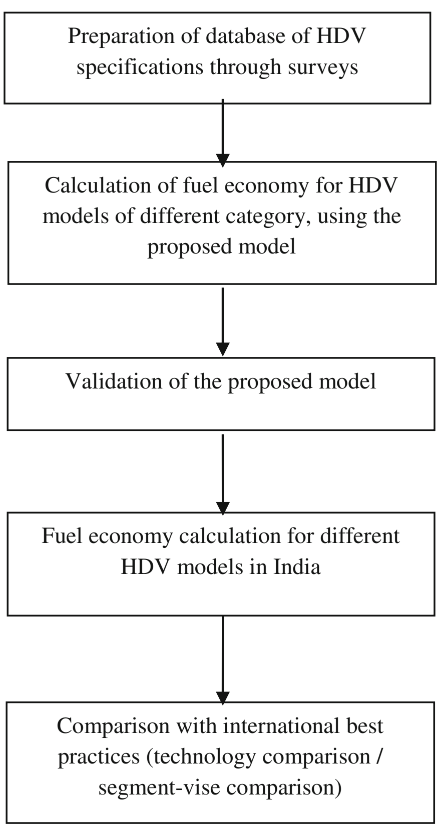


Fig. 1 Overall methodology followed in the study

Fuel efficiency model

The model used in this study follows the way of approximating fuel consumption by calculating the power consumed to overcome rolling resistance, aerodynamic resistance, and power required for acceleration. The rolling resistance is estimated based on Eq. (1) which is directly proportional to the square of the vehicle velocity. Equation (2) shows the estimation of Fv which is the rolling resistance offered by ground on wheels and Eq. (3) computes Pr which is the power consumed to overcome rolling resistance offered by ground, in watts.

Table 2 Survey results of HDVs in India

Parameter		Trucks	Buses
Weight class	N1 (3.5–7.5 MT)	9%	33%
	N2 (7.5–12 MT)	11%	30%
	N3 (> 12 MT)	80%	37%
No. of axles	2 axles	66%	96%
	4 axles	34%	4%
Vehicle length	< 3.5 m	2%	Negligible
	3.5–5 m	Negligible	3%
	5–10 m	90%	68%
	> 10 m	8%	29%
Wheel base	2–4 m	23%	62%
	4–8 m	71%	31%
	> 8 m	6%	7%
Emission regulation	Euro II	4%	Negligible
	Euro III	89%	75%
	Euro IV	7%	25%
Engine displacement (cc)	2000–4000	23%	62%
	4000–8000	71%	31%
	> 8000	6%	7%

Source: TERI Vehicle model survey 2014

Aerodynamic resistance Fa is computed using Eq. (4) and Eq. (5) is used to estimate the power consumed Pa to overcome the aerodynamic resistance offered by the wind. Equation (6) computes the power required Paa for acceleration. The total power required; P is computed as in Eq. (7) and thus the total fuel consumption (FC) is estimated using Eq. (8). The fuel economy of the vehicle is computed using Eq. (9) (Macias 2012).

$$\#C_r = 0.006 + \left(0.23^{*}10^{-6*}V^2\right) \tag{1}$$

where C_r is rolling resistance coefficient, and V is vehicle speed in m/s.

(Equation 1 is for calculating the rolling resistance coefficient of radial tires. As per Clark and Dodge 1979, the rolling resistance coefficient of bias tires is assumed to be 27% greater than the radial tires) (Leduc 2009)

$$F_v = M\ g\ C_r \tag{2}$$

where M is vehicle GVW and g is gravitational acceleration constant, typical value 9.8 m/s^2 (Leduc 2009)

$$P_r = F_v\ V \tag{3}$$

$$F_a = {}^1/_2 \sigma\ A\ C_d v^2 \tag{4}$$

where F_a is the aerodynamic resistance.

