Costs of Reducing Greenhouse Gas Emissions from Australian Road Freight Vehicles: An Application of the BTCE TRUCKMOD Model

Working Paper

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Bureau of Transport and Communications Economics

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COSTS OF REDUCING GREENHOUSE GAS EMISSIONS FROM AUSTRALIAN ROAD FREIGHT VEHICLES: AN APPLICATION OF THE BTCE TRUCKMOD MODEL

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FOREWORD

The then Prime Minister announced in his 21 December 1992 Statement on the Environment that the Bureau of Transport and Communications Economics (BTCE) would provide a comprehensive analysis of the range of possible measures for reducing greenhouse gas emissions from the transport sector. The project is scheduled for completion in mid-1996.

In March 1995, the BTCE published base case projections of emissions of greenhouse gases as Report 88 *Greenhouse Gas Emissions from Australian Transport: Long Term Projections*. Since then, work has focussed on estimating the marginal costs of reducing emissions from base case levels. Initial results for a set of policy instruments were presented at a 'work in progress' seminar in Canberra on 7 December 1995.

Two of the policy instruments being assessed are the enhancement of fuel efficiencies in new trucks, and faster scrappage of older trucks. Both rely on the TRUCKMOD model of the dynamics of the Australian truck fleet presented in this working paper.

TRUCKMOD was developed by David Mitchell under the direction of Dr David Gargett, and edited by Belinda Jackson.

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Canberra
March 1996

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ABSTRACT

TRUCKMOD is the BTCE's model of the Australian road freight vehicle fleet. It was designed principally to estimate the dynamic effects of policies that alter the distribution of the vehicle task. As far as the BTCE is aware this is the first vintage specific model of the road freight vehicle fleet in Australia. The model covers the period 1991 to 2015.

Two possible policy measures to reduce greenhouse gas emissions from road freight vehicles are examined—the accelerated uptake of more fuel efficient vehicle technology and the accelerated retirement of less fuel efficient vehicles.

Analysis using TRUCKMOD shows that accelerated vehicle technology uptake would result in a significant reduction in greenhouse gas emissions. Accelerated retirement of less fuel efficient vehicles is a very expensive policy, with a very small reduction in emissions at very high cost.

CHAPTER 1 INTRODUCTION

The Interim Planning Target adopted by the Australian Government in October 1990 aims to stabilise greenhouse gas emissions at 1988 levels by the year 2000, and to further reduce these emissions on a national basis by 20 per cent by the year 2005.

The BTCE's approach is to estimate the costs and size of greenhouse gas reductions from a range of different greenhouse gas abatement measures for the transport sector. The costs and effects of different policies are used to derive a marginal cost curve of greenhouse gas abatement for each policy measure. The methodology is outlined in BTCE Working Paper 10, *Costs of Reducing Greenhouse Gas Emissions in Australian Transport* (BTCE 1993).

The marginal cost approach allows comparison of policy measures between different sectors of the Australian economy. Marginal cost curves provide a guide to the cost effectiveness of different greenhouse reduction policies and allow an ordering of implementation, so that greenhouse gas abatement is undertaken at least cost, from a national perspective.

In practice, estimating marginal costs is more of an ideal than a practical option. It is, however, generally possible to measure changes in emissions and costs between discrete states, generating a species of incremental costs. The incremental cost of reducing carbon dioxide (CO_2) equivalent emissions has been calculated as the change in cost divided by the change in CO_2 equivalent emissions between one discrete state and another. In contrast marginal costs are normally defined in terms of minute changes such that they measure the cost of forgoing the last unit of CO_2 equivalent emissions. Where this working paper refers to marginal costs, the numerical estimate is in fact equal to a weighted average incremental cost.

The costs reported in this working paper are all in terms of Australian dollars at 1996 market prices ($1996). All future costs are converted to present value $1996 using a 10 per cent discount rate.

Road freight transport is expected to contribute an increasing share of total greenhouse gas emissions from the transport sector. According to BTCE estimates (BTCE 1995, p. 31), by 2015 total road *freight* transport emissions will approximately equal total road *passenger* transport emissions. Depending on the relative costs of abatement, this may have implications for the size of greenhouse gas emission reductions required in the road freight sector.

Reductions in carbon based fuel consumption may be achieved by either reducing total transport activity (through regulation, tradeable permits or carbon taxes), improving the efficiency of the vehicle fleet (through the introduction of new technology or accelerated scrappage of older vehicles), adoption of non-carbon based fuels (for example hydrogen), or some combination of all of these measures.

The scope for reducing emissions from road freight vehicles through the adoption of new technology and accelerated scrappage forms the focus of this working paper.

To measure the potential reduction in greenhouse gas emissions, the BTCE constructed TRUCKMOD, a model of the Australian truck fleet that apportions the freight task, number of vehicles and total fuel use according to age of truck for each year from 1991 to 2015. Simulation of the annual effects of new technology and accelerated scrappage is possible because TRUCKMOD contains an age profile of the truck fleet, freight task and fuel consumption.

Using TRUCKMOD, the analysis shows that accelerated uptake of technology enhancements in truck engines and vehicles has the potential to significantly reduce emissions from road freight transport. If present growth in road freight vehicle activity continues, however, earlier uptake of technology enhancements will not reduce emissions in absolute terms. Based on the estimates of individual vehicle costs for the technology enhancements considered in this working paper, accelerated uptake of technology is forecast to result in net cumulative benefits to the Australian economy over the period to 2015.

Analysis of accelerated scrappage of older vehicles using TRUCKMOD suggests that such a policy does not offer a significant scope for reducing greenhouse gas emissions. Further, the costs of an accelerated scrappage policy for trucks are very high.

CHAPTER 2 STRUCTURE OF THE MODEL

TRUCKMOD is a model of the Australian truck fleet and road freight task. It provides estimates of the size of the aggregate freight task, the number of new vehicles, the size of the vehicle stock required to undertake the task, total fuel usage, and total emissions produced by vehicle usage.

TRUCKMOD apportions the total freight task, vehicle usage, fuel consumption and greenhouse gas emissions by age of vehicle. It allows the simulation of both the timing and the effectiveness of policies designed to reduce greenhouse emissions from road freight transport. In its present form, the model contains annual data, observed and projected, for the period 1971 to 2015.

The main output from the model includes:

- the annual number of new vehicles entering the fleet each year;
- the number of vehicles scrapped annually, by vehicle age;
- fuel consumption, by vehicle age; and
- total emissions by type of gas, and total CO_2 equivalent emissions.

To run the model, the required inputs include:

- the estimated total stock of vehicles in the fleet each year;
- average annual kilometres travelled by each vehicle; and
- average fuel intensity (litres/100km), by vehicle vintage (that is, cohort or year of vehicle manufacture).

TRUCKMOD is composed of six main elements or sub-models (figure 2.1):

i. Task/split sub-model;

ii. Vehicle stock sub-model;

iii. Vintage distribution sub-model;

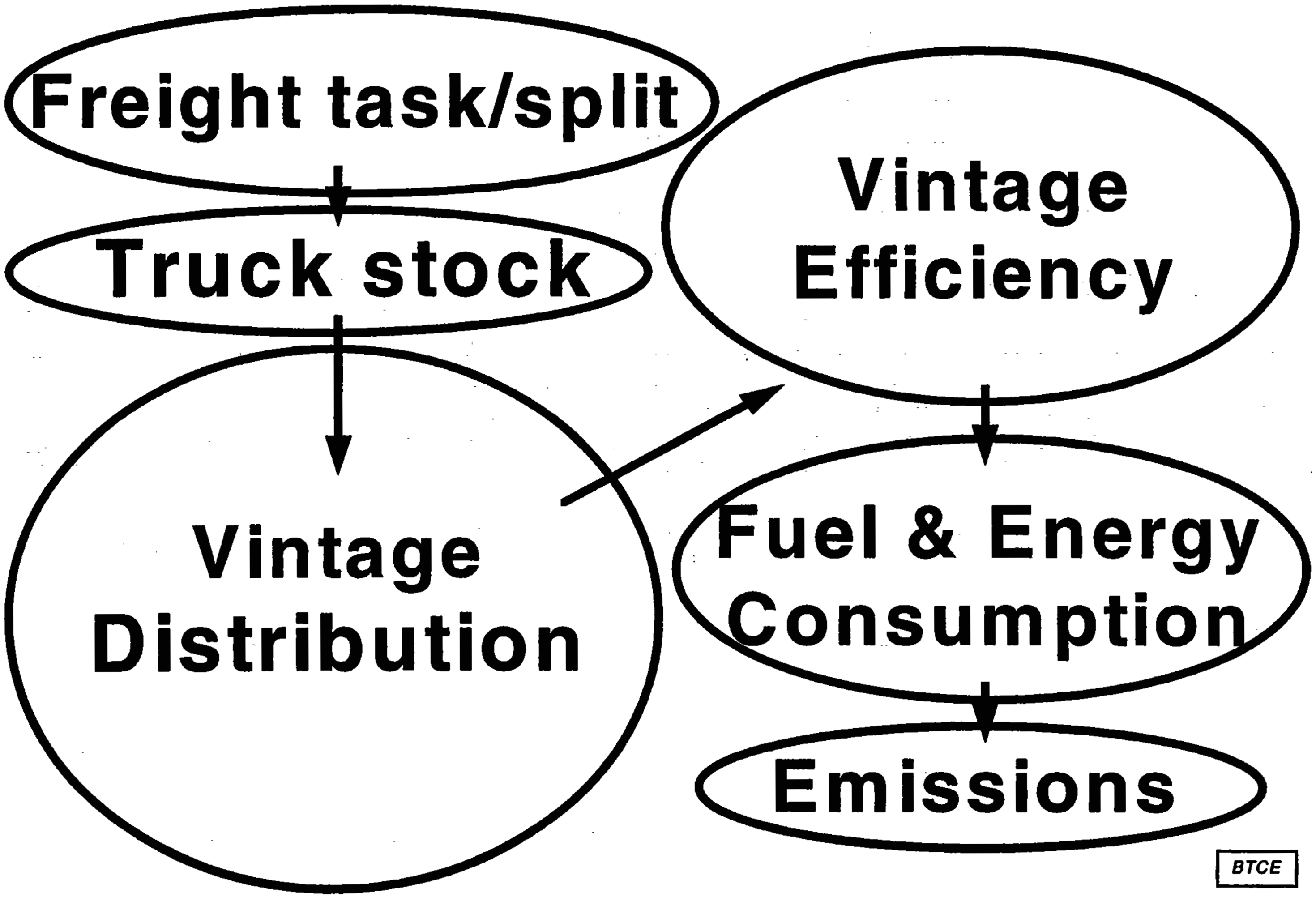
iv. Vintage efficiency sub-model;

v. Fuel and energy consumption sub-model; and

vi. Total emissions sub-model.

