

Empirical evidence of direct rebound effect in Indian two-wheeler sector

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Abstract The transport sector is the main contributor to the greenhouse gas emissions in India. The rise in atmospheric pollution due to greenhouse gases has triggered the energy efficiency improvement policy in the Indian automotive sector. The extent of success of the energy efficiency improvement policy in any sector is substantially influenced by the phenomenon of “rebound effect”. The present study is aimed at seeking for the existence of direct rebound effect and its stability over time in two-wheeler transport sector in India using aggregate time series data. The study found out the presence of this effect in the two-wheeler sector, and it experiences a partial rebound of 25.5%. The direct rebound effect was found to be declining over time which is in line with the Greene (*Energy Policy*, 41, 14–28, 2012) and Small and Van Dender (*Energy Journal*, 28(1), 25–51, 2007) models. The rebound effect existence in the two-wheeler sector should be considered during the development and implementation of energy efficiency related policies in the Indian transport sector in order to reap the maximum benefits out of these policies in the future.

Keywords Two-wheeler sector · Energy efficiency improvements · Direct rebound effect · Granger

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causality · Two-stage least squares · Recursive least squares

Introduction

The rise in atmospheric pollution due to greenhouse gas (GHG) emissions from the consumption of fossil energy is of at most concern for the entire world. This has motivated the policy makers to target the policy of energy efficiency improvements through which the issue of emission abatements can be achieved. Perhaps every major automobile manufacturing economy in the world has adopted some form of energy efficiency standards with the aim of mitigating the GHG emissions (An et al. 2007; Greene 2012). The policy of energy efficiency improvements is already adopted by countries like European Union, the USA, Canada, and China (Barla et al. 2009; Kejun 2009; Matos and Silva 2011).

The Indian transport sector mainly relies on fossil energy (gasoline/diesel). The meagre fossil energy resources and increasing greenhouse gas emissions from the transport sector have posed a challenge to India (Menon and Mahanty 2015). The high levels of greenhouse gas emissions are and continue to be a threat to India towards maintaining pollution reduced cleaner environment. The major contributor to the atmospheric emissions in the country is the transport sector (Menon and Mahanty 2012, 2015). The two-wheelers constitute the major portion of the transport sector in India. As per the Central Statistical Organisation data, transport accounts for the greater proportion of household budget in

the last decade (CSE 2008). The two-wheelers constitute about 85% of the entire transport fleet and the rest by other modes. Since the mid of 1980s, the two-wheeler sector has witnessed an exponential growth as evidenced from Fig. 1. This in turn shows that the two-wheeler sector is the major contributor to the increasing fuel consumption and GHG emissions from the transport sector in the country. India also has focused on energy efficiency improvement policy towards reducing the fuel consumption and GHG emissions in the country and specifically that from the transport sector.

The policy of energy/fuel efficiency improvements is affected with the expectation that there will be a reduction in energy consumption and GHG emissions compared to a scenario in which there are no energy efficiency improvements or with the present ongoing situation. The extent of success of the policy of energy efficiency improvements has been questioned and criticised by many researchers in the field of energy research over the last decade (Ajanovic and Haas 2012; Berkhout et al. 2000; Herring and Sorrell 2009; Matos and Silva 2011; Menon and Mahanty 2012, 2015; Nassen and Holmberg 2009; Roy 2000; Sorrell and Dimitropoulos 2008). This is because even after implementing this policy, many countries experienced a further increase in energy consumption leading to the increase in energy import dependency and GHG emissions. The researchers have attributed this situation to the phenomenon known as “rebound effect”. An understanding over the dimension of rebound effect is necessary for successful implementation of energy efficiency related policies in any country. The rebound effects are of three types and are discussed in detail in the following section. The present study focuses on the “direct rebound effect” in the two-wheeler personal transport sector in India. The core objective of this work is to analyse the direct rebound effect in the Indian two-wheeler personal transport sector due to efficiency improvements. The study also analyse the stability of rebound effect over time in the two-wheeler personal transport sector. This shows whether the reduced energy utilisation due to energy efficiency improvement policy at the micro level will result in a reduction in the energy consumption and greenhouse gas emissions in a macro level. This in turn will point towards the extent of success of energy efficiency improvement policy in reducing the energy consumption and

greenhouse gas emissions from the two-wheeler sector in India.

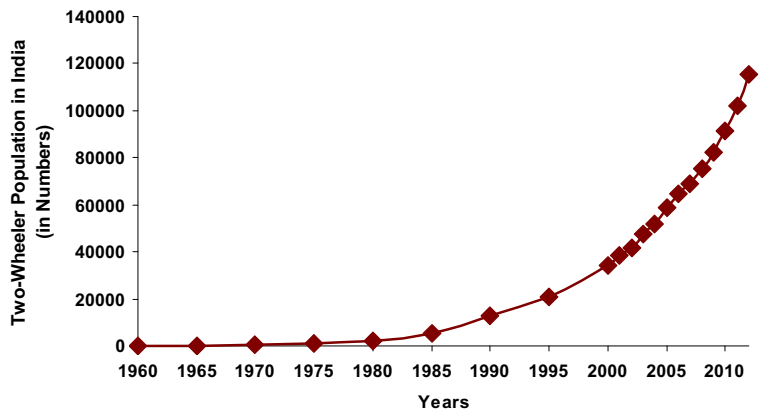
Literature review

The rebound effect

The concept of rebound effect is researched from a fundamental perspective (Greening et al. 2000; Khazzoom 1980; Sorrell 2007; Sorrell and Dimitropoulos 2008; Sorrell et al. 2009, etc.) and application perspective (Ajanovic and Haas 2012; Matiaske et al. 2012; Menon and Mahanty 2012, 2015; Roy 2000, etc.) by several researchers since the last three decades. The concept of rebound effect was first put forth by William Jevons as “Jevons paradox” which hypothesised that efficiency improvements will backfire resulting in the more usage of resources (Alcott 2005). Alcott (2005) presents literature and debates on rebound effect. Chakravarty et al. (2013) provides a vast literature on the studies on rebound effect around the world.

