Road transport energy demand in Australia

A cointegration approach

Rodney Samimi

A cointegration framework is used to examine the short-run and long-run characteristics of energy demand in the Australian road transport sector. A lagged endogenous equation based on a partial adjustment process is proposed and estimated. Results indicate that energy demand, output and real energy prices are integrated of order 1 and cointegrated. The long-run output and price elasticities of energy demand are estimated to be 0.52 and -0.12 respectively. Causality tests reveal a bidirectional causality path between output and energy demand and a unidirectional path from energy consumption to prices. No other causality paths between output, prices and energy demand are detected. The short-run output elasticity of energy demand is estimated to be 0.25 based on an error-correction model. The short-run price elasticity is found to be insignificant. The inertia parameter is 0.48 corresponding to 95% of the demand adjustment occurring after five periods. The results are compared with previous findings and the variations are partially attributed to the structural changes in the road transport sector in the 1980s, some of which are discussed.

Keywords: Energy; Transport; Australia

The transport sector is the largest user of energy in Australia given the size factor of the continent and the relative dispersion of urban population. The transport sector accounts for approximately 38% of the total final energy consumption or 76% of liquid petroleum fuels (ABARE [1]).

Road transport is in turn the most important mode of transport, responsible for 79% of the total tonne kilometres carried. It is the most heavily concentrated sector with respect to energy type with virtually only petroleum products used. While the usage of natural gas is expected to grow, no other alternative fuels (eg hydrogen or alcohol) or electric vehicles are expected to be economically viable in the absence of a major technological advancement or government action.

There is a wide range of economic models for energy demand in the related literature which may be broadly grouped into the following classifications:

(i) models for examining the relationship between energy consumption and the whole economy on an aggregate basis;
(ii) models for optimizing fuel allocation that deal

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1 Total final energy consumption is the total amount of energy used outside the energy conversion sector. It is equal to total energy used less the amount consumed in the conversion process and during transmission and distribution.
2 Commercial heavy vehicle fleet, urban bus fleet and light commercial vehicles where natural gas conversion is technically and economically viable are expected to show a growth in the usage of natural gas.
with types of fuel within the economy or within a particular sector;

(iii) sectoral demand models that examine energy consumption in a particular sector or subsectors of the economy;

(iv) models for energy systems that provide an integrated view of supply and demand for all types of energy sources, including international comparisons.

The focus of this article is in relation to the models of type (iii). The energy consumption projections may be based mainly on past time series data and generally rely on exogenous assumptions about economic growth and energy prices. The relation between energy demand output and prices therefore requires an estimation of the elasticities.

Within the sectoral demand models there are two basic approaches in the literature. The first method is as used by Donaldson et al [5]. Fuel demand is derived as the product of fleet size average distance travelled and average fleet fuel efficiency which is also proposed by Sweeney [14]. This type of (fleet performance) modelling has the advantage of taking into account the changing patterns of vehicle ownership per person as it approaches saturation level. However, fleet performance models have the disadvantage of over relying on multiple average measurements. These models generally do not take into account unit root or cointegration testing of the series used in the regression. The lag structure in energy demand modelling is also not well presented in fleet performance models.

The second general approach is by deriving the fuel demand directly as a function of a series of economic variables. The theory behind this type of modelling is based on the assumption that transport fuel demand is positively related to output and negatively related to fuel prices (see Figure 1) which to some extent shares aspects of the fleet performance models above. Sterner and Dahl [13] classify these type of models into a number of categories. The simplest models are of the form:

\[ E_t = f(P_t, Y_t) \]  

(1)

where \( E_t \), \( P_t \), and \( Y_t \) are energy demand, prices and output respectively, in period \( t \). As transport fuel consumption depends on the stock of existing vehicles, any adjustments are likely to take longer than the periodicity of the data used. Hence, a crucial aspect of energy demand modelling is the lag structure which Equation (1) does not capture. The elasticities derived in this manner do not take into account the lagged price effects or any time trends.

Other types of model add dynamic mechanisms to Equation (1). A widely used presentation of dynamic behaviour is based on partial adjustment processes. It shows energy demand as a function of real prices, output and the quantity of energy consumption in the last period. This provides a lagged endogenous framework:

\[ E_t = f(P_t, Y_t, E_{t-1}) \]  

(2)

An extension of these models is where in addition to Equation (2) above, output is also expressed as a function of energy consumption. Koshal et al [8] apply a two stage least squares estimation in order to simultaneously estimate Equation (2) and the following relationship:

\[ Y_t = f(E_t, S_t) \]  

(3)

where \( S_t \) is a proxy variable reflecting the technological characteristic and the structure of the economy.