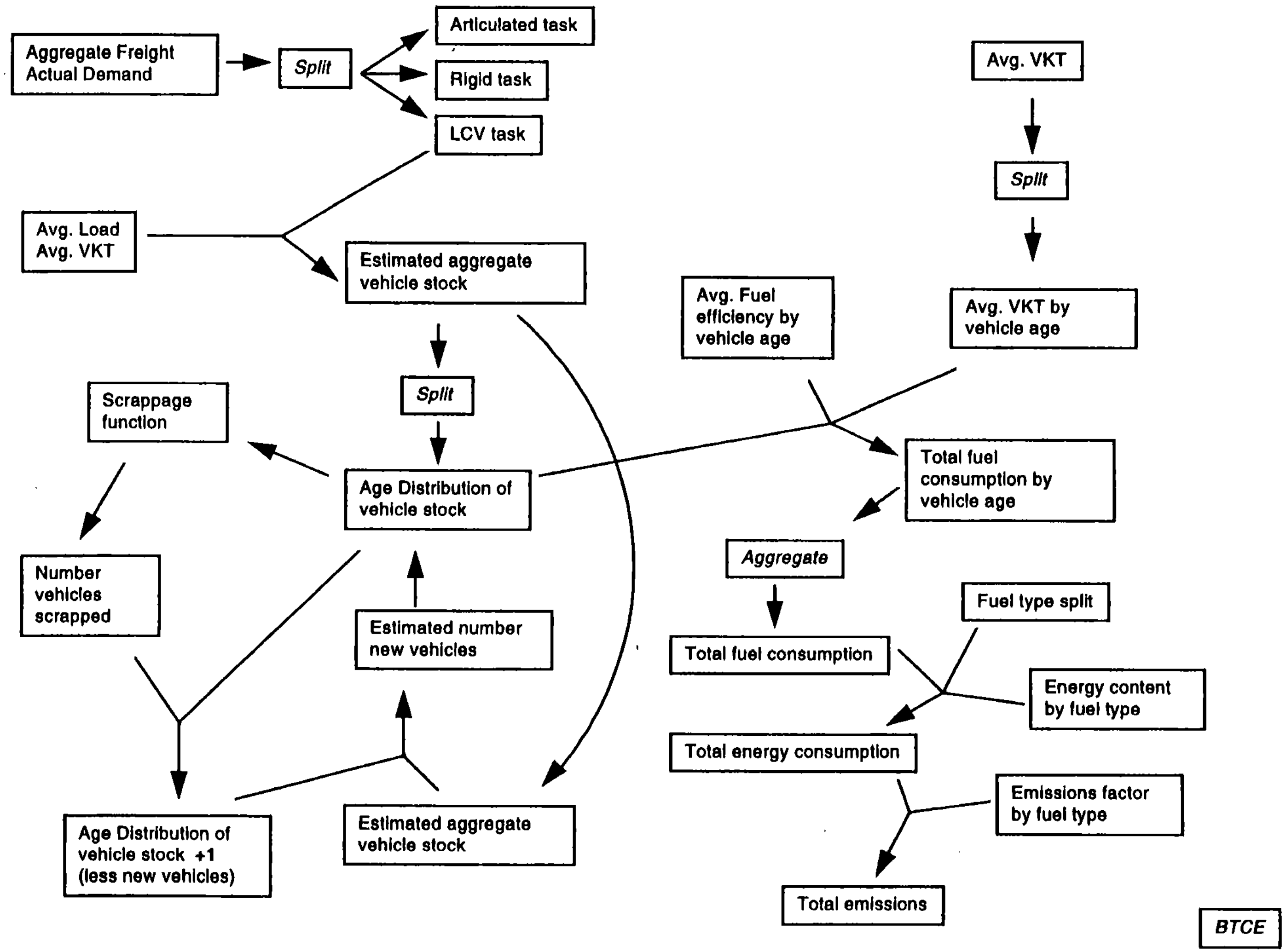
These functions are highlighted in a more detailed flow chart of the model, presented in figure 2.2.

FIGURE 2.1 BROAD STRUCTURE OF TRUCKMOD



Source BTCE.

FIGURE 2.2 DETAILED STRUCTURE OF TRUCKMOD



Source BTCE.

TASK/SPLIT SUB-MODEL

The task/split sub-model performs two operations. The first operation determines the total road freight task. The second apportions the aggregate road freight task across the three different vehicle types: articulated trucks, rigid trucks and light commercial vehicles (LCVs).

TRUCKMOD uses the forecast aggregate freight task as the main determinant of the number of vehicles in the fleet. Forecasts of the aggregate freight task are based on an empirical relationship between aggregate freight tonne-kms, real GDP and real (long-haul) average road freight rates.

The estimated relationship has the following functional form:

$$\text{(1)} \quad \ln(TOTFRT) = \underset{(-3.6)}{-4.46} + \underset{(14.9)}{1.058} \ln(RGDP) - \underset{(-12.8)}{0.923} \ln(RROADLH)$$

$\bar{R}^2 = 0.99$

Estimation: Cochrane-Orcutt iterative technique

Estimation period: 1964–65 to 1990–91.

where

ln(TOTFRT)	natural log of total road freight task (measured in tonne-kilometres);
ln(RGDP)	natural log of the expenditure measure of gross domestic product (GDP(E)) at constant 1989/90 prices; and
ln(RROADLH)	natural log of the real road freight rate for long haul road freight.

The t-ratios of the significance of the parameter estimates are given in parentheses. See BTCE (1995, p. 38) for further details about the regression results.

Assumptions for base-case projections of freight task and split

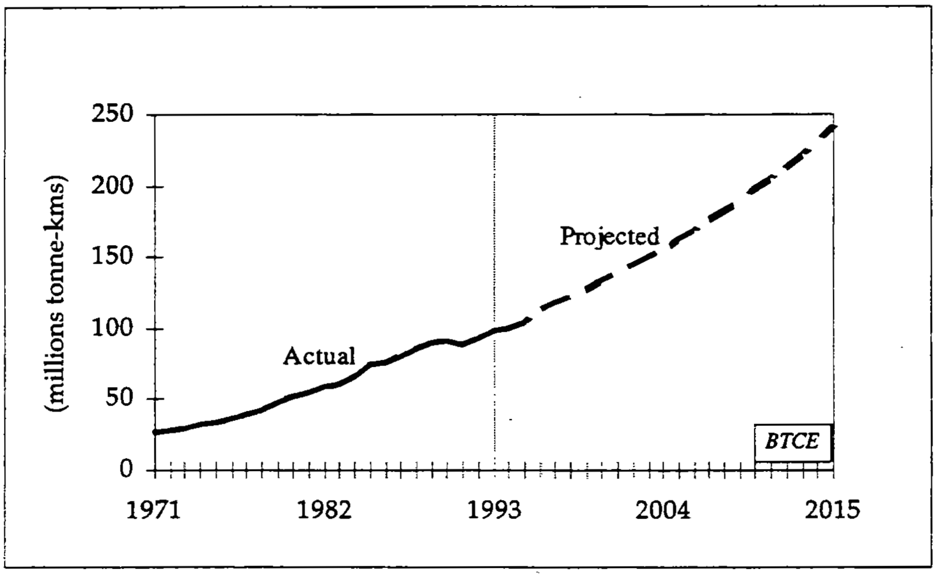
Base-case projections of the total road freight task are determined by assumptions about future GDP growth and future trends in real road freight rates.

In the base case it is assumed that real GDP will grow by 3.2 per cent per annum to 1997–98 and by 3.3 per cent per annum from 1997–98 to 2014–15. These assumptions are based on BIS Shrapnel long-term forecasts for the Australian economy (BIS Shrapnel 1993).

Real road freight rates are assumed to fall by 15 per cent over the period from 1992–93 to 2014–15. It is arguable that heavier loads will be carried per truck as B-doubles and other trailer combinations become more common in the Australian truck fleet, with resulting decreases in freight rates. This accords with recent experience. Between 1970 and 1990, real long haul road freight rates declined by approximately 46 per cent. Over a similar period, the average freight carrying capacity of articulated trucks has increased from 16.4 tonnes in 1971 to 23.4 tonnes in 1988, an increase of approximately 43 per cent. The projected decline in real road freight rates over the next 20 years is well within past experience.

Based on these assumptions, the total road freight task (in tonne-kms) is projected to grow at approximately 4 per cent per annum from 1992–93 to 2014–15. Figure 2.3 illustrates the total road freight task growing along an exponential growth path to 2015.

FIGURE 2.3 TOTAL AUSTRALIAN ROAD FREIGHT TASK, 1971 TO 2015



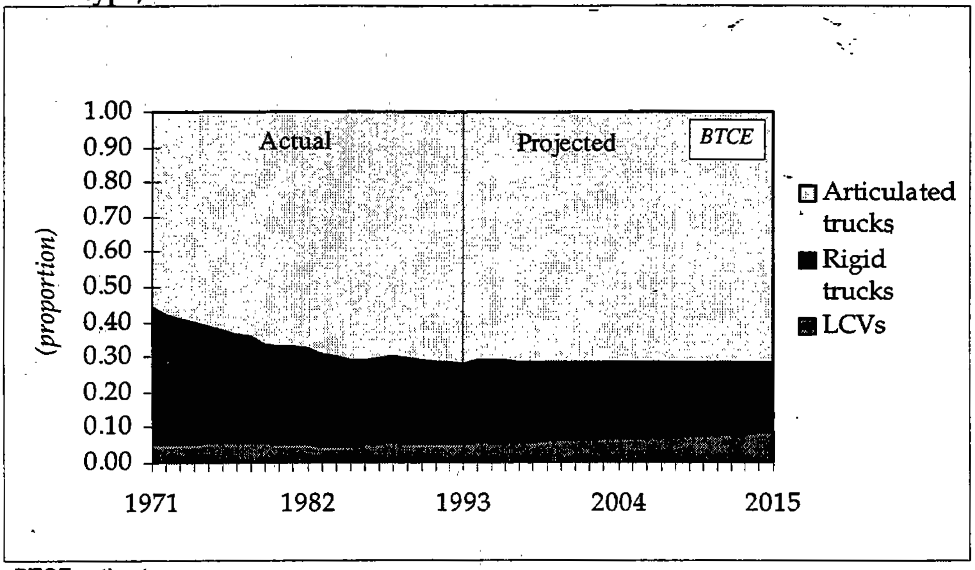
Source BTCE estimates.

The projected aggregate road freight task is allocated in TRUCKMOD between the different vehicle types according to the following assumptions:

- tonne-kilometre task undertaken by LCVs is assumed to grow by 5.8 per cent per annum (similar to growth experienced during the 1980s);
- tonne-kilometre task undertaken by rigid trucks is assumed to grow by 3 per cent per annum (similar to growth in 1970s and 1980s); and
- the remaining growth projected for the total tonne-kilometres task is allocated to articulated trucks, which is therefore assumed to grow at about 3.8 per cent per annum.