There are three types of rebound effects explained in literature which are (i) direct rebound effect, (ii) indirect rebound effect and (iii) economy wide rebound effect (Frondel et al. 2008; Greening et al. 2000). The energy efficiency improvement policy is to trigger certain feedback flows (Fig. 2) in the system that can nullify the benefits out of this policy in the long run. The improvements in energy efficiency result in a reduction in the energy service cost that can motivate the consumers of this service to use it more leading to an increase in the energy consumption. This increase in energy consumption can either nullify the expected benefits out of this policy or make the system worse by a substantial increase in the energy demand. This phenomenon is known as direct rebound effect in energy literature. The changes in the price of a particular energy service can induce the changes in consumption of other goods and services thereby leading to “indirect rebound effect”. “Economy wide rebound effect” occurs when reduced demand for energy reduces its price, inducing increased consumption in other areas (Greene 2012). The present study is on estimating the direct rebound effects out of fuel efficiency improvements in the two-wheeler sector in India. The improvements in energy efficiency of two-wheelers result in a reduction in travel cost which motivates the two-wheeler users to drive more leading to an increase in energy consumption. This

Fig. 1 The growth in two-wheeler population in India over the last decades



in turn induces direct rebound effect in the two-wheeler sector.

The direct rebound effect is an information flow rather than a physical flow (Fig. 2). The estimation of direct rebound effect can bring out the extent of effectiveness of the energy efficiency improvement policy in any sector. The success of the energy efficiency improvement policy is linked to the consumer behaviour (Menon and Mahanty 2016; Onoda 2008). The consumers’ attitudes and its induced behaviour towards the information of energy efficiency improvements need to be studied so as to reap the benefits of reduced energy consumption and emissions out of this policy.

The rebound effect measurement

The quantification of direct rebound effect is enumerated by Sorrell and Dimitropoulos (2008) through micro-economic definitions. Some of the proxy variables in the definitions are utilised as a measure of the rebound effect. Presently, two definitions given by Sorrell and Dimitropoulos (2008) are utilised for estimating the direct rebound effect in the present study and which

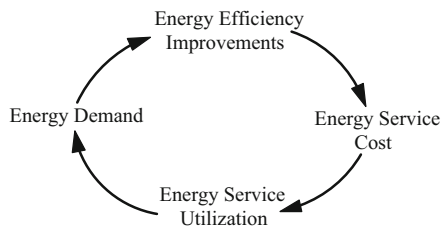


Fig. 2 Information feedback flow representation of direct rebound effect

are depicted in this section. Consider the notations below.

- ϵ Average fuel efficiency of the two-wheeler fleet
- E Energy demand
- S Demand for useful work
- P_S Energy service cost
- P_E Energy price

Definition 1. The energy service cost elasticity of demand for useful work, $\eta_{P_S}(S)$

$$\eta_{\epsilon}(E) = -\eta_{P_S}(S) - 1 \tag{1}$$

where $\eta_{P_S}(S) = \frac{\partial S}{\partial P_S} \frac{P_S}{S}$.

In this definition, the energy service cost elasticity of demand for useful work is the proxy for direct rebound effect. Here, the measure of rebound is obtained from price elasticity estimations. This definition (Eq. (1)) was utilised by Binswanger (2001), Greene et al. (1999) and Matos and Silva (2011) for estimating the direct rebound effect. The demand for useful work can be measured utilising the proxy variables like vehicle miles travelled (VMT) in case of transportation.

The application of this definition is subjected to the assumption of exogeneity. The assumption of exogeneity implies a situation when the endogenous/dependent variable in fact can determine the exogenous/independent variables. For example, according to the economic theory, price is a function of supply of goods, i.e. supply of goods

predicts the price of that good in the marketplace while keeping demand constant. These makes price an endogenous/dependent variable and supply an exogenous/independent variable. But the supply of good is also influenced by the price of that good in the market place thereby reversing the causality. Thus, the unidirectionality of supply in measuring the price in econometric modelling is questioned. This situation can be tackled by the use of simultaneous equation models and instrumental variables in estimation process.

Definition 2. The energy price elasticity of energy demand, $\eta_{P_E}(E)$

$$\eta_\varepsilon(E) = -\eta_{P_E}(E) - 1 \quad (2)$$

where $\eta_{P_E}(E) = \frac{\partial E}{\partial P_E} \frac{P_E}{E}$.

In this definition, the energy price elasticity of energy demand is the proxy for direct rebound effect. Like Eq. (1), Eq. (2) also is based on the assumption of exogeneity. The Eq. (2) is easier to utilise than Eq. (1) as the data on energy demand is easily and commonly available when compared to that for demand for useful work. This definition is used only when the energy demand under consideration attributes to a single service (like refrigeration, space heating, etc.) (Sorrell and Dimitropoulos 2008). In the present study, the energy demand is only for two-wheelers in India and no other transport modes are considered. Hence, this definition is suitable for the direct rebound effect estimation in the two-wheeler sector in the country.