A weakness of this approach is that it does not make any attempt to identify causality paths between output and energy consumption and prices in order to validate the structure. Another related methodology for estimating energy demand is by employing input–output type models. These models use an input–output framework to obtain energy multipliers similar to the traditional employment or income multipliers.

**Theoretical framework**

A number of issues are crucial in forming a model for road transport energy consumption. A distinction should be made between structural models and time series models. A link can then be made between the two by using the concept of cointegration to examine the long-run viability of the structural relationships. In this way, the time series models become the unconstrained reduced form equivalents of the structural models.

\[ 3 \text{The Koshal et al [8] model is applied as an energy demand mechanism for intercountry comparisons, but this type of model using two equations and simultaneous estimations is also applicable at a (sub) sector level.} \]

\[ 4 \text{In Koshal et al [8],} S_t \text{is expressed as the percentage of output produced by the agriculture sector. For comparison, in the Australian road transport context} S_t \text{may be expressed as the percentage of national output produced by the construction and retail sectors which according to the ABS [2] input–output tables have the largest impact on the transport sector.} \]

\[ 5 \text{For instance in a sector such as transport it may be incorrect to attribute an expansion in output to the sector's higher usage of energy. The causality path intuitively seems to be in the opposite direction from a change in output to a change in energy demand.} \]
Figure 1. Road transport output, road transport energy consumption and road transport fuel price 1980-93.
A distinction should be made between short-run and long-run analyses since durable transport equipment is involved. In the short run, energy consuming vehicle stock is fixed and long-run stock is variable. The short-run demand for energy arises from the rate of short-run utilization for transport equipment.

The demand for energy is derived demand and the extent of adjustment to price changes depends on the elapsed time following the change. The presence of such lags reflects the fact that energy input is dependent on the existing stock of energy using transport equipment. There is a lag in the adjustment of the actual demand to the level of planned demand. This is as a result of existing vehicles using a specific rate of energy (which cannot be changed instantly) and the behaviour of the users, who do not view any price change as permanent unless it prevails for some time. The response to a change in price is not immediate, but may be lagged after a dynamic path is taken to a new equilibrium. A long-run elasticity therefore has to be defined which takes into consideration the new energy demand level when behavioural and technological changes have fully adjusted to the new price level.

The demand for energy $E$ expressed as a short-run flow adjustment, becomes a function of the equipment utilization rate $U$: \[ E = U(Y, EP, t)H \]

where $H$ is a quantitative (unit) measure of energy (in barrels or BTUS) and the utilization rate is expressed as a function of output $Y$, energy prices $EP$ and $t$ is time. Such a relationship is also suggested by Jacoby and Paddock [7] and Koshal et al [8]. Using a log-linear relationship Equation (4) may be written as:

\[
\ln E_t = (\alpha_0 + \alpha_1 \ln Y_t + \alpha_2 \ln EP_t)H
\]

where $\alpha_1$ and $\alpha_2$ are the income and price elasticities of the desired (or planned) level of energy demand.\(^6\) The output is assumed to be based on an increasing, quasi-concave production function, presented by a Cobb–Douglas functional form:

\[
Y = f(K, L, E, t) = a_0 L_t^a K_t^b E_t^c
\]

where $L$, $K$ and $E$ denote labour, capital and energy inputs respectively, used to produce transport output $Y$. Technical progress is assumed disembodied and neutral, represented by the time variable $t$ to reflect the effects of technical change. Using the duality relationship between production profit maximization and expenditure minimization, the cost function $C$ can be written as:

\[
C = w^*L + i^*K + E^*EP
\]