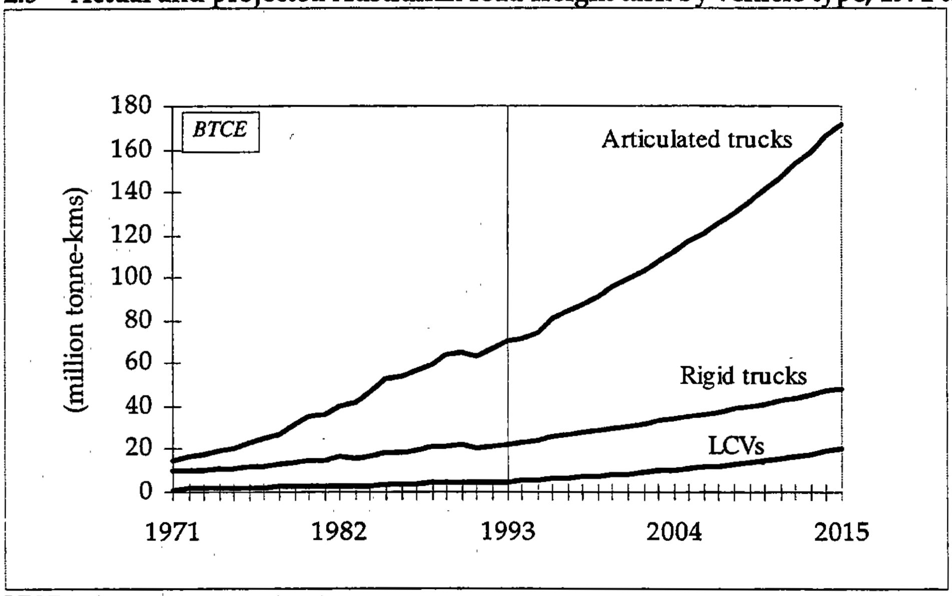
These assumptions imply that the total task of each of the three vehicle types will grow over the period to 2015, but the rigid truck share of the total task will shrink each year to 2015. The share of the road freight task for each vehicle type is shown in figure 2.4. Historical patterns are presented in appendix table III.1.

Figure 2.4 Actual and projected share of the total Australian road freight task by vehicle type, 1971 to 2015



Source BTCE estimates.

Figure 2.5 Actual and projected Australian road freight task by vehicle type, 1971 to 1995



Source BTCE estimates.

The implicit assumption underlying these assumed growth rate differentials is an expectation that there is greater scope for growth in small suburban delivery type services, undertaken by smaller commercial vehicles, than there is for large commercial vehicles. It is expected that groceries and possibly small consumer durables will be increasingly home delivered, fuelled by the convenience and increased availability of teleshopping and other new communication services.

VEHICLE STOCK SUB-MODEL

The vehicle stock sub-model provides an estimate of the total vehicle stock required to undertake the total road freight task. Assumptions about the average load size and the average distance travelled by vehicle type for each year to 2015, are combined with the estimated aggregate freight task (from the task split sub-model) to derive an estimate of the total vehicle stock required to handle the estimated total freight task.

Assumptions for base-case projections of truck stocks

In the base case the average load of articulated trucks is assumed to grow by about 0.7 per cent per annum, similar to growth rates during the 1980s.

For rigid trucks, the average load is assumed to increase by 1 per cent per annum.

Average loads for urban LCVs are assumed to increase at 1.6 per cent per annum, and those for non-urban LCVs by 2.3 per cent per annum (roughly equal to growth rates in the 1980s and early 1990s).

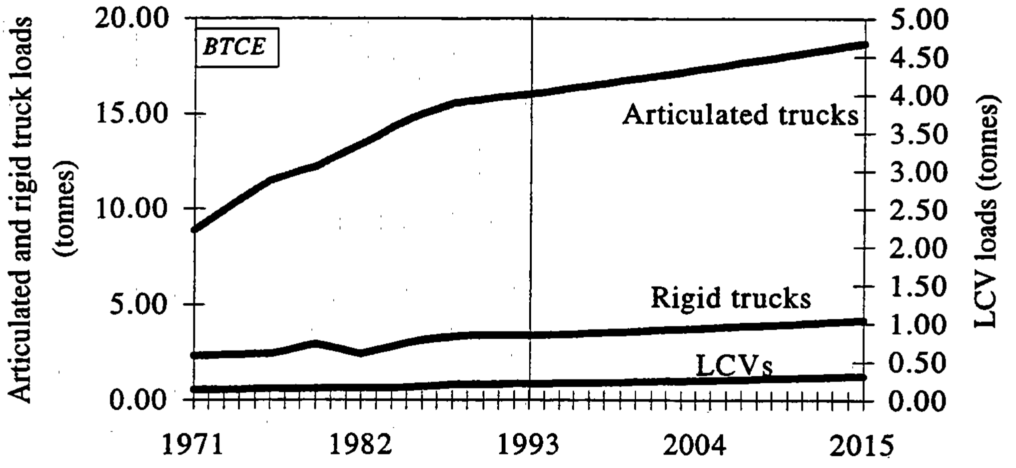
These assumptions are based on the expectation that competition will continue to force road freight operators to increase the intensity of vehicle use. Increased average loads reflect this expected increase in vehicle utilisation. The assumed magnitude of growth in average loads is in line with past trends. Over the past twenty years the average load of articulated trucks has increased at approximately 1.04 per cent per annum, for rigid trucks at 0.90 per cent per annum, and for LCVs at 2.45 per cent per annum. These assumptions are also used in BTCE Report 88 (BTCE 1995, p. 38–39).

The overall effect of these assumptions is:

- average vehicle kilometres travelled (VKT) is assumed to remain constant from 1991 to 2015 for each vehicle type;
- average load is forecast to grow by approximately 48 per cent for LCVs, 24 per cent for rigid trucks, and 17 per cent for articulated trucks over the period 1991 to 2015.

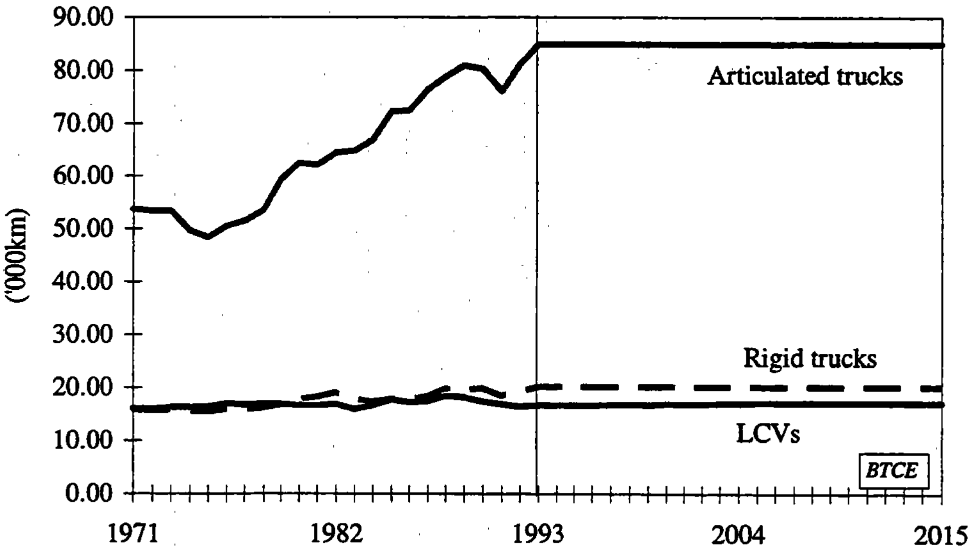
Actual and projected average loads and average VKT are presented in appendix tables III.2 and III.3.

FIGURE 2.6 ACTUAL AND PROJECTED AVERAGE LOAD BY VEHICLE TYPE, 1971 TO 2015



Source BTCE estimates.

FIGURE 2.7 ACTUAL AND PROJECTED AVERAGE VKT BY VEHICLE TYPE, 1971 TO 2015



Source BTCE 1995.

VINTAGE DISTRIBUTION SUB-MODEL

The vintage distribution sub-model provides estimates of the age profile of the vehicle fleet for each year to 2015.

The estimated vehicle stock is allocated by vehicle age using the actual 1991 age distribution of the vehicle fleet, obtained from the Australian Bureau of

Statistics (ABS) *Motor Vehicle Census* (MVC) 1991 (ABS 1992). The age distribution of the fleet for each year from 1992 to 2015 is then derived by applying the estimated scrappage function (described below) to the 1991 distribution, for each vehicle type.

The scrappage function

In order to build the vintage specific part of TRUCKMOD, it was necessary to obtain information about the rates of scrappage of commercial vehicles. Using information from the ABS publications (ABS 1993b, and earlier issues), age specific scrappage rates were estimated for each vehicle type. (Appendix II provides more detail about the scrappage rates used in the model.)

To derive the age distribution of the fleet for each year to 2015, the scrappage function is applied in the following manner. The total number of vehicles scrapped each year is derived by applying the age specific scrappage function to the age distribution of the vehicle fleet. The number of new vehicles entering the fleet each year is then calculated as the difference between the forecast aggregate stock of vehicles in the fleet in each year (from the Vehicle Stock sub-model) and the size of the vehicle stock in the previous year, less the number of vehicles scrapped the previous year.

The process is repeated for each year from 1991 to 2015, giving an age distribution of the vehicle fleet for each year from 1991 to 2015, for each vehicle type.

The key assumptions underlying the scrappage function are:

- the scrappage function is assumed to be a logistic function. (Note that this means the number of vehicles remaining in the fleet, by vintage, follows a logistic function. The conditional scrappage rate—the rate at which vehicles remaining in the fleet are scrapped—is also an S-shaped function. See appendix II for more detail.); and
- scrappage rate functions are assumed to remain constant across different vintages. This may not be a realistic assumption, but is adopted because of the difficulty in determining whether scrappage rates vary between different vehicle vintages. There was insufficient data to provide estimates of any change in scrappage rates across different vintages.

VINTAGE EFFICIENCY SUB-MODEL

The vintage efficiency sub-model calculates total fuel consumption by vehicle vintage and vehicle type for each year from 1991 to 2015.

Calculating total fuel consumption is again a two step process. The first step takes fleet average VKT and allocates this across all vehicle vintages to derive a profile of average VKT by vehicle age. The second step then uses the average VKT age profile, the average fuel efficiency age profile and the vehicle stock age profile to calculate total fuel consumption of each vehicle vintage.

For years beyond 1993, average fuel efficiency for each vintage is based on assumptions about average fuel efficiency of new vehicles and the rate of deterioration in vehicle fuel efficiency.

As a vehicle ages, it is assumed that its fuel efficiency will deteriorate. Deterioration will tend to reduce the average fuel efficiency of the vintage. At the same time, as the vehicle fleet ages, vehicles will drop out of the fleet through natural attrition. It is assumed that the less fuel efficient vehicles will drop out of the fleet first, improving the average fuel efficiency of that vehicle vintage. Deterioration in fuel efficiency and natural attrition will therefore have offsetting effects on average fuel efficiency for a particular vintage.

It is assumed that for each vintage of commercial vehicle, the deterioration effect outweighs the attrition effect over the first 10 years, so that average fuel consumption deteriorates at approximately 1 per cent per annum up to ten years. After 10 years of age, the natural attrition effect outweighs the deterioration effect, so that the average fuel efficiency of a 20 year old vehicle is about 10 per cent worse than that of a new vehicle. (The projected base case fuel efficiency for all commercial vehicles is given in appendix table III.4. The assumed deterioration in vintage average fuel efficiency is given in appendix table III.5.)