σ is the air density in kg/m^3, C_d is the coefficient of aerodynamic drag, A is the frontal area of the vehicle, and V is the velocity of vehicle in m/s (93% of the frontal area is used in this model) (Nam and Giannelli 2005).

$$P_a = F_a V \tag{5}$$

$$P_{aa} = M\ A_c V \tag{6}$$

M is the GVW and A_c is the acceleration of the vehicle (Bachman et al. 2006), (Leduc 2009).

$$P = \frac{P_r + P_a + P_{aa}}{1000} \tag{7}$$

$$\mathrm{FC} = \frac{P}{\eta_{th}{}^{*}\eta_{trans}{}^{*}\mathrm{LHV}} \tag{8}$$

where LHV is the calorific value of fuel in KJ/kg, η_{th} is the brake thermal efficiency of engine, and η_{trans} is the transmission efficiency,

$$\mathrm{FE} = \frac{\text{Total distance covered}^{*}\rho_{diesel}}{\mathrm{FC}^{*}1000} \tag{9}$$

where ρ_{diesel} is the density of diesel in kg/m^3.

A proper listing of technological parameters for thermal efficiency, tires, aerodynamics, vehicle weighs, and fuel quality is made to prepare inputs for the model. Various technical parameters used in the study for computation of modeling the fuel efficiency of various HDV models in India are listed in Table 3.

Table 3 Base vehicle configurations

Parameters	Values	Values
Vehicle category	Haulage	Bus
Usage	Used for carrying goods, tankers	Passenger bus
Technology	Turbocharged after-cooled, DI engine	Turbocharged water cooled, DI engine
Emission standard compliance	BS III	BS III
Engine displacement (in cc)	5883	5883
No. of cylinder	6	6
Kerb weight, M (in kg)	4950	4950
GVW (in kg)	16,200	16,200
Vehicle height, H (in mm)	2704	2704
Ground clearance, GC (in mm)	260	260
Width, W (in mm)	2315	2315
Drivetrain	4 × 2	4 × 2
Transmission type	Manual 6 + 1 speed gearbox	Manual 6 + 1 speed gearbox
Maximum speed (in km/h)	80	80

(Source: Based on HDV model survey in 2014)

Model run and sensitivity analysis

The model runs are carried out first on OBDC (overall bus driving cycle) driving cycle, which is used by ARAI, MoRTH/CMVR/TAP-115/116 (Issue 4) for estimation of emission factors for CO_2, CO, and HC. The technical parameters listed in Table 3 and the OBDC driving cycles are fed into the model and fuel consumption is computed for the two HDV model types. The results were compared and validated with the fuel consumption estimates derived from carbon balance method (ARAI 2009), using CO_2, CO, and HC emissions in ARAI, MoRTH/CMVR/TAP-115/116 (Issue 4). ARAI, MoRTH/CMVR/TAP-115/116 (Issue 4) conducted the tests on a chassis dynamometer tests and used the road load equation (Eq. (10)) to account for aerodynamic drag as well as rolling resistance is generated for the vehicle under test.

$$F = a + \mathrm{bv}^2 \tag{10}$$

where F = wheel force in N, a = coefficient of rolling resistance, b = coefficient of aerodynamic drag, v = vehicle speed in km/h.

However, ideally, the model needs to be validated in real-world conditions with real-time measurement of fuel efficiency in HDVs, which is a limitation in the current study.

The validated model is then used estimate the fuel economy trend of HDVs of different categories in India. A sensitivity analysis is carried out to check the degree of dependency of fuel efficiency on some of the vehicle/engine parameters and vehicle operating parameters. The HDVs in India are also compared with those in the international market to check the fuel efficiency gap in the same segment of vehicles. Finally, the potential of different technologies for improvement of fuel efficiency in HDV sector in India is evaluated using the validated model.

Results and discussions

Model simulation results and validation

The fuel economy for the three HDV vehicles was estimated for the two HDV models (haulage truck and a bus). The modeled results were then compared with the fuel efficiencies computed through carbon balance method for the same models. Table 4 shows the modeling results which are found to be about 2.65 km/l for haulage truck and for a passenger bus. For the purpose of comparison, same weight class, engine capacity, and driveline configuration are used in the analysis as that of the vehicles tested in ARAI, MoRTH/CMVR/TAP-115/116 (Issue 4). The modeled results are approximately 25% less than that from carbon balance method, using emission factors from ARAI, MoRTH/CMVR/TAP-115/116 (Issue 4). The results in the laboratory tests deviate from the results in actual driving on-road. This is mainly because the driving conditions during the laboratory tests (based on engine dynamometers) are very different from that of actual on-road driving conditions considering aerodynamic drags and rolling resistances. According to Sharpe and Muncrief 2015; Mock et al. 2014, the real-world fuel economy values are, therefore, less than those observed in laboratory tests on dynamometers.