The rebound effect and transportation

The presence of the direct rebound effect in transport sector is widely studied. Matiaske et al. (2012) studied the linkage between higher fuel efficiency of cars and travel activities. Greene (2012) tested the existence, size and stability over time of direct rebound effect for vehicle fuel efficiency on vehicle travel. Utilising the US light-duty vehicle miles travelled, Greene (1992) estimated the size of the rebound effect in this sector. Small and Van Dender (2005) estimated the rebound effect for motor vehicles using panel of US states and found the rebound effect to decline with income. Sorrell

et al. (2009) gives the details on studies of direct rebound effect in personal automotive transport.

The studies on the direct rebound effect in India are sparse. Roy (2000) studied the effect of technical efficiency gains on energy use in three sectors in India which included the transport sector. Menon and Mahanty (2012) studied the presence of direct rebound effect in four-wheeler personal transport sector in India and concluded that the sector experiences a partial rebound. Menon and Mahanty (2015) used system dynamics methodology to experiment with four different policies to mitigate the direct rebound effect in four-wheeler personal transport sector in the country. The present study aims to estimate the direct rebound effect and its stability in the two-wheeler personal transport sector in India.

Theoretical model

This section is on the development of a theoretical model for the influence of various factors on energy consumption from the two-wheeler sector in India. Here, the methodological framework and steps given by Matos and Silva (2011) are appropriately adapted for estimating the direct rebound effect in the Indian two-wheeler sector. The energy consumption by the two-wheeler sector is influenced by the two-wheeler activity and economic activity. The factors with notations are described below:

C_t	Energy demand by the two-wheeler sector in India in period t measured in litres
D_t	Disposable income in period t in rupees
P_t	Energy price in period t in rupees per litre
V_t	Two-wheeler on-road in India in period t measured in numbers
VMT_t	Distance travelled by two-wheelers in period t measured in kilometres.

The time period t for the model variables are for a period of 1 year. The C_t is the annual energy demand by the two-wheeler sector; D_t is the annual disposable income of Indians; P_t is the annual energy price fluctuations in India; V_t is the annual growth in two-wheeler on-road population; and VMT_t is the distance travelled by two-wheelers annually.

Then,

$$C_t = f(D_t, P_t, V_t, VMT_t) \quad (3)$$

The following exponential model was developed as this combination requires a Napierian logarithmic transformation which will in turn make the error terms normal.

$$C_t = e^{\beta_0} D_t^{\beta_1} P_t^{\beta_2} V_t^{\beta_3} VMT_t^{\beta_4} \quad (4)$$

The above mathematical expression can be utilised for estimating the income and price elasticities that can aid in the estimation of direct rebound effect in the two-wheeler sector in India. The variable C_t is the measure for energy consumption or energy demand, and P_t is the measure for energy price.

The growth rate in gross domestic product is a way of measuring the economic output of a region/country. The disposable income of Indians is decided by the growth in gross domestic product in a period t (GDP_t) and is calculated as Disposable income = $GDP \times$ Income growth rate, where the income growth rate (Igr_t) is 0.012.

$$D_t = GDP_t \times Igr_t \quad (5)$$

The fuel used in two-wheelers in India is gasoline (Singh et al. 2008), and the fuel price in the present study is the gasoline price. The energy price (P_t) is calculated as a function of travel cost (TC_t) and the average fuel efficiency (ε_t) of the two-wheelers in India. The travel cost is expressed in rupees per kilometre, and fuel efficiency is in kilometres per litre of petrol. Hence, Energy price = Travel cost \times Average fuel efficiency of two-wheelers and is depicted as follows.

$$P_t = TC_t \times \varepsilon_t \quad (6)$$

It cannot be expected that the entire two-wheeler population (i.e. two-wheeler ownership, VO_t) in India will be present on the road at time t . Instead, a fraction of two-wheeler population (i.e. two-wheeler on-road, V_t) will be present on the road which is calculated as Two-wheeler on-road = Two-wheeler ownership \times Two-wheeler on-road fraction, which is expressed as follows.

$$V_t = VO_t \times Rf_t \quad (7)$$

where two-wheeler on-road fraction (Rf_t) is 0.75 (CMIE 2015a).

The data

The data for the variables in the modelling was adopted from Indian government approved and scientific community accepted sites of Centre for Monitoring Indian Economy (CMIE), Open Government Data Platform India (OGD), Ministry of Petroleum & Natural Gas (MPNG), Petroleum Planning & Analysis Cell, All India Federation of Motor Vehicles Department (AIFMVD), Motor Vehicles Department India (MVD), and Central Pollution Control Board (CPCB). The variables/parameters in the model and its sources are provided in Table 1. The variables/parameters in the model and its descriptive statistics are provided in Table 2.