Under the base case the fuel intensity of new vehicles (litres/100km) is assumed to decrease over the forecast period by 10 per cent for petrol vehicles and 15 per cent for diesel vehicles. These assumptions result in a 20 per cent reduction in fleet average fuel intensity for articulated trucks between 1992–93 and 2014–15.

The average fuel intensity of LCVs is assumed to remain unchanged. The implicit assumption is that advances in new engine fuel efficiency will be offset by increases in vehicle size, so that new LCVs will maintain the same average fuel intensity as at present.

Average VKT enters the model as the average VKT travelled each year by all vehicles. To derive total fuel consumption, the fleet average VKT is split into average VKT by vehicle age. This is achieved by applying the 1991 VKT age distribution to each subsequent year in the model. (See appendix table III.6 for the assumed VKT age distribution.)

Total fuel consumption for each vehicle age group is calculated for each year by multiplying the number of vehicles, the average fuel efficiency, and the average VKT for each vehicle age group. Total fuel consumption for each year is then obtained by aggregating over age groups.

Assumptions for base-case projections of vintage efficiencies

The main assumptions made in the base case are:

- new vehicle average fuel efficiency improves by 30 per cent between 1995 and 2015 (a 1.32 per cent increase per year);
- vintage specific average vehicle fuel efficiency deteriorates according to the deterioration schedule in appendix table III.5; and
- the distribution of VKT by vehicle age is based on two parts, the average VKT travelled by the fleet, which was assumed to be constant in the base case, and the distribution of average VKT by vehicle age.

The age distribution of average VKT is derived by applying an intensity of use function distribution to the fleet average VKT. It is assumed that newer vehicles are used more intensively (travel more VKTs) than older vehicles. For LCVs, for example, the intensity of use function is piecewise linear and assumes that brand new vehicles are driven, on average, 1.4 times further than the fleet average down to 21–30 year old vehicles which are used, on average, only 0.35 times as intensively than the fleet average.

FUEL AND ENERGY CONSUMPTION SUB-MODEL

Total energy consumption is derived from total fuel consumption by using the energy content per unit of fuel for each different fuel type.

To estimate total energy consumption the model splits total fuel consumption by fuel type (automotive gasoline, diesel, Liquid Petroleum Gas (LPG) and Liquid Natural Gas (LNG)) based on assumptions about the proportion of total fuel consumption attributable to each fuel type. The present fuel type split is assumed to remain approximately constant until 2015. Total energy consumption is then estimated by applying the unit energy content of each fuel type to total fuel consumption of each fuel type, for each year 1991 to 2015. Detail on the fuel type split and the energy content of different fuel types is given in appendix tables III.7 and III.10.

Using this approach the fuel type split is assigned in an ad hoc manner. It would be desirable to split fuel use by fuel type before calculating total fuel consumption, within the vintage efficiency sub-model. However, the increased complexity of the model, and, more importantly, the fact that the required data are not available, are the main reasons for assigning fuel usage by fuel type after deriving total fuel consumption.

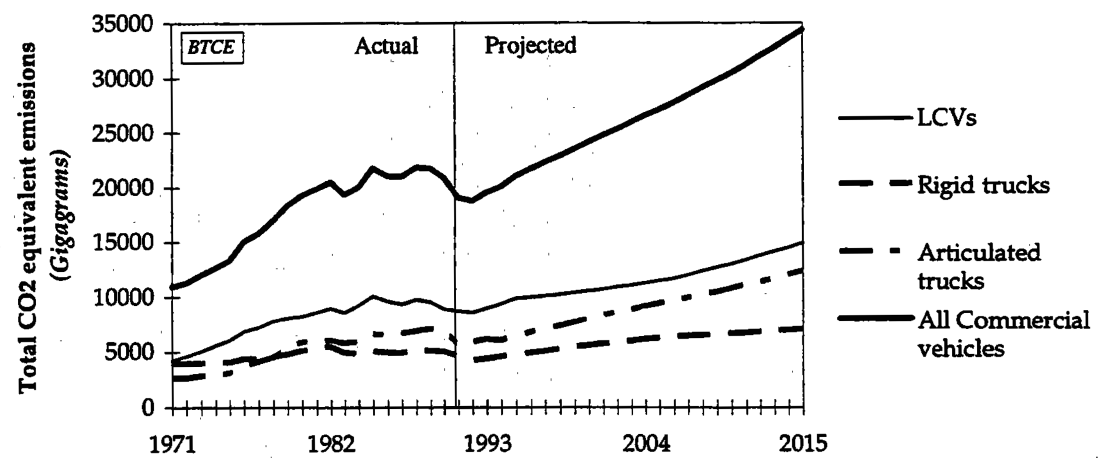
TOTAL EMISSIONS SUB-MODEL

The carbon content of each fuel type is fixed. Therefore, the yield of CO_2 emissions upon combustion of a given volume of fuel is given by a fixed emissions factor for each fuel type. Multiplying total fuel consumption by the relevant emissions factor gives the total quantity of CO_2 emissions for each fuel type. It is assumed that there is full combustion of all fuel.

The model also includes average emission factors for nitrogen oxides (NO_x), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), and non-methane volatile organic compounds (NMVOCs) emissions (appendix table III.8). Emission rates will vary with the efficiency of the engine and conditions during combustion. Over the past decade, advances in engine technology have led to large reductions in emissions and increased fuel efficiency. Driven largely by increasingly stringent regulations, rates of vehicle emissions are expected to be further reduced. In the model it is assumed that emissions of non-CO_2 gaseous emissions fall at the same rate as emission of CO_2. The model can handle differing emission rates for different gases.

The model also includes the Global Warming Potential (GWP) of the different gases to provide a numeraire in terms of their contribution to global warming. The GWP is used to convert emission levels of each gas into CO_2 equivalent emissions. Summing over all gases gives total CO_2 equivalent emissions from the road freight task. The GWPs used in the model are given in appendix table III.9.

FIGURE 2.8 BASE CASE EMISSIONS PROJECTIONS BY VEHICLE TYPE, 1971 TO 2015



Source BTCE estimates.

LIMITATIONS OF TRUCKMOD

TRUCKMOD is the BTCE's first approximation to a dynamic model of the Australian truck fleet and road freight task. For the purpose of analysing possible policy options, the major limitations of TRUCKMOD in its present form are:

- There are no endogenous feedback effects built into the model apart from the scrappage function in the vehicle stock sub-model, which itself has a 'closed' feedback effect. The lack of endogenous feedback effects is a significant weakness of the model given that for many policy options feedback effects may significantly reinforce or negate the initial effects.

- The aggregate total emissions produced by this 'distributional' model do not exactly match the estimated aggregate total emissions produced by an aggregate model, although the size of the discrepancy is accounted for within the model (see appendix IV for a discussion of model calibration).
- The split of average VKT and average fuel efficiency by vehicle age are based on 1991 estimates. At present the split is assumed constant to 2015.
- The split by fuel type is also an area for which there is little information; the split by fuel type has been placed at the end of the model, and is assumed constant to 2015.
- The scrappage function is assumed to be the same for different vehicle vintages. There is no in-built adjustment in the scrappage function to allow for more recent vintages being more durable (in contrast to the BTCE 'CARMOD' (BTCE forthcoming), where changes in vehicle durability by vintage are allowed for in the scrappage rates).

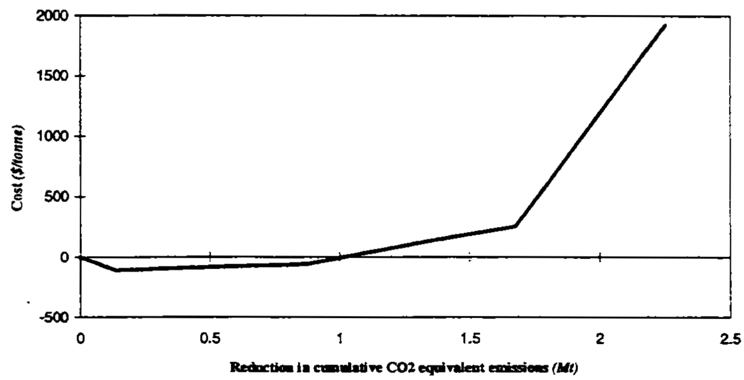
...AT A GLANCE

Advances in engine technology can reduce greenhouse gas emissions without the cost of forgoing current road freight activity. This chapter examines the cost-effectiveness of accelerated introduction of currently proven road freight vehicle technology.

Key features

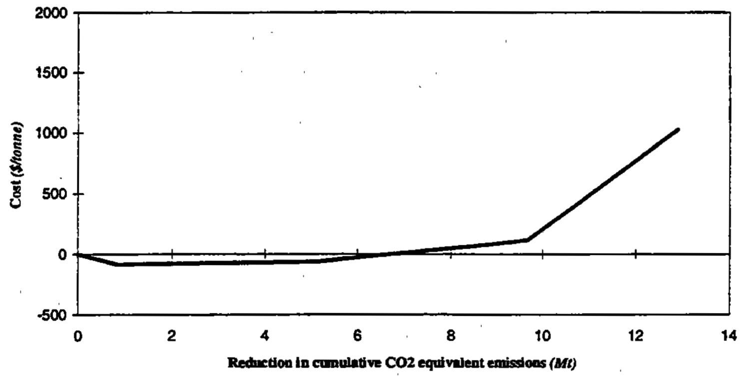
- The instrument assessed here focuses on the effect of new technology on the average fuel efficiency of new vehicles.
- Most of the technological developments considered consist of incremental improvements to existing technology that are considered to be commercially feasible within the next twenty years.
- Changes in emissions resulting from accelerated uptake of more efficient vehicle technology is estimated using TRUCKMOD, a model of the Australian truck fleet and road freight task that has been developed by the BTCE.
- The accelerated introduction of currently proven technology enhancements that increase the fuel efficiency of road freight vehicles would achieve large reductions in greenhouse gas emissions.
- BTCE cost estimates suggest that such a policy involves lower costs over the long term compared with the short term.
- The main equity effects of accelerated uptake of technology enhancements are an increased vehicle cost to vehicle purchasers, offset to some extent by a reduction in fuel costs per kilometre.

Figure 3.1 Marginal cost of accelerated commercial vehicle technology enhancements, 2000



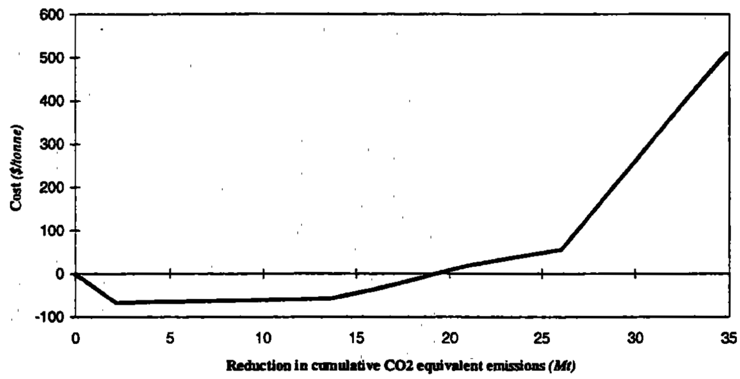
Source BTCE estimates.