Although, the assumptions for this model are realistic, there are few areas which are not covered in the scope of this model. The power consumed in auxiliary devices such as cooling/heating system and electrical/electronic components are neglected. The frontal area calculation is done on the basis of basic dimensions of vehicle chassis and does not include the area of mirror, flaring, and other secondary components mounted on vehicle body. The energy consumed in rotating components is also ignored because of unavailability of realistic value of rolling inertia. There are few constrains related to operation as well. The proposed model assumes all the tires to be moving with same velocity (equal to vehicle velocity), but actually all the tires move with different velocities, which depend on factors like profile of road (straight/turning), alignment of wheels, and braking. Lastly, the proposed model is not a very accurate method to calculate the fuel consumption in idling condition. Although, lot of fuel is consumed in idling condition (especially long idling hours), the driving cycles used for this model typically have very less time allocated for idling (e.g.: 6.2% of total cycle time for ETC cycle) and, thus, idling fuel consumption is assumed to be negligible.

Predicted HDV fuel efficiencies of different models in India

The validated model is then used for estimation of fuel economy of different HDV types in India. The results are then plotted against the kerb weight to understand the variations of fuel economy with the kerb weights. The analysis is presented in the Fig. 2 which shows variation of fuel economy values with changing kerb

Table 4 Assumptions for base engine/vehicle

Parameters	Value	Explanation
Aero-drag coefficient	0.63	General range for aero-drag coefficient is 0.6–0.9 for HDVs. The values can be obtained by using Reynolds's number (Roy and Srinivasan 2000)
Brake thermal efficiency of engine	37%	The brake thermal efficiency of diesel engine is generally in the range of 30–50%. For Indian HDVs, the peak efficiency is not more than 35~40% (Singh et al. 2013)
Transmission efficiency	95%	General value for maximum transmission efficiency for HDVs transmission. The actual transmission efficiency must be lesser than the assumption (Moawad and Rousseau 2012)
Type of tire	Bias tire	Indian HDVs are generally equipped with bias or cross-ply tires. (ITP 2012)
Tyre pressure and tire temperature	Constant	Although the rolling resistance coefficient depends on both of these factors, the values are assumed constant for this model in absence of realistic data and complexity in measurement process.
Internal engine losses (frictional)	Negligible	The values are negligible as compared to rolling resistance losses and aero-drag losses (at higher speeds).
Air density	1.229 kg/m^3	Standard value at 15 °C atmospheric temperature and sea level atmospheric pressure
Calorific value of diesel	10,800 kcal/kg	Standard value for diesel used in India
Density of diesel	820–860 kg/m^3 @ 15 °C	Density of high-speed diesel (HSD) used in India
Power consumption in auxiliary devices	Negligible	Absence of realistic data
Vehicle weight	*GVW weight	Gross vehicle weight (GVW) is specified by the manufacturers. (primary vehicle model survey)
Tangential velocity of wheels	Similar to vehicle	Assuming the vehicle is moving on a straight line and all the wheels experience same tangential velocity
Frontal area	Calculated using formula prescribed by EPA	Neglects the area of rare view mirrors and other components mounted on the front area of the cab (Nam and Giannelli 2005)
Rolling inertia	Negligible	Absence of realistic data

*According to ARAI road load test specifications, the vehicle weight used in road load/mass emission tests should be equal to GVW of the vehicle. In succeeding sections, we have also used kerb weight in place of GVW, to understand the effect of vehicle weight (unladen) on fuel economy

weights of different truck and bus models in India tested over different driving cycles like OBDC and ETC (European test cycle).