In order to derive a long-run relationship, a lag adjustment should be incorporated to represent the difference between actual and planned levels of energy demand. Prosser [12] examines the issue of the most appropriate lag mechanism by comparing approaches based on Koyck and Almon structures. Prosser concludes that Koyck lags perform best. Using a partial adjustment (log-linear) approach, it is assumed that the actual energy consumption $E_{at}$ adjusts to the desired or planned level $E_t$ with a lag, so that each year's energy demand becomes a function of the current year's variables and the previous year's energy consumption. This adjustment process can be written as:

\[
\ln E_t - \ln E_{t-1} = \sigma (\ln E_t - \ln E_{t-1})
\]

where $\sigma$ ($0 < \sigma < 1$) is the inertia parameter reflecting the proportional adjustment and the inertia of economic behaviour. Similar mechanisms can also be derived from adaptive expectations as in Sterner and Dahl [13]. Rearranging Equation (9) for $E_t$ we obtain:

\[
\ln E_t = (1/\sigma) \ln E_{at} - (1 - \sigma)/\sigma \ln E_{at-1}
\]

Substituting $E_t$ from Equation (10) into the structure suggested by Equation (5), we obtain expression 11, including a Koyck lag structure:

\[
\ln E_{at} = \sigma \alpha_0 + \sigma \alpha_1 \ln Y_t + \sigma \alpha_2 \ln EP_t + (1 - \sigma) \ln E_{at-1}
\]

The short-run output and price elasticity of energy demand suggested by Equation (11) become $\sigma \alpha_1$ and
In the long run, as the equilibrium of energy demand is reached $E_{at} = E_{at-1} = E$ and Equation (11) becomes:

$$
\ln E = \alpha_0 + \alpha_1 \ln Y + \alpha_2 \ln EP
+ (1 - \sigma) \ln E
\ln E = \alpha_0 + \alpha_1 \ln Y + \alpha_2 \ln EP
$$

which is similar to Equation (5) in its form. The long-run output and price elasticities become $\alpha_1$ and $\alpha_2$. Because the speed of adjustment $\sigma$ is less than 1, it is evident that the long-run elasticities exceed the corresponding short-run elasticities. From the above, the ratio of long-run to short-run price and output elasticities become a function of the inertia parameter, $\sigma$:

$$
\mu^{SR}(p)/\mu^{LR}(p) = \mu^{SR}(Y)/\mu^{LR}(Y)
= \sigma \alpha_2/\alpha_2 = \sigma \alpha_1/\alpha_1 = \sigma
$$

where $\mu$ denotes elasticity. The $SR-LR$ difference in elasticities could be attributable to flexible and captive components of the total demand for transport fuel. The short-run effects of price changes are confined to flexible demand. Therefore, short-run effects become smaller than long-run effects because only in the long run can new vehicles substitute for old equipment.\(^8\)

### Estimation method

The cointegration technique evaluates the long-term characteristics of economic time series. This may be a different time span for different series with distinct underlying processes. Nelson et al [10] use a 10 year span to identify discernible long-term trends in transport energy consumption. ABARE [1] uses a sample of up to 20 years for passenger vehicle energy demand. A minimum time span of 10 to 15 years is therefore required for the tests below.

The estimation methodology comprises four steps. Regression equations appear in the appendix.

### Stationarity analysis

The stationarity of the data is tested using augmented Dickey-Fuller (ADF) tests 2 and 3 including an intercept and a time trend with four lags reflecting the quarterly periodicity of the data. The structure of the ADF tests are presented below.\(^9\)

**ADF (4 lags): Test 2**

$$
\Delta W_t = \sigma_0 + \sigma_1 W_{t-1} + \sum \beta_i \Delta W_{t-i} + \epsilon_t
$$

**ADF (4 lags): Test 3**

$$
\Delta W_t = \sigma_0 + \sigma_1 W_{t-1} + \sigma_2 Time + \sum \beta_i \Delta W_{t-i} + \epsilon_t
$$

where $W_t$ and $\Delta$ denote a typical series and the order of difference respectively. The stationarity hypothesis is:

$H_0$: series non-stationary

$$
(\sigma_1/Se(\sigma_1)) > DF_{CV(5\%)}\text{ test 2 or 3}
$$

$H_1$: series stationary

$$
(\sigma_1/Se(\sigma_1)) < DF_{CV(5\%)}\text{ test 2 or 3}
$$

The above tests are carried out for output, prices and energy consumption. If a series is found to be non-stationary, the first difference of that series is generated and again put through the ADF tests above. This process is continued until the new difference series become stationary at which point the order of integration of the original series is determined based on the number of differences.