Figure 3.2 Marginal cost of accelerated commercial vehicle technology enhancements, 2005



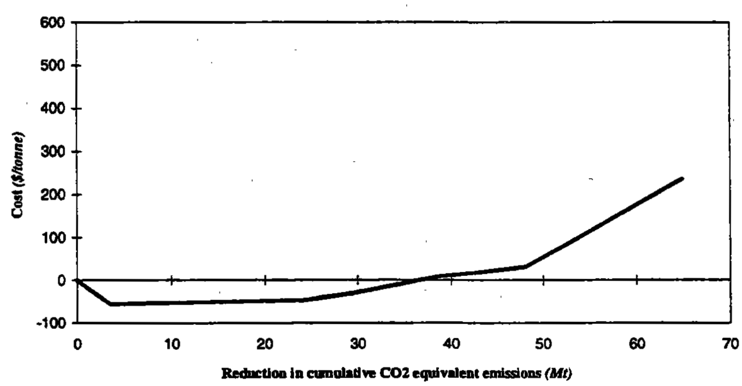
Source BTCE estimates.

Figure 3.3 Marginal cost of accelerated commercial vehicle technology enhancements, 2010



Source BTCE estimates.

Figure 3.4 Marginal cost of accelerated commercial vehicle technology enhancements, 2015



Source BTCE estimates.

CHAPTER 3 ACCELERATED UPTAKE OF ROAD FREIGHT VEHICLE TECHNOLOGY ENHANCEMENTS

BACKGROUND

Internal combustion engines convert energy released from combustion of fossil fuels into motive power. But not all the energy released upon combustion is converted into movement of the vehicle. Some of the energy is used to overcome resistance forces acting on various parts of the vehicle and some of the energy is lost as heat.

Apart from moving the vehicle the main areas where energy from combustion is used up include:

- Braking—the energy of forward momentum is converted to heat in the brakes. This heat energy is in turn lost to the atmosphere.
- Aerodynamic drag—a resistance force acting on a moving vehicle's surface area. It is a function of wind intensity and direction and a vehicle's frontal area and body shape. The power required to overcome aerodynamic drag is a cubic function of a vehicle's speed through the air. Aerodynamic drag is thus minimal at low speeds but a large proportion of the total resistance forces acting on the vehicle at high speeds (Randall 1991, p. 42 and NELA 1991b, p. 25).
- Transmission losses—the transmission system transfers the energy generated by the engine to the road wheels. The transmission system may include clutch, gearbox, drive shaft and final drive, depending on the design. The transmission system, amongst other things, must allow for disconnection of the engine from the driving wheels, connection with the driving wheels to be made smoothly, enable the leverage between the engine and driving wheels to be varied.
- Engine friction and heat loss—frictional forces between moving parts in the engine result in some of the energy from combustion being lost as heat. The thermodynamic efficiency of the engine itself is also a consideration as a large proportion of the energy from combustion goes towards heating the engine surrounds.
- Rolling resistance—the total of all forces that tend to slow down a moving vehicle, and includes friction within the axles and transmission, wheel bearing friction and friction between the road and the tyres.

- Accessories—the alternator, water pump, oil pump and air conditioner are all powered by energy derived from the engine.

One way to improve the fuel efficiency of vehicles, and reduce the rate of greenhouse gas emissions is to reduce the energy losses arising from the above mentioned areas. The vehicle technology enhancements considered in this chapter reduce energy losses in all of the above mentioned areas, except braking.

METHODOLOGY

The technological developments analysed in this study are largely incremental improvements to existing vehicle technology that are considered commercially feasible within the next twenty years. More radical technological options that were not considered feasible for large scale manufacture by 2015, such as electric vehicles and hydrogen powered vehicles, were not analysed.

The BTCE does not claim any expertise in the area of automotive engineering. Consequently, the individual technology options considered here include only those identified in the motor vehicle engineering literature and road freight trade publications. Where possible, optimistic estimates of the impact of each technology on fuel efficiency have been used to demonstrate the maximum potential reduction in emissions.

Petrol powered LCVs

For petrol powered LCVs, the technology enhancements evaluated in this study are based largely on the enhancements described in NELA (1991a, 1991b) and include:

- Aerodynamic enhancements to vehicle design reducing aerodynamic drag.
- Weight reduction—using lighter weight materials for body parts. The scope for weight reduction in LCVs is limited by their load-carrying requirements.
- Low friction pistons and rings—low mass squeezed cast aluminium pistons, lightweight valves and titanium springs, and improved control of bore and piston dimensions. These improvements reduce mechanical and aerodynamic engine friction.
- Roller cam followers—use of a roller bearing for the camshaft control surface instead of a sliding contact, reducing mechanical engine friction.
- Four-valves per cylinder—replacing two-valve per cylinder overhead camshaft engines of equal performance. Four-valves per cylinder engines offer improved thermodynamic efficiency due to a more compact combustion chamber and centrally placed spark plug. Central spark plug location and improved combustion chamber airflow characteristics allow

the use of higher compression ratios. Pumping losses are reduced because of smaller displacement and larger valve area.

- Variable valve timing—varies intake valve timing and lift to match engine speed and load requirement thereby reducing pumping losses.
- Multi-point fuel injection—use of one fuel injector per cylinder. Allows more precise fuel metering to each cylinder.
- Four/five speed automatic—allows the engine to operate at closer to the most fuel efficient point under all operating conditions.
- Continuously variable transmission (CVT)—extension of the concept of more gears to an infinite selection of gears. Current designs are torque-limited and can be employed only in small cars. Application to LCVs, therefore, is limited by the load under which LCVs must operate.
- Electronic transmission control—integrates engine operating information with vehicle speed information to select the optimum gear for best fuel economy.
- 10W-30 oil.
- Improved tyres—largely evolutionary improvements in tyres, reducing tyre rolling resistance.
- Accessory improvements—evolutionary improvements to alternator, water pump, oil pump, and air conditioning units reducing the demand on engine energy output.

Diesel powered LCVs, rigid trucks and articulated trucks

For diesel powered vehicles, the technology enhancements evaluated in this study are:

- Aerodynamic enhancements to vehicle design reducing aerodynamic drag.
- Electronic fuel injection control—varies fuel injection to match engine speed and load conditions.
- High pressure fuel injection—increases the contact of fuel with the heated air in the combustion chamber, increasing the efficiency of fuel burn.
- Supercharging or turbocharging—a supercharger is an engine driven compressor that forces the air-fuel mixture into the cylinders at higher than atmospheric pressure. This enables a greater amount of the air-fuel mixture to enter the combustion chamber and increases the efficiency of the engine. A turbocharger is an exhaust gas turbine driven compressor that performs the same function as the supercharger.
- Intercooled engines—intercooling increases the volumetric efficiency of the engine by increasing the density of the air before it is delivered to the combustion chamber.
- Turbo-compounding—an exhaust gas driven turbine connected to the crankshaft and used to propel the vehicle.
- High temperature insulation for engines (and use of ceramic materials)—it has been shown that high surface temperatures of combustion chamber

walls cause a significant drop in volumetric efficiency. Substantial fuel efficiency gains can be realised if the engine walls are insulated to reduce heat absorption (Assanis & Heywood 1987).

- Low-heat-rejection engines (also referred to as 'adiabatic' engines)—offer even greater potential to improve the volumetric efficiency of engines and reduce fuel consumption.
- Improved tyres—reducing rolling resistance.

The size of the overall fuel efficiency improvement resulting from adoption of these technologies will be affected by both the rate of penetration of technology enhancements in the vehicle fleet, and the size of the fuel efficiency improvement resulting from individual technology enhancements.

Where possible, estimates of the size of fuel efficiency improvements are based on published results from overseas studies of advanced technology uptake. Where data was not available, the BTCE has relied on reasonable assumptions.

Current vehicle penetration rates are based on a survey of the trade literature (*Truck and Bus Transportation*, 1993, 1994, 1995a), which provides details of specifications of currently manufactured vehicles. Estimates of future penetration rates are largely based on the assumption that most of the technology advances considered in this study will be standard in new vehicles by 2015 at the latest.

The assumed penetration rates and the technology specific individual vehicle fuel efficiency improvements for each technology option are listed in tables 3.1 to 3.4.

Estimates of fuel efficiency improvement under the base case and under the 'accelerated technology implementation' scenario

TRUCKMOD relies on the average vintage specific new vehicle fuel intensity to calculate changes in emissions.

Fuel intensity improvements resulting from each of the individual technology options introduced were weighted by their expected future penetration rates and summed to give an average new vehicle fuel efficiency improvement. The fuel intensity improvements set out in tables 3.1 to 3.4 are therefore estimates of the base case average new vehicle fuel intensity improvement. The estimates are slightly lower than the base case presented in BTCE (1995).

A second set of results was generated using TRUCKMOD to estimate CO_2 equivalent emissions under the 'accelerated technology implementation' scenario. The assumptions made about accelerated introduction of more advanced technology are also listed in tables 3.1 to 3.4. Average new vehicle fuel intensities for each of LCVs, rigid trucks and articulated trucks were derived on the basis of these assumptions. The enhanced fuel intensities formed the basis for the BTCE's projections of total road freight transport emissions to 2015 assuming accelerated implementation of advanced technologies.

Base case fuel intensity assumptions

The base case fuel intensity assumptions used in this working paper differ slightly from the base case fuel intensity assumptions in BTCE (1995, pp. 38–39). In general, fuel intensity is assumed to decline slightly more in this paper as a result of the assumed technology penetration rates in tables 3.1 to 3.4.

LCVs

For LCVs, the average vehicle load is assumed to increase by about 17 per cent over the period 1995 to 2015, as outlined in BTCE (1995, pp. 38–39). The additional fuel penalty of higher loads is offset against the fuel efficiency gains from the assumed technological advances outlined in tables 3.1 and 3.2. The net result is an improvement in new vehicle fuel efficiency of approximately 5.6 per cent between 1995 and 2005, 11.6 per cent between 2005 and 2010, and 1.5 per cent between 2010 and 2015. This is a fuel efficiency improvement of approximately 19.6 per cent over the period 1995 to 2015.