The reliable data on disposable income of Indian population was not sufficiently available from any of the government authorised or scientific community accepted data banks (like CMIE, OGD, etc.). Hence, gross domestic product (GDP) for India was utilised to estimate the disposable income of Indian population. The GDP data for estimating disposable income was available in real term at constant prices adjusted for inflation from CMIE (2015b), OGD (2015a) and MPNG (2015). The GDP data was available for almost 30 years from the above data banks. It was found that for a unit increase in GDP annually, the disposable income increased by a factor of 0.012. This factor is named as income growth rate in Eq. (5). Thus, the disposable income was estimated using GDP and income growth rate for the present modelling. Similarly, the energy

Table 1 Variables/parameters in the model and its sources

Variables/parameters in the model	Source
Energy demand (C_t)	Petroleum Planning and Analysis Cell (2015); MPNG (2015)
Gross domestic product (GDP_t)	CMIE (2015b); MPNG (2015); OGD (2015a)
Disposable income (D_t)	Estimated
Energy price (P_t)	Estimated
Two-wheeler on-road (V_t)	Estimated
Two-wheeler population (VO_t)	AIFMVD (2015); OGD (2015b)
Distance travelled (VMT_t)	CPCB (2015); MVD (2015)

Table 2 Descriptive statistics of the variables in the model

Variables/parameters in the model	Descriptive statistics	
	Mean	Standard deviation
Energy demand (C_t)	8700.25	2711.977
Disposable income (D_t)	31,858.19	13,971.54
Energy price (P_t)	51.3658	25.5366
Two-wheelers on-road (V_t)	63,130.67	21,674.93
Distance travelled (VMT $_t$)	688.8375	250.502

price was also estimated based on the travel cost data and the average fuel efficiency of two-wheelers data available. The two-wheeler on-road (V_t) was also estimated based on the two-wheeler ownership data (OGD 2015b) and two-wheeler on-road fraction (CMIE 2015a).

Estimation

In the present study, the estimation of direct rebound effect is carried out utilising the ordinary least square method (Guertin et al. 2003; Haas et al. 1998). Sorrell et al. (2009) provides a vast literature on the various estimation techniques used in estimating the rebound effect in various sectors. Moreover, ordinary least square (OLS) was utilised by Blair et al. (1984), Greene (1992, 2012) and Wheaton (1982) to estimate the direct rebound effect on personal transportation/light-duty vehicles in the USA.

Econometric model using ordinary least squares

The equation for energy consumption C_t is expressed as follows.

$$\ln C_t = \ln \beta_0 + \beta_1 \ln D_t + \beta_2 \ln P_t + \beta_3 \ln V_t + \beta_4 \ln \text{VMT}_t + e \tag{8}$$

Substituting Eqs. (5), (6) and (7) in the above equation, the Eq. (9) is obtained.

$$\begin{aligned} \ln C_t &= \ln \beta_0 + \beta_1 \ln(\text{GDP}_t \times \text{Igr}_t) \\ &+ \beta_2 \ln(\text{TC}_t \times \varepsilon_t) + \beta_3 \ln(\text{VO}_t \times \text{Rf}_t) \\ &+ \beta_4 \ln \text{VMT}_t + e \end{aligned} \tag{9}$$

Using ordinary least square estimation method to estimate the above regression equation, the following linear regression equation was obtained for the energy consumption (Eq. (10)). Initially, the data points were given a logarithmic transformation to make the error terms normal. The Augmented Engle-Granger test (Engle and Granger 1987) on the residuals from the regression (Eq. (10)) rejected the hypothesis of a unit root at the 0.05 level, indicating that the variables in the linear model are co-integrated.

$$\begin{aligned} \ln C_t &= -5.75 + 0.346 \ln D_t - 0.256 \ln P_t \\ &+ 1.49 \ln V_t - 0.644 \ln \text{VMT}_t \end{aligned} \tag{10}$$

(<i>t</i>)	(-5.08)	(4.00)	(-10.38)	(5.61)	(-3.94)
(sig)	(0.001)	(0.005)	(0.000)	(0.001)	(0.006)

- $F = 1218.86$
- Prob (F -statistic) = 0.000
- Adjusted $R^2 = 0.998$
- Durbin-Watson statistic = 2.132
- Breusch-Pagan-Godfrey test statistic = 5.683

The Table 3 depicts the ordinary least squares regression model statistics. The adjusted R^2 value was utilised here as it is free from bias resulting from the increase or decrease in the independent variables. The adjusted R^2 value interprets the variation in the response as explained by the predictor variables. The adjusted R^2 value for the present model shows that the independent

Table 3 Ordinary least squares regression model statistics

Coefficient	Coefficient value	Std. error	<i>t</i> -Statistic	Prob.
β_1	0.346	0.08657	4.00	0.005
β_2	-0.256	0.02466	-10.38	0.000
β_3	1.490	0.2653	5.61	0.001
β_4	-0.644	0.1637	-3.94	0.006
Adjusted R^2	0.998	F-statistic 1218.86		
		Prob (F -statistic) 0.000		
		Durbin-Watson statistic (<i>d</i> -statistic) 2.132		
		Breusch-Pagan-Godfrey test statistic 5.683		

variables explained the maximum percentage of the variation in the dependent variable.

The time series data usually exhibits serial correlation which is the correlation between the data points of a variable over time (Gujarati et al. 2013). The presence of serial correlation violates the assumptions of ordinary least squares estimation thereby making this estimation technique no longer the best linear unbiased estimator (BLUE). The Durbin-Watson statistic is used to identify the presence of serial correlation within the data. The value of Durbin-Watson statistic in the Eq. (10) rejected the hypothesis of the presence of serial correlation in the regression variables. The Breusch-Pagan-Godfrey (BPG) test for heteroscedasticity gave a test statistic value of 5.6825 which was tested at both $\chi_{0.05, 3}$ and $\chi_{0.01, 3}$ ($\alpha = 0.05, 0.01$; d.f. $n = 4 - 1 = 3$). It was found that the calculated BPG test statistic did not exceed the critical χ^2 values at 0.05 and 0.01 levels of significance, thereby accepting the hypothesis of homoscedasticity of constant error variance.