### Cointegration analysis

The long-run characteristics of Equation (12) are examined using a Dickey-Fuller (DF) test 1 (ie without an intercept to reflect the white noise characteristics of having a zero mean) on the stochastic component of the regression Equation (A 10) in the appendix. The structure and hypotheses of the DF test 1 is:

$$
\Delta U_t = \phi U_{t-1} + \epsilon_t
$$

$H_0$: series not cointegrated ($\epsilon_t$ non-stationary)

$$
(\Phi/Se(\Phi)) > PO_{CV(5\%)}\text{ test 1}
$$

$H_1$: series cointegrated ($\epsilon_t$ stationary)

$$
(\Phi/Se(\Phi)) < PO_{CV(5\%)}\text{ test 1}
$$

As the cointegration vector equation has to be estimated, Phillips–Ouliaris critical values are used in place of the DF ones to reflect the loss of degrees of freedom. Cointegration tests are also carried out for

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\(^8\)The divergence between short-run and long-run elasticities depends on the relative magnitude of the flexible demand in year $t$. The greater the flexible demand, the smaller the ratio of long-run to short-run elasticities.

\(^9\)For further detail on cointegration, Dickey–Fuller tests, Granger causality tests and error correction models, see Holden et al [6] and Perman [11].
energy consumption—transport output, energy consumption—price, and transport output—price to determine the structure of the causality tests.

Causality analysis
Granger causality tests are carried out based on a vector auto regressive (VAR) structure using four lags. These tests take the following form:

\[ Q_t = \Omega_0 + \Omega_1 Q_{t-1} + \Omega_2 Q_{t-2} + \Omega_3 Q_{t-3} + \Omega_4 Q_{t-4} + \nu_1 W_{t-1} + \nu_2 W_{t-2} + \nu_3 W_{t-3} + \nu_4 W_{t-4} + \Pi (Q_{t-1} - \beta W_{t-1}) + \epsilon_t Q_t \]

(17)

\[ + u_1 W_{t-1} + u_2 W_{t-2} + u_3 W_{t-3} + u_4 W_{t-4} + u_5 Q_{t-2} + u_6 Q_{t-3} + u_7 Q_{t-4} + \epsilon_t \]

(18)

where Equations (17) and (18) show unrestricted and restricted structures respectively. \( W \) and \( Q \) denote typical series. The cointegration vector \( (Q_{t-1} - \beta W_{t-1}) \) is only added to the first difference VAR structure if the series are shown to be cointegrated. The test amounts to examining the joint significance of blocks of lags using an F-test to establish the causality in terms of the contribution of series \( W \) in predictability of series \( Q \). The F-statistic is constructed in the following manner:

\[ F_{(calc)} = \left[ \frac{(RSR - RSU)/Z}{RSU - T} \right] \]

(19)

where \( RSR \) is the restricted residual sum of squares in Equation (18) and \( RSU \) is the unrestricted one in Equation (17). Parameter \( Z \) denotes the number of restrictions (four lags) and \( T \) is the degree of freedom of the unrestricted model. The hypothesis is:

\[ H_0 \text{ no causality } W_t \text{ to } Q_t, \quad F_{(calc)} < F_2, T \text{ (5%) } \]

\[ H_1 \text{ causality } W_t \text{ to } Q_t, \quad F_{(calc)} > F_2, T \text{ (5%) } \]

The causality tests are also carried out on output—energy demand, output—prices, and energy demand—prices and vice versa. It is important to evaluate the causality paths between each series pair to avoid spurious results that could occur when two series show bidirectional causality only because both are caused by a third underlying series. The VAR causality test results can then be used to verify the proposed structure of the model discussed above.

Error correction model (ECM)
The final step in the estimation procedure is the examination of the short-term characteristics of road transport energy demand using an error correction structure of the following form:

\[ \Delta \ln E_t = \Gamma_0 + \Gamma_1 \Delta \ln Y_t + \Gamma_2 \Delta \ln EP_t + [4 \text{ lags } \Delta E] + \beta [\ln E_{t-1} - \alpha_1 \ln Y_{t-1} - \alpha_2 \ln EP_{t-1}] + \epsilon_t \]

(20)

The ECM structure suggests that short-run movements in road transport energy consumption (\( \Delta E \)) are related to short-run changes in road transport output and real energy prices (\( \Delta Y \) and \( \Delta EP \)). The cointegrating vector coefficient \( \beta \) is expected to be negative in order to correct deviations from the long-term trend.