TABLE 3.1 TECHNOLOGY ENHANCEMENTS FOR PETROL POWERED LCVS

(per cent)

Technology option	*Fuel efficiency improvement (per cent/ vehicle)*	*Technology penetration base rate* 1995	*Assumed technology penetration rate[a] — base case* 2005	2010	2015	*Assumed technology penetration rate[a] — accelerated technology scenario* 2005	2010	2015
Aerodynamic improvement—drag reduction	2.3	20.0	50.0	100.0	100.0	80.0	100.0	100.0
4-speed automatic[b]	4.5	54.5	60.0	100.0	100.0	100.0	100.0	100.0
Torque converter lock-up	3.0	58.5	62.5	100.0	100.0	100.0	100.0	100.0
Electronic transmission control	0.5	12.0	46.0	100.0	100.0	100.0	100.0	100.0
Accessory improvements	0.5	..	68.0	100.0	100.0	100.0	100.0	100.0
Roller cam followers	2.0	19.0	46.0	100.0	100.0	100.0	100.0	100.0
Low friction piston/rings	2.0	48.5	83.0	100.0	100.0	100.0	100.0	100.0
10W-30 Oil	0.5	0.0	66.0	100.0	100.0	100.0	100.0	100.0
Tyre improvements	0.5	..	68.0	100.0	100.0	100.0	100.0	100.0
4-valve engines[d]	5.0	33.3	53.8	100.0	100.0	100.0	100.0	100.0
Multi-point fuel injection (additional gain over CFI)[c]	3.0	66.3	79.8	100.0	100.0	100.0	100.0	100.0
Central fuel injection[c]	3.0	10.9	16.9	100.0	100.0	100.0	100.0	100.0
Front wheel drive	1.5	80.0	100.0	100.0	100.0	100.0	100.0	100.0
5-speed automatic (additional gain over 4-speed auto.)[b]	2.5	0.0	20.0	20.0	20.0	100.0	100.0	100.0
Variable valve timing[d]	3.0	0.0	30.0	80.0	100.0	100.0	100.0	100.0
Electric power steering	1.0	0.0	20.0	80.0	80.0	100.0	100.0	100.0
CVT (additional gain over 5 speed auto)[b]	1.0	0.0	0.0	0.0	0.0	100.0	100.0	100.0
Weight reduction (increase)	-5.0	..	33.0	33.0	33.0	40.0	50.0	50.0
Performance increase	-2.2	..	54.0	54.0	54.0	0.0	0.0	0.0

.. not applicable.

a. Unless otherwise stated all penetration rate estimates are based on BTCE assumptions.

b. Mutually exclusive transmission systems. Based on NELA (1991, p. 41) assumption for passenger cars.

c. The effects of the central fuel injection and multi-point fuel injection are additive in this spreadsheet and are based on NELA (1991, p. 41) assumption, but adjusted because of assumed difference between LCVs and passenger cars.

d. Mutually enhancing technology options.

Source NELA (1991) table 4.4 (p. 41).

TABLE 3.2 TECHNOLOGY ENHANCEMENTS FOR DIESEL POWERED LCVS

			(per cent)					
	Fuel efficiency improvement	*Technology penetration base rate*	*Assumed technology penetration rate[a] — base case*			*Assumed technology penetration rate[a] — accelerated technology implementation*		
Technology option	*(per cent/ vehicle)*	1995	2005	2010	2015	2005	2010	2015
Supercharging/turbocharging[b]	7.0	35.0	50.0	75.0	75.0	100.0	100.0	100.0
High pressure fuel injection[b]	10.0	0.0	20.0	20.0	20.0	100.0	100.0	100.0
Electronic fuel injection control[b]	10.0	50.0	75.0	100.0	100.0	100.0	100.0	100.0
Aerodynamic enhancements	4.0	35.0	65.0	65.0	65.0	65.0	100.0	100.0
Low-heat-rejection (adiabatic) engines	6.0	0.0	0.0	20.0	50.0	50.0	100.0	100.0
Turbo-compounding	4.0	0.0	20.0	20.0	20.0	75.0	100.0	100.0
Intercooled engines	4.0	50.0	52.5	52.5	52.5	100.0	100.0	100.0
High temperature insulation (eg. use of ceramics)	2.0	0.0	5.0	5.0	5.0	50.0	100.0	100.0
Tyres	2.0	0.0	50.0	75.0	100.0	100.0	100.0	100.0
Weight reduction (increase)	-5.0	..	33.0	33.0	33.0	40.0	50.0	50.0

.. not applicable.

a. Unless otherwise stated all penetration rate estimates are based on BTCE assumptions.

b. Brosthaus1991.

Source BTCE estimates.

TABLE 3.3 TECHNOLOGY ENHANCEMENTS FOR DIESEL POWERED RIGID TRUCKS

(per cent)

Technology option	*Fuel efficiency improvement (per cent/ vehicle)*	*Technology penetration base rate*	*Assumed technology penetration rate[a] —base case*			*Assumed technology penetration rate[a]— accelerated technology implementation*		
		1995	2005	2010	2015	2005	2010	2015
Supercharging/turbocharging[b]	6.0	30.0	80.0	80.0	80.0	100.0	100.0	100.0
High pressure fuel injection[b]	10.0	0.0	20.0	50.0	50.0	100.0	100.0	100.0
Electronic fuel injection control[b]	10.0	50.0	75.0	100.0	100.0	100.0	100.0	100.0
Aerodynamic enhancements	4.0	35.0	65.0	65.0	65.0	100.0	100.0	100.0
Low-heat-rejection (adiabatic) engines	10.0	0.0	0.0	0.0	20.0	50.0	100.0	100.0
Turbo-compounding	5.0	0.0	20.0	20.0	20.0	100.0	100.0	100.0
Intercooled engines	5.0	50.0	52.5	52.5	52.5	100.0	100.0	100.0
High temperature insulation (eg. use of ceramics)	2.0	0.0	5.0	5.0	5.0	50.0	100.0	100.0
Tyres	4.0	0.0	50.0	75.0	100.0	100.0	100.0	100.0

a. Unless otherwise stated all penetration rate estimates are based on BTCE assumptions.

b. Brosthaus 1991.

Source BTCE estimates.

TABLE 3.4 TECHNOLOGY ENHANCEMENTS FOR DIESEL POWERED ARTICULATED TRUCKS

(per cent)

Technology option	*Fuel efficiency improvement (per cent/ vehicle)*	*Technology penetration base rate*	*Assumed technology penetration rate[a] — base case*			*Assumed technology penetration rate[a] — accelerated technology implementation*		
		1995	2005	2010	2015	2005	2010	2015
Supercharging/Turbocharging	10.0[b]	85.0	95.0	95.0	95.0	100.0	100.0	100.0
High pressure fuel injection	10.0[b]	0.0	20.0	20.0	20.0	100.0	100.0	100.0
Electronic fuel injection control	10.0[b]	50.0	75.0	100.0	100.0	100.0	100.0	100.0
Aerodynamic enhancements	7.0	55.0	75.0	75.0	75.0	100.0	100.0	100.0
Low-heat-rejection (adiabatic) engines	10.0	0.0	0.0	0.0	20.0	50.0	100.0	100.0
Turbo-compounding	5.0	0.0	20.0	20.0	20.0	100.0	100.0	100.0
Intercooled engines	5.0	50.0	52.5	52.5	52.5	100.0	100.0	100.0
High temperature insulation (eg. use of ceramics)	2.0	0.0	5.0	5.0	5.0	50.0	100.0	100.0
Tyres	4.0	0.0	50.0	75.0	100.0	100.0	100.0	100.0

a. Unless otherwise stated all penetration rate estimates are based on BTCE assumptions.

b. Brosthaus 1991.

Source BTCE estimates.

Rigid trucks

As in BTCE (1995, pp. 38–39) the average load carried by rigid trucks is assumed to increase by 1 per cent per annum to 2015. The assumed increase in vehicle loads is offset against the assumed technological advances outlined in table 3.3. This results in an improvement in new vehicle fuel efficiency of approximately 8.3 per cent between 1995 and 2005, 5.5 per cent between 2005 and 2010, and no further improvement in vehicle fuel efficiency between 2010 and 2015. This represents an overall fuel efficiency improvement of 14.3 per cent over the period 1995 to 2015.

Articulated trucks

The average load carried by articulated trucks is assumed to grow by 0.7 per cent per annum, similar to growth during the 1980s (BTCE 1995, pp. 37-39). Based on the assumptions outlined in table 3.4, the improvement in new vehicle fuel efficiency for articulated trucks is approximately 10.3 per cent between 1995 and 2005, 6.5 per cent between 2005 and 2010, and 3.0 per cent between 2010 and 2015. This represents an overall fuel efficiency improvement of approximately 21.0 per cent improvement over the period 1995 to 2015; broadly consistent with assumptions made in BTCE (1995, p. 216).

'Accelerated technology implementation' fuel efficiency assumptions

LCVs

Based on the fuel efficiency improvements and penetration rates outlined in tables 3.1 to 3.4, the average fuel efficiency gain for new vehicles from accelerated uptake of technology enhancements is approximately 27.7 per cent between 1995 and 2005, and 2.8 per cent between 2005 and 2010, for LCVs. There are no further fuel efficiency gains to be exploited between 2010 and 2015, as the accelerated technology implementation practically exhausts all of the currently proven technologies by about 2005. The assumptions result in new vehicle average fuel efficiency improving by 31.3 per cent over the period 1995 to 2015.

Rigid trucks

Based on the fuel efficiency improvements and penetration rates outlined in tables 3.1 to 3.4, the average fuel efficiency gain for new vehicles from accelerated uptake of technology enhancements is approximately 37 per cent between 1995 and 2005, and 6 per cent between 2005 and 2010 for rigid trucks. All fuel efficiency gains from currently applicable technology enhancements have been exploited by 2010. The assumptions result in new vehicle average fuel efficiency improving by 45.2 per cent over the period 1995 to 2015.

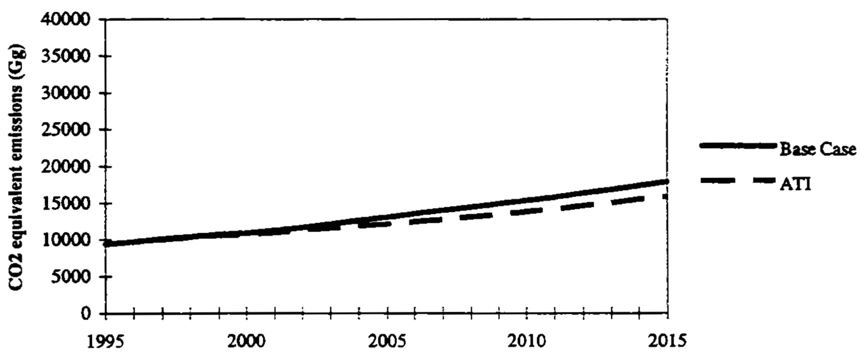
Articulated trucks

Based on the fuel efficiency improvements and penetration rates outlined in tables 3.1 to 3.4, the average fuel efficiency gain for new vehicles from accelerated uptake of technology enhancements is approximately 43 per cent between 1995 and 2005, and 6 per cent between 2005 and 2010 for articulated trucks. All fuel efficiency gains from potentially applicable technology enhancements are assumed to have been exploited by 2010. The assumptions result in new vehicle average fuel efficiency improving by 51.6 per cent over the period 1995 to 2015.