Testing for the exogeneity of the price variable

Hausman specification test

The economic theory speaks that the price of any good is a function of the supply of this good provided the demand remains constant. Moreover, the market price determines the amount of supply of the good. This makes the identification of direction of causality between price and supply for goods difficult. In econometric models, this situation creates issues when the endogenous variable seeks to explain the exogenous variable (Matos and Silva 2011). The exogeneity (or the problem of simultaneity as in econometric modelling) of the energy price variable (P_t) is tested utilising the Hausman specification error test (Hausman 1978; Nakamura and Nakamura 1981). This method involves testing of exogeneity of price variable by estimating the price variable as a function of other exogenous variables (here D_t, V_t and VMT_t) in the system. The equations for Hausman test are as follows.

$$C_t = \alpha_0 + \beta_1 P_t + \bar{\beta}_n IV_t + u_t \quad (11)$$

where IV_t is the independent or other exogenous variables in the system which are D_t, V_t and VMT_t .

$$P_t = \eta_0 + \eta_1 D_t + \eta_2 V_t + \eta_3 VMT_t + \nu_t \quad (12)$$

$$\text{i.e. } \bar{P}_t = \bar{\eta}_0 + \bar{\eta}_n IV_t + \nu_t \quad (13)$$

$$\bar{P}_t = \bar{\eta}_0 + \bar{\eta}_1 D_t + \bar{\eta}_2 V_t + \bar{\eta}_3 VMT_t \quad (14)$$

$$P_t = \bar{P}_t + \bar{\nu}_t \quad (15)$$

$$C_t = \alpha_0 + \beta_1 \bar{P}_t + \beta_1 \bar{\nu}_t + \bar{\beta}_n IV_t + u_{t1} \quad (16)$$

From the results of Hausman test, it was found that the coefficient of ν_t in Eq. (16) to be statistically significant with a P value of 0.006, thereby rejecting the null hypothesis that the price variable is exogenous.

Similarly, the Hausman specification error test is used to test for exogeneity of the distance travelled by two-wheelers variable (VMT_t). This involves testing of exogeneity of distance travelled variable by estimating the distance travelled variable as a function of other exogenous variables (here D_t, V_t and P_t) as follows.

$$C_t = \eta_0 + \gamma_1 VMT_t + \bar{\gamma}_n IV_t + u_t \quad (17)$$

where IV_t is the independent or other exogenous variables in the system which are D_t, V_t and P_t .

$$VMT_t = \rho_0 + \rho_1 D_t + \rho_2 V_t + \rho_3 P_t + \varepsilon_t \quad (18)$$

$$\text{i.e. } \bar{VMT}_t = \bar{\rho}_0 + \bar{\rho}_n IV_t + \varepsilon_t \quad (19)$$

$$\bar{VMT}_t = \bar{\rho}_0 + \bar{\rho}_1 D_t + \bar{\rho}_2 V_t + \bar{\rho}_3 P_t \quad (20)$$

$$VMT_t = \bar{VMT}_t + \bar{\varepsilon}_t \quad (21)$$

$$C_t = \eta_0 + \gamma_1 \bar{VMT}_t + \gamma_1 \bar{\varepsilon}_t + \bar{\gamma}_n IV_t + u_{t1} \quad (22)$$

From the results of Hausman test, it is found that the coefficient of ε_t in Eq. (22) to be statistically not significant with a P value of 0.75, thereby accepting the null hypothesis that the distance travelled by two-wheeler

variable (VMT_t) is exogenous. The same error testing procedure was applied for the disposable income variable (D_t) and two-wheeler on-road variable (V_t). The error coefficient for both the error tests were not statistically significant thereby accepting the null hypothesis that the disposable income variable (D_t) and two-wheeler on-road variable (V_t) are exogenous in nature. Thus, only the price variable in the econometric model is identified as endogenous variable.

Granger causality test

The granger causality test (Granger 1969) is utilised to test for the direction of causality that exist between two variables. It can be utilised for testing whether an independent variable is endogenous or exogenous in nature. Here, the granger causality test is utilised to test for the causality that exist between the variables energy consumption (C_t) and energy price (P_t). It is expected that, and as in regression model developed, the energy price predicts the energy consumption. This assumption has to hold or else will be a violation of the assumptions of ordinary least squares (OLS) estimation method utilised in developing the regression model prior.

To analyse the causality existing between two variables P_t and C_t , the granger causality test assumes that the relevant information for estimating a variable (P_t) is contained solely in the series of these variables P_t and C_t . Statistically, this is formulated as follows.

$$P_t = \alpha C_{t-1} + \beta P_{t-1} + \mu_{t1} \quad (23)$$

$$C_t = \gamma P_{t-1} + \psi C_{t-1} + \mu_{t2} \quad (24)$$

where μ_{t1} and μ_{t2} are uncorrelated errors. From the estimated OLS coefficients of the above two equations, four causal hypotheses regarding the relationship between P_t and C_t can be formulated as follows.