The ability to form an ECM structure depends on the stationarity characteristics of Equation (12). Only if the long-run relationship can be verified by a cointegration analysis it is then possible to examine the short-term characteristics by using an ECM framework.

Results
Stationarity
The results are presented in Table 1 (see appendix equations (A1) to (A6)). Referring to the stationarity hypothesis above, we accept \( H_0 \) and conclude that the three series above are non-stationary. In order to establish the order of integration of the above series, the results of the stationarity tests on the first differences of the series are presented in Table 2 (see appendix Equations (A7) to (A9)). \( H_1 \) is accepted and with the first differences of the series being stationary it is concluded that the three series are integrated of order 1, \( I(1) \).

### Table 1: ADF stationarity tests on \( Y \) (road transport output), \( E \) (road transport energy demand) and \( EP \) (real road transport energy/fuel prices)

<table>
<thead>
<tr>
<th>Series</th>
<th>Test 2 ADF(4) Statistic</th>
<th>DF(4) CV(T = 50, 5%)</th>
<th>Test 3 ADF(4) Statistic</th>
<th>DF(4) CV(T = 50, 5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Y )</td>
<td>-9.932</td>
<td>-2.93</td>
<td>-1.787</td>
<td>-3.50</td>
</tr>
<tr>
<td>( E )</td>
<td>-0.867</td>
<td>-2.93</td>
<td>-2.144</td>
<td>-3.50</td>
</tr>
<tr>
<td>( EP )</td>
<td>-1.514</td>
<td>-2.93</td>
<td>-2.198</td>
<td>-3.50</td>
</tr>
</tbody>
</table>
### Table 2: ADF(4) test 2: stationarity results on first differences

<table>
<thead>
<tr>
<th>Series</th>
<th>Test 2 ADF(4) statistic</th>
<th>CV(T = 50, 5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔY</td>
<td>-3.010</td>
<td>-2.93</td>
</tr>
<tr>
<td>ΔE</td>
<td>-3.639</td>
<td>-2.93</td>
</tr>
<tr>
<td>ΔEP</td>
<td>-3.924</td>
<td>-2.93</td>
</tr>
</tbody>
</table>

### Table 3: Cointegration results - ADF(0): test 1 on the stochastic components of Equation (21)*

<table>
<thead>
<tr>
<th>Series</th>
<th>Test 1 ADF(0) statistic</th>
<th>PO CV (Test 2, 3 variables, 5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>-8.65</td>
<td>-4.11</td>
</tr>
</tbody>
</table>

*Because the cointegration vector has to be estimated (with an intercept and three dependent variables), the critical values of Phillips–Ouliaris distribution tables are used.

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**Cointegration**

The long-run characteristics of the model are represented by regression Equation (21) (see appendix equations (A10) and (A11)). The cointegration results of $U_1$ appear in Table 3:

$$TE = 4.709 + 0.518 TO - 0.131 EP + U_1, \quad (21)$$

The above results indicate that the residuals are stationary. Therefore, each series is integrated of order 1, but the relative movements of these series become stationary, indicating a valid long-run relationship of the form specified in the model. This outcome combined with the previous unit root results, yield the superconsistency of the estimates in Equation (21). The coefficients may be interpreted as the long-run output and price elasticities of energy demand. These are 0.52 for output elasticity and -0.12 for price elasticity in the long run.

**Causality**

Table 4 contains a summary of the causality tests. The results show bidirectional causality between output and energy demand and a unidirectional path from energy demand to prices. The first validates approaches similar to those of Koshal et al [8], where output and demand are simultaneously estimated. The second outcome indicates that the inclusion of energy prices in the model Equation (12) is of little value in the short run, as the causality path appears to be from fuel demand to prices and not vice versa. Similarly, there are no significant direct causality paths between road transport output and energy prices, which is intuitively acceptable.

**Error correction model: SR results**

The variables in the ECM are I(0) and therefore, the $t$-statistics can be used to determine the significance level of the estimates. Based on Equation (A29), the short-run output and price elasticities of energy demand are 0.25 and -0.02 respectively. However, as expected based on the causality tests above, the coefficient of the price variable is not significant. The coefficient of output is significant at 10% level.

Using Equation (13), the adjustment inertia of energy demand in road transport may be estimated:

$$\mu^S(Y)/\mu^L(Y) = \sigma = 0.25/0.52 = 0.48$$

A summary of short-run and long-run values appear in Table 5.