RESULTS

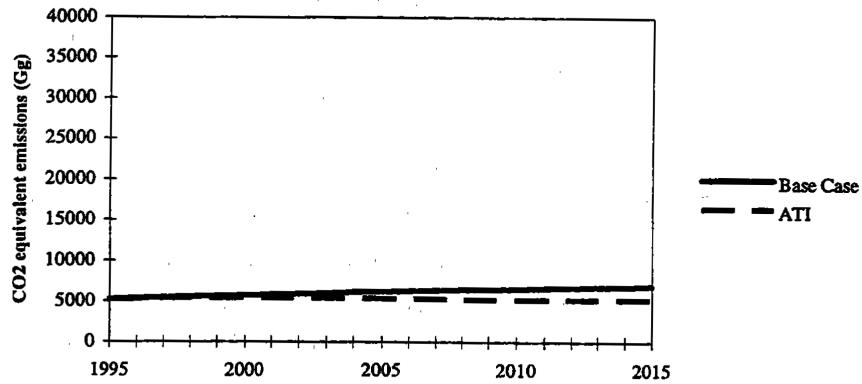
Tables 3.5 and 3.6 show total CO_2 equivalent emission levels for each year 1995 to 2015 under the base case and the accelerated technology implementation scenarios.

FIGURE 3.5 PROJECTED CO_2 EQUIVALENT EMISSIONS—LCVS



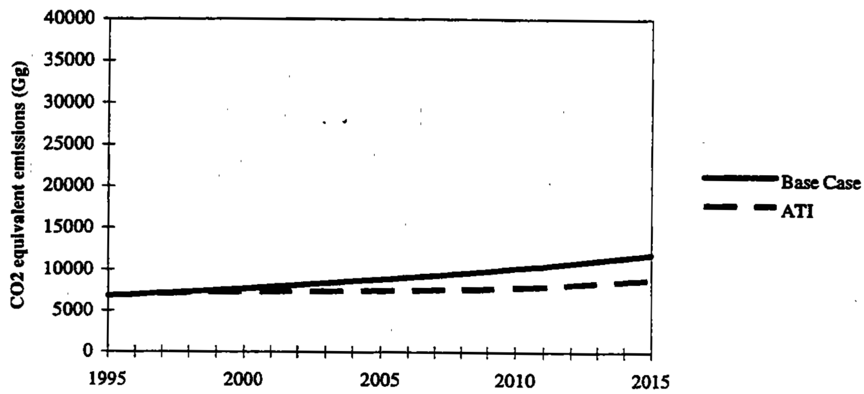
Source BTCE estimates.

FIGURE 3.6 PROJECTED CO_2 EQUIVALENT EMISSIONS—RIGID TRUCKS



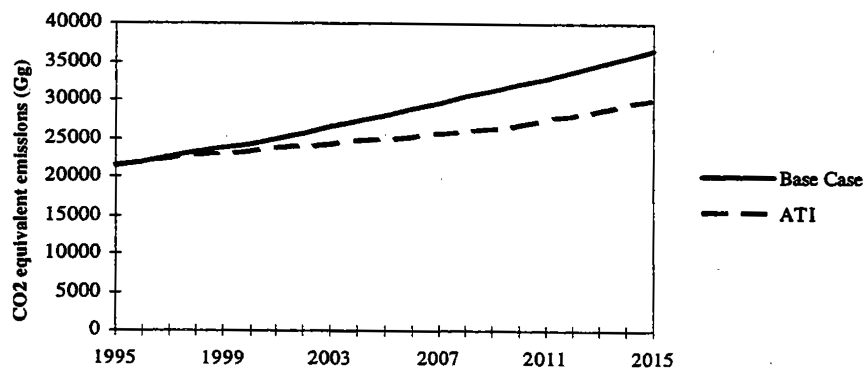
Source BTCE estimates.

FIGURE 3.7 PROJECTED CO_2 EQUIVALENT EMISSIONS—ARTICULATED TRUCKS



Source BTCE estimates.

FIGURE 3.8 PROJECTED CO_2 EQUIVALENT EMISSIONS—ALL COMMERCIAL VEHICLES



Source BTCE estimates.

TABLE 3.5 PROJECTED CO_2 EQUIVALENT EMISSIONS UNDER THE BASE CASE SCENARIO, 1995 TO 2015

(Gg)

Year	*LCVs*	*Rigid trucks*	*Articulated trucks*	*All commercial vehicles*
1995	9346	5200	6761	21308
1996	9702	5305	6936	21944
1997	10052	5408	7122	22581
1998	10380	5508	7294	23182
1999	10656	5606	7490	23752
2000	10808	5703	7693	24204
2001	11221	5798	7900	24919
2002	11646	5893	8113	25652
2003	12084	5986	8327	26398
2004	12536	6079	8555	27169
2005	13001	6170	8784	27954
2006	13465	6256	9033	28753
2007	13931	6338	9288	29557
2008	14399	6416	9560	30374
2009	14866	6488	9838	31193
2010	15333	6555	10148	32036
2011	15823	6623	10453	32899
2012	16337	6692	10772	33801
2013	16850	6762	11111	34723
2014	17379	6828	11475	35682
2015	17926	6893	11805	36625

Source BTCE estimates.

TABLE 3.6 PROJECTED CO_2 EQUIVALENT EMISSIONS UNDER THE ACCELERATED TECHNOLOGY IMPLEMENTATION SCENARIO, 1995 TO 2015

(Gg)

Year	*LCVs*	*Rigid trucks*	*Articulated trucks*	*All commercial vehicles*
1995	9346	5200	6761	21308
1996	9688	5284	6900	21872
1997	10010	5346	7017	22373
1998	10294	5390	7098	22781
1999	10511	5417	7176	23104
2000	10593	5429	7241	23264
2001	10913	5429	7294	23636
2002	11226	5418	7337	23980
2003	11533	5396	7367	24296
2004	11833	5365	7395	24592
2005	12123	5323	7412	24858
2006	12423	5284	7456	25164
2007	12745	5251	7518	25514
2008	13086	5221	7604	25911
2009	13441	5195	7705	26342
2010	13814	5174	7839	26827
2011	14213	5161	7985	27358
2012	14638	5156	8155	27950
2013	15054	5161	8352	28566
2014	15487	5168	8578	29233
2015	15933	5182	8792	29906

Source BTCE estimates.

TABLE 3.7 PERCENTAGE REDUCTION IN CO_2 EQUIVALENT EMISSIONS FROM ACCELERATED TECHNOLOGY IMPLEMENTATION SCENARIO RELATIVE TO THE BASE CASE, 1995 TO 2015

(per cent)

Year	*LCVs*	*Rigid trucks*	*Articulated trucks*	*All commercial vehicles*
1995	0.00	0.00	0.00	0.00
1996	0.14	0.40	0.53	0.33
1997	0.42	1.13	1.47	0.92
1998	0.83	2.14	2.69	1.73
1999	1.36	3.38	4.20	2.73
2000	1.99	4.80	5.87	3.88
2001	2.74	6.37	7.67	5.15
2002	3.61	8.07	9.57	6.52
2003	4.56	9.86	11.53	7.96
2004	5.61	11.75	13.56	9.49
2005	6.75	13.72	15.62	11.08
2006	7.74	15.53	17.45	12.48
2007	8.52	17.16	19.05	13.68
2008	9.12	18.62	20.46	14.69
2009	9.59	19.92	21.68	15.55
2010	9.91	21.07	22.75	16.26
2011	10.18	22.07	23.61	16.84
2012	10.40	22.95	24.30	17.31
2013	10.66	23.68	24.83	17.73
2014	10.89	24.31	25.24	18.07
2015	11.12	24.83	25.53	18.34

Source BTCE estimates.

Figures 3.1 to 3.4 show the level of CO_2 equivalent emissions under the base case and accelerated technology implementation scenarios for each type of commercial vehicle. It is clear that CO_2 equivalent emissions from the road freight sector continue to increase, even under what the BTCE considers is a most optimistic accelerated technology implementation scenario. Table 3.7 shows that under the accelerated technology implementation scenario, CO_2 equivalent emissions would be reduced by approximately 18 per cent compared to the base case by 2015.

Most of the savings in emissions come from the shift of freight that is currently handled by rigid trucks, to articulated trucks. It is primarily the assumed increase in the urban freight task of LCVs that causes total emissions of LCVs to increase, and this outweighs the reduction in emissions from increased fuel efficiency of new LCVs.

Costs of accelerated technology implementation

The costs of accelerated technology implementation are equal to the additional capital cost of the technology enhanced vehicles, less any fuel cost savings resulting from the increased efficiency of the new vehicles, plus the benefits forgone due to the reduction in the number of vehicles purchased, plus any change in tax receipts in related markets where distortions such as taxes or subsidies are present, and any additional external costs such as health and safety. Most of the costs are made up of the additional technology costs and the fuel cost savings. A useful discussion on the measurement of costs in markets where distortions occur is to be found in Just, Hueth and Schmitz (1982, pp. 177–199) and Sugden and Williams (1982, pp. 134–147).

Tables 3.8 and 3.9 give the assumed additional per vehicle cost of technology enhancements for commercial vehicles. For many of the enhancements for diesel powered vehicles, the cost is assumed to be the same for different vehicle types. This assumption was required because there are few estimates available about the cost of enhancements for different vehicle types.

The different technology options will operate for different lifetimes. Tyres, for example, have to be replaced just over once a year for passenger cars but more frequently for freight vehicles because of the higher kilometre usage. In estimating the additional costs of technology over the lifetime of the vehicle, each technology had to be weighted by how often it would have to be replaced within the life of the vehicle. The additional vehicle technology costs were calculated using the 'weighted lifetime' cost of each technology.

TABLE 3.8 ADDITIONAL PER VEHICLE COST OF TECHNOLOGY ENHANCEMENTS—DIESEL POWERED VEHICLES

(A$1996 / vehicle)

Technology option	*LCVs*	*Rigid trucks*	*Articulated trucks*
Supercharging/turbocharging	1100	1100	1100
High pressure fuel injection	2100	2100	2100
Electronic fuel injection control	600	600	600
Aerodynamic enhancements	2100	7100	10600
Low-heat-rejection (adiabatic) engines	11000	11000	11000
Turbo-compounding	8500	8500	8500
Intercooled engines	1600	1600	1600
High temperature insulation (eg. use of ceramics)	8000	8000	8000
Tyres	400	800	1500

Note The costs contained in the table are the 'on-road' costs of each type of technology. The costs were converted to A$ using the retail exchange rate. The A$ costs were scaled up by the tariff rate and sales tax rate to derive the cost to the consumer.

Source DeCicco et al. (1993).

Applying the cost estimates in tables 3.8 and 3.9 resulted in the cost of a new rigid truck increasing by about 45 per cent over current average prices, whereas the cost of new LCVs and articulated trucks increased by between 10 and 15 per cent. In the initial cost calculation, this caused a large discrepancy between the net costs of implementing new technology for different vehicle types. A large difference in the relative costs of different vehicles would be expected to result in a shift out of rigid trucks by transport operators. This in turn would mean the assumptions made about the number of new rigid trucks entering the fleet would be invalid. For the analysis it was decided to analyse the costs based on an increase in rigid truck prices of around 10 to 15 per cent over current market prices, equal in percentage terms to the increase in average vehicle prices for LCVs and articulated trucks. In contrast to the assumptions used here, it is possible that the cost of rigid truck technology will be large relative to the market price. This would significantly affect the number of new rigid trucks purchased in comparison to the present assumptions about future growth in rigid truck numbers. While the possibility that the costs for rigid trucks may be significantly higher, quantitative results were not estimated for such a scenario.