1. Unidirectional Granger-causality from C_t to P_t : $\alpha \neq 0$ and $\psi = 0$
2. Unidirectional Granger-causality from P_t to C_t : $\alpha = 0$ and $\psi \neq 0$
3. Bidirectional or feedback causality: $\beta \neq 0$ and $\psi \neq 0$
4. Independence between the variables: $\beta = 0$ and $\psi = 0$

The estimation of parameters using the above equations yielded the following results

$$P_t = 0.00225C_{t-1} + 0.748P_{t-1} \quad (25)$$

(t)	(1.85)	(3.88)
(sig)	(0.098)	(0.004)

$$C_t = 21.0P_{t-1} + 0.976C_{t-1} \quad (26)$$

(t)	(1.94)	(14.32)
(sig)	(0.084)	(0.000)

From the estimates obtained, it is to be concluded that there exists a causal relationship from C_t to P_t as $\alpha \neq 0$ and $\psi = 0$.

Thus, the Granger causality test shows that the energy price variable (P_t) which was expected to be exogenous in nature in fact is also influenced by the energy demand variable (C_t) (Fig. 3a, b). Hence, the variable P_t is statistically dependent on the variable C_t . Thus, the assumption of exogeneity does not hold.

Two-stage least squares

The two-stage least squares estimation is a solution when the assumptions underlying the ordinary least squares estimation method are violated. In the present study, through Hausman specification test and Granger causality test, it is evidenced that the explanatory variable is also endogenous. The energy price variable (P_t) which is explanatory and thus exogenous in the regression Eq. (10) in turn is influenced by the endogenous variable energy demand (C_t) in the same equation (Fig. 3a, b). Hence, the assumption of exogeneity is violated as evidenced through the granger causality test. To overcome the violation of ordinary least squares

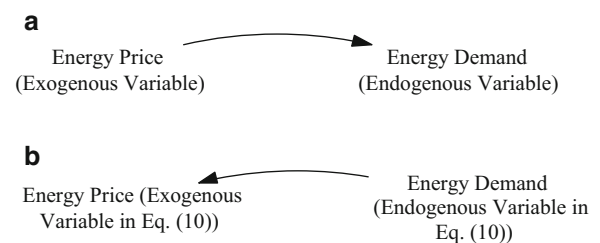


Fig. 3 **a** The causality as in the regression Eq. (10). **b** The causality evidenced through Granger causality test

assumption of exogeneity, the two-stage least squares estimation technique involving instrumental variable ($\ln V_t$) is utilised for the estimation process (Gonzalez 2010). The instrumental variable is a variable that is correlated with the exogenous variable (here energy price, P_t) but is not a part in the formulation of the final regression model. Moreover, the instrumental variable is also uncorrelated with the residuals (e_t) in the regression model (Eq. (10)). This implies that the selection of instrument variable shall satisfy the criteria $\rho(P_t, \ln V_t) \neq 0$ and $\rho(e_t, \ln V_t) = 0$.

The energy/fuel price (P_t) is composed of two variables which are travel cost (TC_t) and average fuel efficiency (ε_t) of the two-wheelers (see Eq. (6)). Thus, one of these variables can be used as the instrumental variables in two-stage least squares estimation. The variable with the highest correlation with the fuel price variable (P_t) and least correlation with the residuals (e_t) will be the instrumental variable. The average fuel efficiency variable (ε_t in km/l) is found to be the suitable instrumental variable for two-stage least squares estimation as it gives the following correlations.

$$\rho(P_t, \varepsilon_t) = 0.919; \rho(e_t, \varepsilon_t) = 0.005.$$

Utilising average fuel efficiency variable as the instrumental variable and which is statistically correlated with P_t variable and uncorrelated with the residuals estimated in Eq. (10), the two-stage least squares estimation resulted in the following log-linear energy consumption function.

$$\ln C_t = -5.76 + 0.344 \ln D_t - 0.255 \ln P_t + 1.48 \ln V_t - 0.643 \ln VMT_t \tag{27}$$

(t)	(-5.09)	(3.97)	(-10.35)	(5.59)	(-3.93)
(sig)	(0.001)	(0.005)	(0.000)	(0.001)	(0.006)

$$F = 1219.89$$

Table 4 Two-stage least squares model statistics

Coefficient	Coefficient value	Std. error	t-Statistic	Prob.
β_1	0.344	0.08652	3.97	0.005
β_2	-0.255	0.02464	-10.35	0.000
β_3	1.480	0.2652	5.59	0.001
β_4	-0.643	0.1637	-3.93	0.006
Adjusted R^2	0.998	F-statistic 1219.89		
		Prob (F-statistic) 0.000		

$$\text{Adjusted } R^2 = 0.998$$

The Table 4 depicts the two-stage least squares model statistics.

The Eq. (10) estimated using OLS method and Eq. (27) estimated using two-stage least squares method have shown less difference in its estimated coefficients. This can be attributed to the fact that even though there is causality existing from energy demand variable to energy price variable, this causality can be a weak causation. This weak causation from C_t to P_t has resulted in the weak difference between Eqs. (10) and (27). This is also evidenced from Eqs. (25) and (26). In Eq. (25) showing the causality from C_t to P_t , the α -coefficient value for C_t is 0.00225 showing a weak relationship from C_t to P_t . While in Eq. (26) showing the causality from P_t to C_t , the γ -coefficient value for P_t is 21.0 showing a strong relationship from P_t to C_t .

Computation of elasticities

Utilising the estimates from the regression, we compute the direct rebound effect using the two definitions in Sorrell and Dimitropoulos (2008) as follows.