**Discussion**

The cointegration estimates of long-run output and price elasticities of 0.48 and -0.12 respectively, compare with Brian and Schuyers [3] long-run output and price elasticity estimates of 0.72 and -0.22 respectively, based on 1970s' data. The difference in the results could be attributable to structural and technological changes in road transport during the 1980s. Some of these variations are:

1. Introduction of higher allowable gross combination mass (GCM) from 32 tonnes to 42.5 tonnes for freight vehicles;
2. Introduction of the Canadian type B-Double (59T GCM) and triple road trains (116T GCM) to freight fleets;
3. Introduction of higher speed limits from 85 kph to 100 kph for freight vehicles and 110 kph for passenger vehicles, as well as an increase in the number of dual carriage way freeways;
4. Introduction of electronic fuel injection systems to passenger vehicle fleets and electronic engine management systems to freight vehicles;
5. Introduction of exhaust emission control limits.

A restructuring of technology towards more efficient engines and lower vehicle tariff is built into long-term
Table 4 Granger causality results (VAR with ECM term)*

<table>
<thead>
<tr>
<th>Series</th>
<th>Y</th>
<th>E</th>
<th>EP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td></td>
<td>FTE(stat) = 4.04</td>
<td>FTE(stat) = 1.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F4,40(5%) = 2.61</td>
<td>F4,40(5%) = 2.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accept $H_1$, causality</td>
<td>Accept $H_0$, no causality</td>
</tr>
<tr>
<td>E</td>
<td>FET(stat) = 2.71</td>
<td>-</td>
<td>FET(stat) = 5.07</td>
</tr>
<tr>
<td></td>
<td>F4,40(5%) = 2.61</td>
<td>-</td>
<td>F4,40(5%) = 2.61</td>
</tr>
<tr>
<td></td>
<td>Accept $H_0$, causality</td>
<td>-</td>
<td>Accept $H_1$, causality</td>
</tr>
<tr>
<td>EP</td>
<td>FTP(stat) = 0.48</td>
<td>FPE(stat) = 1.87</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>F4,40(5%) = 2.61</td>
<td>F4,40(5%) = 2.61</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Accept $H_0$, no causality</td>
<td>Accept $H_0$, no causality</td>
<td>-</td>
</tr>
</tbody>
</table>

* Causality paths are read from the row element to the column elements.

price elasticity. The issue of technological progress, however, cannot be tackled unless a proper way of measuring it can be found. In the road transport sector a proxy variable showing litres per tonne kilometre for freight or kilometres per litre for passenger vehicles may be used. However, because of the presence of multicollinearity between time trends and income or price variables it could be preferable (in the absence of engineering data that properly describe technical progress) to estimate output and price effects without an explicit allowance for technological change.

The ECM shows the short-run price elasticity of energy demand to be insignificant as expected from the causality tests. Changes in road transport output, on the other hand, can be considered the main factor that determines the utilization of energy consuming transport equipment and, hence short-term energy demand. The speed of adjustment in road transport energy demand can then be expressed as the ratio of SR to LR elasticities to be 0.48. This indicates that 95% of adjustment from actual demand to the planned level in road transport occurs within five periods based on a partial adjustment assumption.

By using a different specification or different sample periods different estimates of elasticities would be obtained. Judgement is therefore necessary to supplement econometric applications when interpreting the results. Kouris [9] provides a table of road transport fuel elasticities in the USA which shows considerable variations across different periods. He suggests that the most likely explanation is the changing market structure and questions the existence of stable price elasticities.

This estimation approach may also be used to establish the validity of some of the other models discussed above which were based on simultaneous estimation structures that presume a two-way causality between output and energy demand. Stationarity test results also point to some of the current literature where models are compared using $t$-statistics on this type of data. These could be subject to spurious results, as $t$-statistics are not reliable when used on non-stationary variables.

Conclusion

Cointegration analysis can be extended to energy demand modelling in the road transport sector. Stationarity tests on variables used in energy demand models such as prices and output, show these variables to be non-stationary entities and integrated of order 1. It can be shown that these variables are cointegrated by examining stationarity characteristics of the stochastic component of the reduced form equation in the model. The estimated coefficients become superconsistent and can also be interpreted as long-run elasticities. It can be shown that it is only in the long run that price elasticity becomes meaningful in projecting energy demand.