Figure 2 shows the results of fuel economy of different HDV models in India with varying kerb weights (unladen weight). Clearly, vehicle weight is a significant parameter affecting the fuel consumption of vehicles. In India, there are variety of HDVs with different vehicle weight and payload capacities, but other parameters such as thermal efficiency of engines, type of tires installed, and cab design are more or less the same. Figure 2 also displays the fuel economy difference, when calculated over ETC driving cycle and over OBDC cycle. OBDC driving cycle consists of six identical cycles, repeating after fixed time interval, whereas, ETC driving cycle is transient in nature. On OBDC cycle, fuel efficiency varies in between 4 and 12 km/l for buses and about 2–7 km/l for trucks. On ETC, the fuel efficiencies are found to be lower mainly due to transient nature of the cycle leading to losses.

Sensitivities of vehicle/engine parameter on fuel efficiency of haulage trucks

The validated model is further used to carry out the sensitivity analysis for the truck/haulage category for various technological parameters like GVW, aerodynamics, and thermal efficiency. An analysis was carried out for different engine/vehicle parameters to understand their individual effect on the fuel efficiency of

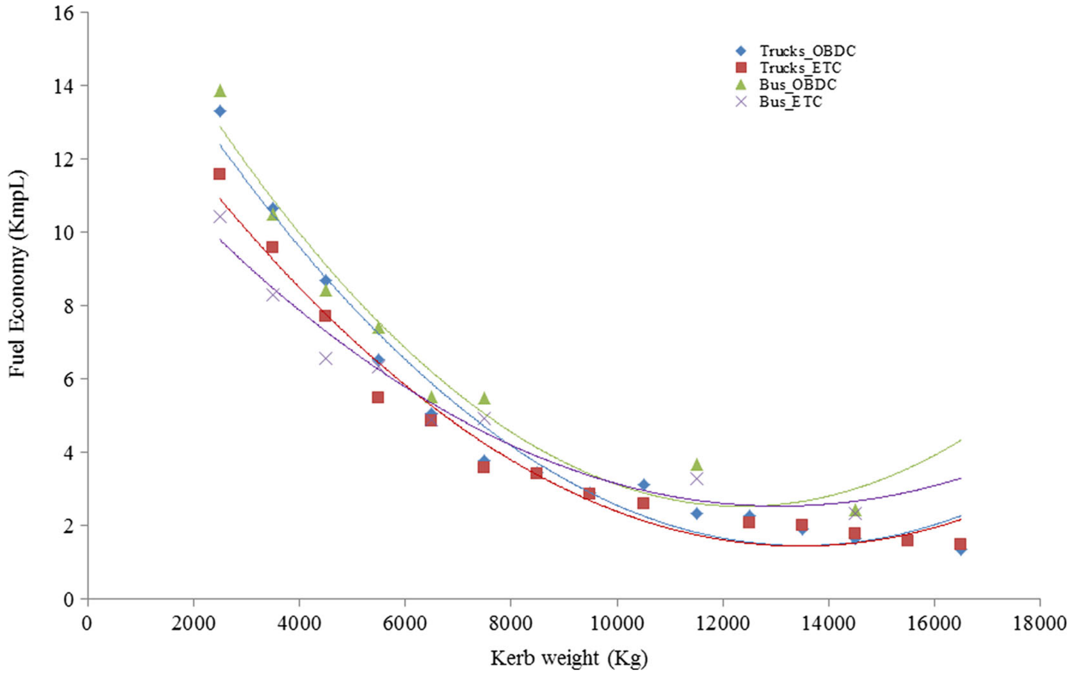


Fig. 2 Variation of fuel economy with changing kerb weights of different truck and bus models in India (over different driving cycles)

haulage trucks (Table 5). The sensitivity of each parameter is tested on the fuel efficiency by varying it between − 10 and + 10% of its original value, while keeping rest of the parameters same.

This analysis presents the extent up to which the fuel efficiency can be improved by changing each of these parameters in the given range. The results show that thermal efficiency affects the fuel efficiency of the vehicle significantly. An increase of 10% in thermal efficiency results into approximately 10% reduction in fuel consumption. Aerodynamic drag is dominant at higher vehicle speeds (highway driving) and does not have a detrimental effect on fuel economy at lower speeds. The fuel efficiency loss when driving off highway are mainly due to rolling resistance offered by road, extra fuel used for acceleration, driving at slow speeds, and fuel consumption during long idling hours. Thus, technologies to improve overall vehicle efficiency, reduction in rolling resistance, and reduction in idle fuel consumption are essential. These technologies are relatively easy to incorporate as these might require lesser investment as compared to other high end and unconventional technologies. The results are subject to change with the driving cycle in use.