The Definition 1 (Eq. 1) for estimating direct rebound effect used is depicted below.

$$\eta_{P_S}(S) = \frac{\partial S}{\partial P_S} \frac{P_S}{S}$$

But P_S is cost of energy service which is the “travel cost” (TC_t) incurred by the two-wheeler users. Moreover, demand for useful work (S) is a function of energy demand (E) and energy efficiency (ε), $S = E\varepsilon$. Presently, the proxy for energy demand is C_t . Substituting these in the above equation, the following equation is obtained.

$$\eta_{P_S}(S) = \frac{\partial(E_t \varepsilon_t)}{\partial TC_t} \frac{TC_t}{E_t \varepsilon_t} = \frac{\partial(C_t \varepsilon_t)}{\partial TC_t} \frac{TC_t}{C_t \varepsilon_t} \tag{28}$$

$$C_t = D_t^{\beta_1} P_t^{\beta_2} V_t^{\beta_3} VMT_t^{\beta_4} \tag{29}$$

Substituting C_t in the above equation, the following is obtained.

$$\eta_{P_S}(S) = \frac{\partial \left(D_t^{\beta_1} P_t^{\beta_2} V_t^{\beta_3} \text{VMT}_t^{\beta_4} \varepsilon_t \right)}{\partial \text{TC}_t} \frac{\text{TC}_t}{D_t^{\beta_1} P_t^{\beta_2} V_t^{\beta_3} \text{VMT}_t^{\beta_4} \varepsilon_t} \tag{30}$$

P_t can be rewritten as $P_t = \text{TC}_t \times \varepsilon_t$, thereby obtaining the following expression.

$$\eta_{P_S}(S) = \frac{\partial (\text{TC}_t \varepsilon_t)^{\beta_2}}{\partial \text{TC}_t} \left(D_t^{\beta_1} V_t^{\beta_3} \text{VMT}_t^{\beta_4} \varepsilon_t \right) \frac{\text{TC}_t}{D_t^{\beta_1} (\text{TC}_t \varepsilon_t)^{\beta_2} V_t^{\beta_3} \text{VMT}_t^{\beta_4} \varepsilon_t} \tag{31}$$

Reducing the above expression yields the expression below.

$$\eta_{P_S}(S) = \beta_2 (\text{TC}_t \varepsilon_t)^{\beta_2 - 1} (\varepsilon_t) \frac{\text{TC}_t}{(\text{TC}_t \varepsilon_t)^{\beta_2}} \tag{32}$$

Solving the above expression, the energy cost elasticity of the demand for useful work is obtained.

$$\eta_{P_S}(S) = \beta_2 \tag{33}$$

The value of β_2 is estimated in the regression equation Eq. (27).

$$\eta_{P_S}(S) = -0.255$$

$$\eta_\varepsilon(E) = -\eta_{P_S}(S) - 1 = -(-0.255) - 1 = -0.745$$

The Definition 2 (Eq. 2) for estimating direct rebound effect used is depicted below.

$$\eta_{P_E}(E) = \frac{\partial E}{\partial P_E} \frac{P_E}{E}$$

Substituting for $E = C_t$ and energy price, $P_E = P_t$, the following expression is obtained.

$$\eta_{P_E}(E) = \frac{\partial P_t^{\beta_2}}{\partial P_t} \left(D_t^{\beta_1} V_t^{\beta_3} \text{VMT}_t^{\beta_4} \right) \frac{P_t}{D_t^{\beta_1} P_t^{\beta_2} V_t^{\beta_3} \text{VMT}_t^{\beta_4}} \tag{34}$$

Reducing the above expression yields the expression below.

$$\eta_{P_E}(E) = \beta_2 (P_t)^{\beta_2 - 1} \frac{P_t}{P_t^{\beta_2}} \tag{35}$$

Solving the above expression, the elasticity of energy demand in respect to energy cost is obtained.

$$\eta_{P_E}(E) = \beta_2 = -0.255 \tag{36}$$

$$\eta_\varepsilon(E) = -\eta_{P_E}(E) - 1 = -(-0.255) - 1 = -0.745$$

The five rebound conditions are given by Wei (2010) and are as follows.

- $\eta > 0$: Backfire
- $\eta = 0$: Full rebound
- $-1 < \eta < 0$: Partial rebound
- $\eta = -1$: Zero rebound
- $\eta < -1$: Super-conservation