Using cointegrating vectors, a series of causality tests show that there is bidirectional causality between output and energy consumption and unidirectional causality from energy demand to prices. This type of estimation can be used to refine the structure of sectoral energy demand models in the road transport sector, in particular by using error
correction models to estimate the short-term characteristics of variables.

Acknowledgements

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Appendix

Data and (TSP) OLS regression equation

\[ E = \text{road transport energy consumption (log), periodicity: quarterly s/a, sample: 1980:1 to 1993:2, source: Shell Australia Ltd/AIP database, units: billion litres}. \]

\[ EP = \text{Road transport fuel prices (real - log), periodicity: quarterly s/a, sample: 1980:1 - 1993:2, source: dX Shell Australia, units: cents/litre}. \]

\[ Y = \text{road transport output (log), periodicity: quarterly s/a, sample: 1980:1 to 1993:2, source: dX. Road transport output, measured as the level of revenue derived from the activity of carrying goods and passengers for hire and reward and provision of other road transport services (ABS [2]).} \]

Unit root tests

\[ ADF(4 \text{ lags): test 1} \]

\[
\Delta Y = 0.273 - 0.034Y_{(-1)} - 0.309\Delta Y_{(-1)} - 0.072\Delta Y_{(-2)} \\
(0.959) (-0.932) (-2.070) (-0.466) \\
+ 0.751\times 10^{-2}\Delta Y_{(-3)} + 0.137\Delta Y_{(-4)} + \epsilon_t \\
(0.054) (1.034) \\
R^2 = 0.14 \quad DW = 1.99 \quad (A1)
\]

\[ AEP = 0.013 - 0.170EP_{(-1)} - 0.088\Delta EP_{(-1)} \\
(0.102) (-1.514) (-0.533) \\
- 0.180\Delta EP_{(-2)} + 0.021\Delta EP_{(-3)} \\
(-1.089) (1.134) \\
0.541\Delta EP_{(-4)} + \epsilon_t \\
(0.037) \\
R^2 = 0.65 \quad DW = 1.97 \quad (A2)
\]

\[ ADF(4 \text{ lags): test 2} \]

\[
\Delta Y = 1.536 - 0.203Y_{(-1)} + 0.163\times 10^{-2}\text{Time} \\
(1.800) (-1.767) (1.567)
\]
Road transport energy demand in Australia: R Samimi

\[-0.174\Delta Y_{(-1)} - 0.051\Delta Y_{(-2)} + 0.114\Delta Y_{(-3)} \]
\[\quad \quad (-1.025) (0.297) (0.746) \]  
\[+ 0.216\Delta Y_{(-4)} + \varepsilon_t \]
\[\quad \quad (1.548) \]
\[R^2 = 0.19 \quad \quad DW = 2.06 \] (A4)

\[\Delta E = 4.119 - 0.479\Delta Y_{(-1)} + 0.232\text{Time} \]
\[\quad (2.162) (-2.144) (1.984) \]
\[-0.292\Delta E_{(-1)} - 0.107\Delta E_{(-2)} - 0.220\Delta E_{(-3)} \]
\[\quad (-1.232) (-0.502) (-1.163) \]
\[+ 0.253\Delta E_{(-4)} + \varepsilon_t \]
\[\quad (1.689) \]
\[R^2 = 0.19 \quad \quad DW = 2.06 \] (A5)

First difference series, ADF(4 lags): test 1

\[\Delta^2 Y = 0.75*10^{-2} - 1.241\Delta Y_{(-1)} - 0.084\Delta^2 Y_{(-1)} \]
\[\quad (1.383) (-3.010) (-0.229) \]
\[-0.170\Delta^2 Y_{(-2)} - 0.183\Delta^2 Y_{(-3)} \]
\[\quad (-0.569) (-0.844) \]
\[-0.040\Delta^2 Y_{(-4)} + \varepsilon_t \]
\[\quad (-0.293) \]
\[R^2 = 0.66 \quad \quad DW = 1.95 \] (A7)

\[\Delta^2 E = 0.011 - 2.367\Delta E_{(-1)} + 0.685\Delta^2 E_{(-1)} \]
\[\quad (2.126) (-3.639) (1.186) \]
\[+ 0.288\Delta^2 E_{(-2)} + 0.144\Delta^2 E_{(-3)} \]
\[\quad (0.657) (-0.482) \]
\[+ 0.012\Delta^2 E_{(-4)} + \varepsilon_t \]
\[\quad (0.080) \]
\[R^2 = 0.89 \quad \quad DW = 1.98 \] (A8)