Comparison of fuel efficiencies of HDVs in India with world best practices

There is a huge scope of improving the fuel efficiency of HDV diesel engines in India by improving parameters such as engine efficiency, aerodynamics of vehicle by optimizing frontal area and overall aerodynamic profile, and coefficient of rolling resistance of tire. The HDVs used in countries such as the USA, countries in the European Union, and Japan are equipped with superior technologies than those used in India. Most of the

Table 5 Comparison of modeled results of fuel efficiency of two models with results from carbon balance method based on actual tests

Vehicle type/vehicle category	Engine (cc)	CO *(g/km)	HC (g/km)*	CO_2 (g/km)*	FE (km/l)_carbon balance method	FE (km/l)_model
Passenger bus	≈ 6000	4.15	0.12	818.85	3.302	2.649
Truck/haulage	≈ 6000	7	0.23	794.44	3.383	2.649

*Source: ARAI, MoRTH/CMVR/TAP-115/116 (Issue 4)

Table 6 Dependency of fuel economy on vehicle/engine parameters

Parameters	Cycle	Change	−10%	−5%	−3%	−1%	0%	1%	3%	5%	10%
GVW	OBDC	FE (km/l)	2.9	2.8	2.7	2.7	2.6	2.6	2.6	2.5	2.4
		%	11.0	5.3	3.0	1.1	0.0	− 0.8	− 2.7	− 4.5	− 8.7
Coeff. of aerodynamic drag/frontal area	OBDC	FE (km/l)	2.7	2.7	2.7	2.7	2.6	2.6	2.6	2.6	2.6
		%	0.4	0.2	0.1	0.0	0.0	0.0	− 0.1	− 0.2	− 0.3
Thermal efficiency	OBDC	FE (km/l)	2.4	2.5	2.6	2.6	2.6	2.7	2.7	2.8	2.9
		%	− 10.0	− 5.0	− 3.0	− 1.0	0.0	1.0	3.0	5.0	10.0

vehicles in these countries come with automatic transmission or high-speed gear boxes, which help in improving the transmission efficiency, one of the major causes for over fuel consumption. The brake thermal efficiency of the engines used in the USA and the EU is general in the range of 42–44%. The USA is targeting to achieve 50% of brake thermal efficiency in future, while it is around 35 to 40% in India. This, if achieved, will improve the fuel efficiency of the existing engine by approximately 16% from the current level in the USA. Other components like tires, auxiliary devices also have huge scope for improvement in order to cut down the fuel consumption.

A comparative analysis of world best practices in HDV segment is carried out to understand the technological gap. The validated model is used to calculate the fuel consumption of trucks used in the USA and the EU and then compared with similar Indian truck fuel efficiencies. The fuel economy value is modeled using the same approach but with ETC driving cycle. Typical characteristics of trucks used in the USA, India, and the EU are presented in Table 6. While there are considerable variation in the technologies and general configurations of HDVs in the three regions, the fuel efficiencies also show a wide variation.