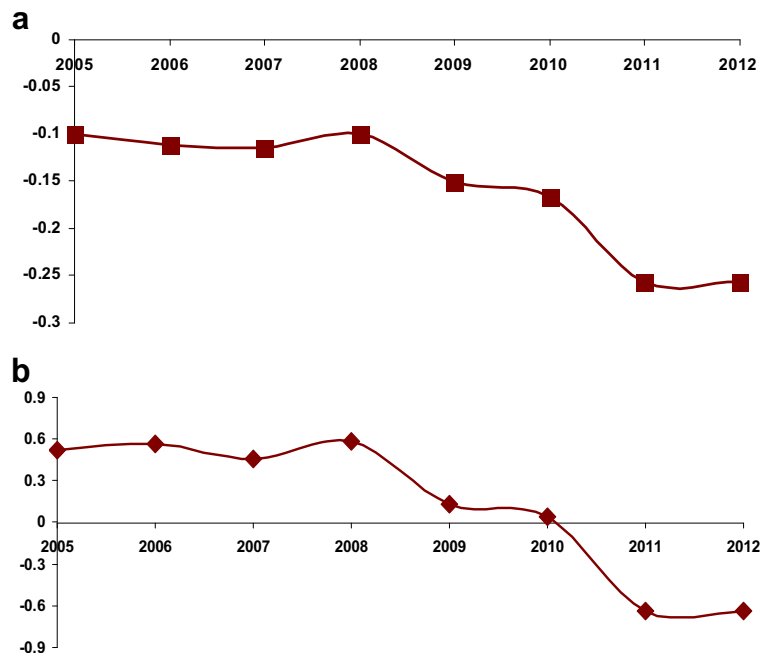
Here, in the above two definitions, $\eta_{P_S}(S)$ and $\eta_{P_E}(E)$ defines the direct rebound effect (Sorrell and Dimitropoulos 2008). According to the rebound range, the estimated value of both $\eta_{P_S}(S)$ and $\eta_{P_E}(E)$ falls between -1 and 0 , i.e. $-1 < -0.255 < 0$, and hence, the two-wheeler sector in India experiences a partial rebound.

Stability of direct rebound effect over time

An important question always posed regarding the direct rebound effect is its stability over time. A previous study argues that the rebound effect is to vary over time proportionately to the fuel cost share of the total travel cost (Gately 1992). Small and Van Dender (2007) tested a model and found the rebound effect to vary with the logarithm of per capita income. Menon and Mahanty (2012) found that the direct rebound effect is not constant over time in Indian four-wheeler personal transport sector. Greene (2012) concluded that the rebound effect to be decreasing over time for US light-duty vehicle fleet.

In the present study, the stability of the direct rebound effect in two-wheeler sector in India is analysed utilising the log-linear model in Eq. (27). The stability of the log-linear model was analysed using recursive least squares (RELS) method (Gujarati et al. 2013). The recursive coefficient estimates were plotted for all the independent variables in the log-linear model. The recursive coefficient estimate plots for two-wheeler on-road variable (V_t) and disposable income variable (D_t) remained almost stable on adding the data points. The recursive coefficients for the energy price variable (β_2 in

Fig. 4 Recursive coefficient estimate plots for energy price variable (a) and two-wheeler distance travelled variable (b)



Eq. (27) for P_t) and two-wheeler distance travelled variable (β_4 in Eq. (27) for VMT_t) showed a declining trend over time (Fig. 4a, b, respectively). In the present study, the value for the coefficient β_2 predicted the direct rebound effect size in the two-wheeler sector in India and which is found to be changing over time through the Fig. 4a. This in turn shows the instability of the direct rebound effect over time in this sector. This observation is in line with that of Greene (2012) and Small and Van Dender (2007).

Conclusions

The present study aims to seek for the existence of direct rebound effect and its stability in the two-wheeler sector in India. The estimation of elasticities was carried out using the two definitions for direct rebound effect. From using these definitions, it was found that the elasticity of distance travelled by two-wheelers (S) with respect to energy cost of useful work (P_S) in case of first definition and the elasticity of energy demand (E) with respect to energy cost per kilometre (P_E) in case of second definition are estimated as -0.255 . Hence, the elasticity of energy (here gasoline) demand with respect to fuel efficiency is estimated to be -0.745 . Thus, the direct rebound effect in the Indian two-wheeler sector due to fuel efficiency improvements that did not benefit in the

fuel consumption reductions is 25.5%. This in turn implies that for an energy efficiency improvement by 1%, the energy demand will fall by 0.745%. In India, an average household spend more on transport of which a significant proportion is the operational cost (CSE 2008). The operational cost includes fuel costs and maintenance cost. In the present modelling venture, the fuel cost is considered while the maintenance cost was excluded due to the unavailability of reliable data on this variable in Indian context.

Presently, the two-wheeler sector in the country is in the state of partial rebound. Moreover, this value falls within the range for the direct rebound effect values for personal automotive transport given by Sorrell et al. (2009). Previous study on the existence of direct rebound effect in Indian four-wheeler sector (Menon and Mahanty 2012, 2015) found a partial rebound occurring in the system. This study brings to light that two-wheeler sector is also passing through the same situation of partial rebound. The present study also found that the direct rebound effect in two-wheeler personal transport sector in India is not stable over time. The rebound effect was showing a declining trend over time, and this trend is consistent with that of Greene (2012) and Small and Van Dender (2007) observations.

The presence of direct rebound effect in the transport sector and especially in two-wheeler sector has important implication in developing and implementing the

energy policies in future. Measures have to be adopted to counteract the rebound effect in this sector in India. The policy of increasing the fuel price to constrain the distance travelled by two-wheelers, thereby reducing the energy consumption, may not be successful in the Indian context as there is an increase in the disposable personal income in the country. The increase in disposable income of Indian population in turn has increased their purchasing power, thereby motivating the vehicle users to purchase fuel for higher prices. Other alternative policies have to be thought of and experimented with to find out the extent of effectiveness of these policies in mitigating the direct rebound effects in this sector. Moreover, the changing direct rebound effect in the two-wheeler sector pose a challenge for the policy makers as it calls for amendments in the implemented policies to mitigate the changing dimension of the rebound effect over time. Thus, along with the energy efficiency improvements affected, alternative policies like carbon tax, registration tax, etc. also have to be devised, implemented and adjusted to mitigate the direct rebound effects in the Indian two-wheeler sector in the long run.

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