Cointegration tests

\[E = 4.709 + 0.518Y - 0.131E + U1_t \]
\[\quad (15.470) (13.371) (-1.930) \]
\[R^2 = 0.85 \quad \quad DW = 2.34 \] (A10)

\[\Delta U1 = -0.1205U1_{(-1)} + \varepsilon_t \]
\[\quad (-8.647) \]
\[R^2 = 0.59 \quad \quad DW = 1.92 \] (A11)

\[\Delta U2 = -1.179U2_{(-1)} + \varepsilon_t \]
\[\quad (-8.479) \]
\[R^2 = 0.56 \quad \quad DW = 1.93 \] (A13)

\[\Delta U3 = -0.323U3_{(-1)} + \varepsilon_t \]
\[\quad (-3.486) \]
\[R^2 = 0.19 \quad \quad DW = 2.51 \] (A15)

Causality tests

Restricted

\[\Delta Y = 0.78*10^{-2} - 3.223\Delta Y_{(-1)} - 0.074\Delta Y_{(-2)} \]
\[\quad (1.511) (-2.173) (-0.477) \]
\[+ 0.0195\Delta Y_{(-3)} + 0.151\Delta Y_{(-4)} + \varepsilon_t \]
\[\quad (0.141) (1.147) \]
\[R^2 = 0.12 \quad \quad DW = 2.00 \] (A20)

\[\Delta E = 0.011 - 0.694\Delta E_{(-1)} - 0.393\Delta E_{(-2)} \]
\[\quad (2.335) (-4.710) (-2.330) \]
\[- 0.423\Delta E_{(-3)} + 0.163\Delta E_{(-4)} + \varepsilon_t \]
\[\quad (-2.535) (1.106) \]
\[R^2 = 0.64 \quad \quad DW = 1.96 \] (A21)
\[ \Delta EP = -0.23 \times 10^{-2} - 0.204 \Delta EP_{(-1)} - 0.281 \Delta EP_{(-2)} \\
\quad - 0.050 \Delta EP_{(-3)} + 0.051 \Delta EP_{(-4)} + \epsilon_t \]
\[ R^2 = 0.10 \quad DW = 2.00 \] (A22)

Unrestricted

\[ \Delta E = 0.63 \times 10^{-2} - 0.265 \Delta E_{(-1)} - 0.124 \Delta E_{(-2)} \\
\quad - 0.307 \Delta E_{(-3)} + 0.139 \Delta E_{(-4)} - 0.024 \Delta Y_{(-1)} \\
\quad - 0.056 \Delta Y_{(-2)} + 0.165 \Delta Y_{(-3)} - 0.88 \times 10^{-2} \Delta Y_{(-4)} \\
\quad - 0.082 U_2_{(-1)} + \epsilon_t \]
\[ R^2 = 0.72 \quad DW = 1.95 \] (A23)

\[ \Delta Y = 0.45 \times 10^{-2} - 0.256 \Delta Y_{(-1)} + 0.071 \Delta Y_{(-2)} \\
\quad + 0.046 \Delta Y_{(-3)} + 0.116 \Delta Y_{(-4)} - 0.192 \Delta E_{(-1)} \\
\quad + 0.250 \Delta E_{(-2)} + 0.408 \Delta E_{(-3)} + 0.077 \Delta E_{(-4)} \\
\quad + 0.308 U_2_{(-1)} + \epsilon_t \]
\[ R^2 = 0.28 \quad DW = 2.01 \] (A24)

\[ \Delta EP = -0.83 \times 10^{-2} - 0.071 \Delta EP_{(-1)} - 0.088 \Delta EP_{(-2)} \\
\quad - 0.045 \Delta EP_{(-3)} + 0.096 \Delta EP_{(-4)} \\
\quad + 0.803 \Delta E_{(-1)} + 0.492 \Delta E_{(-2)} + 0.211 \Delta E_{(-3)} \\
\quad - 0.375 U_3_{(-1)} + \epsilon_t \]
\[ R^2 = 0.82 \quad DW = 1.95 \] (A29)