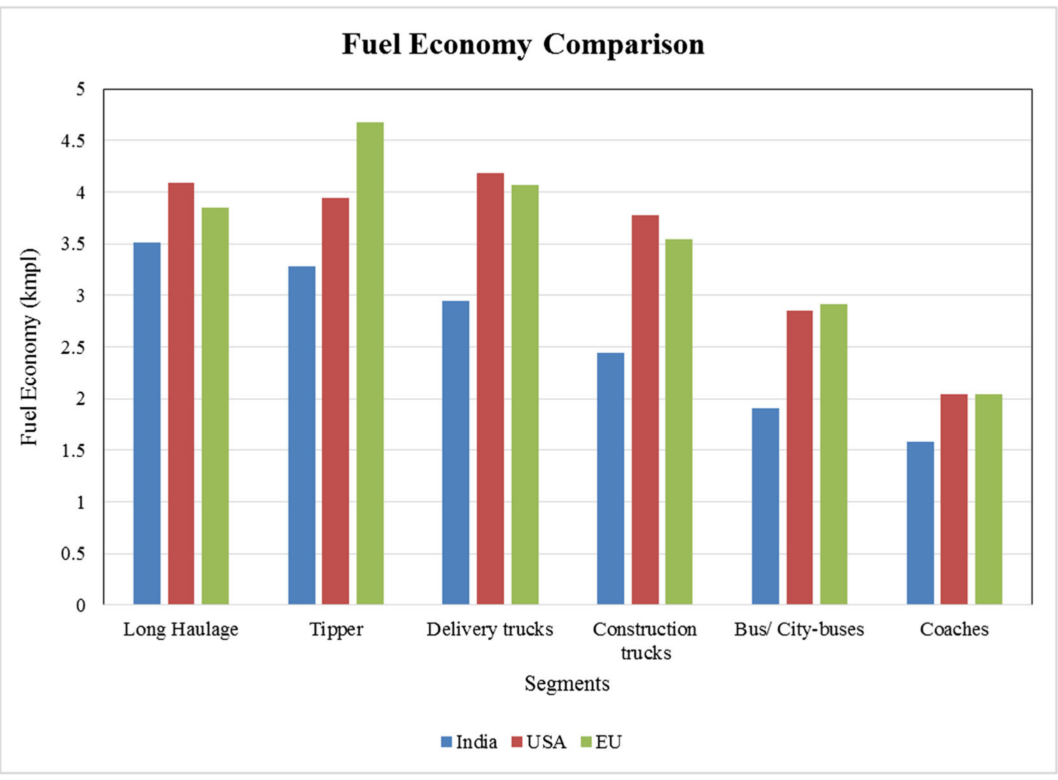


Fig. 3 Segment vise comparison of fuel economy in India, the USA, and the EU

The engine and vehicle capacity in vehicles from the USA and the EU is superior to that of Indian vehicles. The HDVs in India are of lower engine capacity (lower power and torque), lower payload capacity for same vehicle weight, and with manual transmission. Most of the HDVs in the USA and the EU are either equipped with automatic transmission or consists of higher number of gears. Although OEMs in India have started incorporating higher number of gears in vehicles, a large number of HDVs on Indian roads have manual six speed transmission.

A category-vise fuel efficiency analysis is done to understand the category-vise fuel efficiency difference for HDVs from the USA, the EU, and that of from India (Fig. 3). The vehicles compared in each segment have kerb weight in range of ± 1000 kg and vehicles are of similar driveline configuration (6 × 2). This is done to reduce the probability of variation and to establish a common platform for comparison.

This comparison points out the technological gap between the HDVs in India, in the EU and the USA. The parameters altered are cab configuration and brake thermal efficiency and rolling resistance. The thermal efficiency of Indian HDVs is on an average 16% less than that of HDVs in the USA and the EU. Our analysis shows that even in slow and normal driving conditions (aerodynamic losses are less), the fuel efficiency of Indian HDVs can be 29 to 42% lower than that of HDVs from the USA and the EU. However, there are several other factors such as fuel composition and fuel adulteration that affects the functioning and overall life of engines, making them less efficient as compared to vehicles in developed countries.

Potential of different technologies in improving fuel efficiency in HDVs in India

The fuel efficiency of the vehicle can be improved by (a) employing superior engine technology and aerodynamic profile, (b) reducing rolling resistance by improved tire technology, (c) reducing overall weight by reducing the weight of auxiliary components and by opting for light-

Table 7 General configurations of HDVs in India, the USA, and the EU (used in the model for FE estimation)

Parameters	USA	EU	India
Width (m)	2.6	2.55	2.2–2.5
Height(m)	4.09	4	2.8–3.0
Length(m)	7.9	5.7–6.5	5.6–8.1
Frontal area (m^2)	10	< 10	–
Number of axles	3	2	1
Number of tires	10 (dual)	6 (dual)	6 (dual)
Driveline configuration	6 × 4	4 × 2	4 × 2/6 × 4
Weight (tonne)	8.6	7	2.5–8
Coefficient of aerodynamic resistance (Cd)	0.62–0.64	0.62–0.64	0.6–0.8
Coefficient of rolling resistance (Crr)	0.0068	–	–
Engine capacity (L)	11–15	11–15	3.4–7.2
Transmission	10 speed manual	Automated manual	5–9 speed manual
Governed speed (km/h)	120 km/h	90 km/h	80 km/h
GVW (tonne)	36	40–44	10–25
Fuel economy/fuel consumption (L/100 km)	36	30–35	–
Fuel system	CRDi	CRDi	CRDi/direct injection
Induction system	Electrically actuated variable geometry turbo charger	Electrically actuated variable geometry turbo charger	Turbo charged
Fuel economy model (km/l)	**2.33	3.95	1.78
Fuel economy as per GVW (km-tonnes/l)	84	166	58

Source: (Law et al. 2011)

**FE value for HDVs in the USA is for a vehicle with 10 tires. FE when tested for six tires gives 3.32 km/l fuel economy value weight material for manufacturing, (d) and by switching to alternate fuels or hybrid vehicle technology. The extent up to which the fuel efficiency can be affected by different vehicle/operating parameters is presented in Table 7.

There are number of such technologies, which can improve fuel efficiency and overall vehicle performance. Some technologies like duel fuel system or hybrid vehicles can cut down the fuel

Table 8 Effect of different parameters on fuel efficiency

Parameter	Anticipated change (parameter-vise)	Proposed technologies	Purpose	Potential fuel savings
Aerodynamic drag	1% reduction in fuel efficiency if aerodynamic drag is increased by 2%	Optimization of diffuser panel angle, lowering of bus floor	To reduce aerodynamic drag and improve the lift. These technologies are especially effective in high speed driving.	6 to 7%
Rolling resistance	10% reduction in rolling resistance may result into 2–3% improvement in fuel efficiency	Low rolling resistance tires	To reduce the power consumed to overcome the rolling resistance	5%
		Single wide tires[1]	To reduce the power consumed to overcome the rolling resistance	5 to 10%
Tire inflation pressure	10 psi reduction from the prescribed level may reduce the fuel efficiency by 1%	Tire pressure monitoring system	To monitor and indicate when tire pressure goes below prescribed level	0.2 to 0.3%
Vehicle speed	Operating on high speed (> 80 km/h) for long time may result into 0.042 km/l loss in fuel economy	Driver support system[2]	To improve driving practices	4 to 7%
Lubricant temperature	Reduction up to 30° C might reduce the fuel efficiency by 1% due to increased friction level	Oil and water pump with variable speed	To improve the cooling system efficiency and to optimize the energy consumption in pumping coolant/oil	1 to 4%
Idling hour	1 h of continuous idling is almost equivalent to 1% loss in fuel efficiency.	Start/stop system	To cut back long idling hours. This technology reduces the fuel consumption during idling.	4 to 7%
Acceleration		Acceleration control	To reduce the extra fuel lost during acceleration	Up to 6%
Engine efficiency	Depends on technology	Variable valve actuation	To control the valve actuation according to engine condition	1 to 2%
		Sequential turbo	Paired turbocharger, usually each turbocharger smaller than a single unit. It increases response, reduces turbo lag, and at the same time eliminates the requirement of complex piping layout.	Up to 5%
		Waste heat recovery	Exhaust heat is recovered and converted to electrical or mechanical energy.	1.5 to 10%
		Light-weight materials[3]	To reduce the kerb weight/GVW	2 to 5%
		Speed control fuel injection (variable injection timing/ variable injection quantity)	To adjust the air-fuel mixture richness according to requirement	Up to 5%
Transmission efficiency	Depends on technology	Automated manual transmission	To reduce transmission losses	4 to 6%

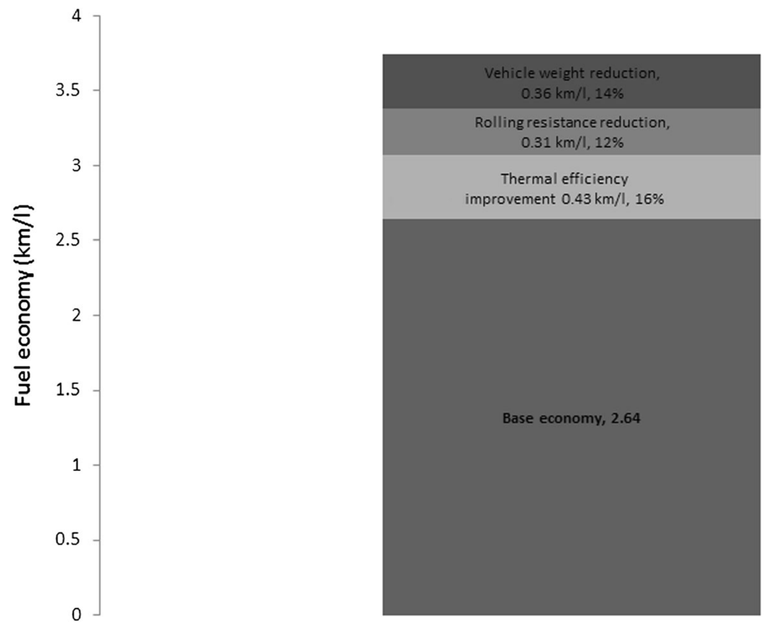
(Source: Cummins 2007; IEA 2012)

[1] Although single wide tires may improve fuel efficiency, they detrimentally affect roads as the load acting on single-point increases

[2] Some studies suggest higher improvement up to 30%

[3] Light-weight material is proposed assuming the load carrying capacity is not affected

Fig. 4 Potential for improvement in fuel efficiency



consumption up to a great extent. The hybrid vehicle technology can improve fuel efficiency from 10 to 20% (IEA 2012), but is not an immediate solution for the fuel efficiency problem in Indian HDVs because of its higher cost. Considering a typical driving pattern in India, technologies which can improve the fuel efficiency in slower driving conditions like in India will result into immediate advantage in fuel consumption by heavy duty vehicles in India. The technologies for better fuel efficiency may result into increased cost as compared with the current levels, but with a smaller payback period (Table 8).

To assess the overall potential of fuel efficiency improvements in Indian scenario, a model run is carried out, with thermal efficiency improved from 37 to 43%, change in tires from bias to radial ones, and vehicle weight reduced by 10%. The changes in different parameters such as thermal efficiency, rolling resistance, and vehicle weight are done so as to match these parameters with the international level. Figure 4 shows the fuel efficiency improvement potential in HDV sector in India based on these changes in thermal efficiency, rolling resistance and vehicle weight. Overall, there is a potential of 36% improvement in fuel efficiency of HDVs with thermal efficiency, rolling resistance, and vehicle weight contributing for 16, 10, and 10% respectively.

Conclusion

Using the proposed model, this study estimates the fuel economy of HDVs in India. The model provides broad directional outputs without time and resource intensive laboratory tests. The model shows satisfactory validation with the observed fuel efficiencies in HDVs in India and is further used for assessing the potential of different technologies that can be employed for fuel efficiency improvement in HDVs. Overall, there is a potential of about 36% improvement in the fuel efficiency in the HDVs, with strategies to improve thermal efficiency by 6%, to introduce radial tires, and to reduce vehicle weight by 10%.

This study also compares the HDVs in India with those in technologically advanced countries to understand the fuel efficiency gaps. The HDVs in the USA and the EU, in general are equipped with higher capacity engines, automated or higher speed gearboxes, superior fuel system and induction systems. Although there are some parameters such as road condition, driving pattern, fuel quality, which significantly affect fuel efficiency, the technological gap cannot be neglected.

The proposed model can serve as a screening tool before the use of advanced simulation tools, which can capture the fuel consumption of HDVs with more accuracy. Thus, this could be an effective directional tool for the manufacturers, and policy makers to anticipate the fuel efficiency of any vehicle, without any requirement to perform expensive tests in laboratory in the first shot. The accuracy of the model can be further studied and validated by using computational simulation models and testing in real-world driving conditions. Although computational simulation techniques and actual testing could be a more precise way of understanding the fuel efficiency of HDVs, this tool can help manufacturers in accessing the effect of some technology on fuel efficiency of their concept vehicles in a cost-effective manner, before physically incorporating those technologies in their HDVs. The work carried out in this paper can be further extended to map individual vehicle performance to national fleet operations, which can enable the calculation of impact across a profiled fleet.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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