TABLE 3.9 ADDITIONAL PER VEHICLE COST OF TECHNOLOGY ENHANCEMENTS—GASOLINE POWERED VEHICLES

(A$1996 / vehicle)

Technology option	*LCVs*
Aerodynamic improvement—Drag reduction	169
4-speed automatic	40
Torque converter lock-up	74
Electronic transmission control	127
Accessory improvements	61
Roller cams	32
Low friction piston/rings	169
10W-30 Oil	0
Tyre improvements	42
4-valve engines	222
Multi-point fuel injection (additional gain over CFI)	141
Central fuel injection	50
Front wheel drive	317
5-speed automatic (additional gain over 4-speed auto.)	317
Variable valve timing	169
Electric power steering	200
CVT (additional gain over 5 speed auto)	211
Weight reduction (increase)	450

Note The costs contained in the table are the 'on-road' costs of each type of technology. The costs were converted to A$ using the retail exchange rate. The A$ costs were scaled up by the tariff rate and sales tax rate to derive the cost to the consumer.

Source DeCicco et al. (1993).

TABLE 3.10 TOTAL DISCOUNTED COST OF ACCELERATED TECHNOLOGY IMPLEMENTATION BY VEHICLE TYPE, 2000

($1996 million)

	LCVs	*Rigid trucks*	*Articulated trucks*	*All commercial vehicles*
Consumer	-24.62	74.45	-55.27	-5.44
Producer	na	na	na	na
Government	55.7	59.8	93.7	209.2
Externalities	0.02	-0.05	-0.13	-0.16
Total	31.1	134.2	38.4	203.7

na Not available.

Note Negative numbers represent a net benefit. A discount rate of 10 per cent was used to convert costs to $1996.

Source BTCE estimates.

TABLE 3.11 TOTAL DISCOUNTED COST OF ACCELERATED TECHNOLOGY IMPLEMENTATION BY VEHICLE TYPE, 2015

($1996 million)

	LCVs	*Rigid trucks*	*Articulated trucks*	*All commercial vehicles*
Consumer	-1506.65	-277.57	-1366.97	-3151.29
Producer	na	na	na	na
Government	869.2	659.0	1030.0	2558.1
Externalities	0.35	-0.33	-0.93	-0.91
Total	-637.2	381.1	-338.0	-594.1

na Not available.

Note Negative numbers represent a net benefit. A discount rate of 10 per cent was used to convert costs to $1996.

Source BTCE estimates.

TABLE 3.12 TOTAL ANNUAL NET SOCIAL COSTS OF ACCELERATED TECHNOLOGY IMPLEMENTATION, 1996 TO 2015

($1996 million)

Year	*LCVs*	*Rigid trucks*	*Articulated trucks*	*All commercial vehicles*
1996	5.5	14.5	7.9	27.9
1997	8.1	24.1	10.6	42.8
1998	8.2	29.6	9.3	47.2
1999	6.3	32.8	7.3	46.5
2000	3.0	33.1	3.3	39.3
2001	-1.6	33.2	-1.4	30.2
2002	-7.1	31.4	-6.1	18.2
2003	-13.2	29.5	-10.7	5.5
2004	-19.6	27.6	-14.6	-6.6
2005	-26.3	25.4	-18.7	-19.6
2006	-40.7	20.4	-23.8	-44.1
2007	-51.4	17.9	-27.5	-61.0
2008	-59.1	15.9	-29.4	-72.7
2009	-64.6	14.7	-30.7	-80.6
2010	-68.1	14.0	-29.7	-83.9
2011	-66.7	9.5	-34.1	-91.3
2012	-65.0	5.6	-36.4	-95.8
2013	-63.4	2.8	-37.4	-98.0
2014	-61.6	0.5	-37.6	-98.7
2015	-59.8	-1.4	-38.2	-99.4

Note Negative numbers represent a net benefit. A discount rate of 10 per cent was used to convert costs to $1996.

Source BTCE estimates.

Tables 3.10 and 3.11 show the cumulative costs, in constant $1996, of accelerated technology implementation scenarios in 2000 and 2015. Consumer costs represent the additional cost to vehicle buyers of technology enhanced vehicles less any fuel cost savings attributable to those vehicles. Government costs represent the reduction in fuel excise receipts as a result of the reduced sale of automotive fuels. The reduction in government fuel excise receipts is not a resource cost, but is a transfer payment.

The accelerated uptake of vehicle technology enhancements will have a beneficial impact on health and safety as a result of reduced fossil fuel consumption. The technology options considered will be likely to have different effects on different gas types. For diesel powered vehicles, some technology enhancements may have adverse effects on noxious emissions. This paper has focussed on greenhouse gas emissions, and principally CO_2, which is the most potent greenhouse gas in terms of long term global warming potential. Data limitations are the main reason that non-CO_2 emissions have been assumed to change at the same rate as CO_2 emissions. Therefore, the reduction in total fuel consumption is assumed to result in beneficial health effects.

As the number of new vehicles in the fleet is assumed to remain the same, the change in total congestion costs is negligible. The value of externality benefits presented in tables 3.10 and 3.11 are based on estimates of the approximate unit costs of environmental damage by airborne pollutants (BTCE forthcoming). The externality benefits are calculated using an average urban and non-urban driving cycle. Emissions of particulates are not presently included in TRUCKMOD and so are not included in the measure of the external benefits, though they are potentially of high cost in urban areas. The value of the externality benefits are less than 1 per cent of the total costs.

All costs reported in this working paper are counted in the year in which they are incurred. That means that fuel cost savings are counted in the year in which they occur, and are not attributed back to the year the vehicle was purchased.

Table 3.12 shows the total annual cost to society of the accelerated technology implementation scenario. Given the individual technology costs outlined in tables 3.8 and 3.9, the accelerated implementation of technology enhancements would generate a net welfare gain to society by the year 2004. That is, the analysis suggests that 'accelerated technology implementation' is a 'no regrets' policy. Such a result begs the question: if new technology is a 'no regrets' strategy, why is it not being exploited now?

The quantitative analysis suggests that accelerated technology implementation is a 'no regrets' policy because the analysis relies on source cost data (DeCicco et al., 1989) that appears to be the price in $1995 of new technologies to be introduced progressively between 1990 and 2030. As the cost data appears to report the real price of new technology to be produced at some future date, there are significant research and development costs and plant set-up costs that would be much larger on a real discounted basis if they had to be brought forward. That is, to accelerate the development of new technology vehicles would increase costs significantly above the estimated levels included in this paper. The BTCE could not find any information to estimate how the technology costs would increase if the introduction of new technology were brought forward. The BTCE undertook the analysis using the best available information and has included some sensitivity results that show the point at which new technology is not a 'no regrets' policy.

To calculate the marginal costs of an accelerated technology implementation scenario, each individual technology enhancement was introduced into the fleet in stages according to the per unit cost of the expected fuel efficiency improvement. The total cost and cumulative emissions benefit from each individual technology enhancement were used to calculate the 'marginal cost'.

Figures 3.1 to 3.4 show the marginal cost of accelerated technology implementation in 2000, 2005, 2010 and 2015. Comparison of the figures shows that the cumulative reduction in emissions is greater by 2015 than in 2000. Consequently, the marginal cost per unit reduction of CO_2 equivalent emissions is lower over the longer time period.

Sensitivity Analysis

The cost of technology enhancements and the rate of penetration are highly uncertain. Table 3.13 gives the cumulative total net cost of accelerated technology implementation under various technology cost scenarios, which show that under the base technology cost scenario the discounted fuel cost savings from new technology outweighs the additional vehicle costs over the period to 2015. However, if technology costs are 50 per cent above the base cost scenario the results show that accelerated technology uptake would be a net cost to society.

TABLE 3.13 SENSITIVITY ANALYSIS—TOTAL NET COSTS OF ACCELERATED TECHNOLOGY IMPLEMENTATION UNDER VARIOUS COST SCENARIOS

($1996 million)

Vehicle type	*2000*	*2015*
Base technology cost scenario		
LCVs	31.1	-637.2
Rigid trucks	134.2	381.1
Articulated trucks	38.4	-338.0
All Commercial vehicles	203.7	-594.1
50 per cent higher technology cost		
LCVs	85.2	-355.6
Rigid trucks	242.5	1026.1
Articulated trucks	122.3	204.2
All Commercial vehicles	450.0	875.2
100 per cent higher technology cost		
LCVs	139.2	-74.1
Rigid trucks	350.8	1672.1
Articulated trucks	206.2	746.4
All Commercial vehicles	696.3	2344.5

Source BTCE estimates.

TRUCKMOD was also used to estimate the size of the average new vehicle fuel efficiency improvement required to lower emissions to 1988 levels by the year 2000 and maintain emissions below 1988 levels for each year to 2015, under the BTCE's assumptions about the growth in the road freight task. The increase in average new vehicle fuel efficiency would have to be approximately 70 per cent for articulated trucks, 50 per cent for rigid trucks and 80 per cent for LCVs over the period 1995 to 2015 to maintain emissions at 1988 levels over the period 2000 to 2015.

The sensitivity of the cumulative discounted total costs of accelerated uptake of vehicle technology enhancements to the choice of discount rate is shown in table 3.14. The use of a lower discount rate increases the cumulative net benefits to 2015, as the fuel cost savings are greatest towards 2015 as a greater number of more fuel efficient vehicles have entered the fleet. Equally, the higher discount rate penalises future fuel cost savings more heavily and this reduces the net benefits of the accelerated technology scenario.

TABLE 3.14 SENSITIVITY ANALYSIS—CUMULATIVE DISCOUNTED TOTAL COSTS OF ACCELERATED TECHNOLOGY IMPLEMENTATION UNDER VARIOUS DISCOUNT RATE SCENARIOS

($1996 million)

	Cost period	
Discount rate (per cent)	*1996-2000*	*1996-2015*
5	225.3	-1421.5
10	203.7	-594.1
15	185.6	-215.6

Source BTCE estimates.

EQUITY ISSUES

Under the accelerated technology scenario, the principal cost of the scheme would fall upon purchasers of new vehicles, who had to outlay the additional capital cost of new vehicles. The additional capital costs would be offset to some extent by the reduction in fuel costs over the life of the vehicle.

Motor vehicle manufacturers would face increased research and development costs and production costs. These increased producer costs would be offset by increased revenue from higher vehicle prices. Overall, motor vehicle manufacturers would probably experience some fall in total profits. Most commercial vehicles are manufactured overseas.

Increased vehicle costs would be passed on by vehicle operators, through higher road freight cartage rates. As most goods sold for final consumption, require transport to the final point of sale, higher road freight cartage rates would result in small increases in the shelf price of most goods within the economy.

Government revenue from new vehicle sales would be expected to fall initially, due to reduced demand for new vehicles following a price increase. Government fuel excise revenue from road freight vehicles is also likely to shrink as a result of reduced demand for freight services.

In summary, if the capital cost of the new technology options outweighs the present value of future fuel savings, government revenue will shrink, general consumer goods prices will increase, the road freight transport sector will shrink, and new road freight vehicle sales will decline.

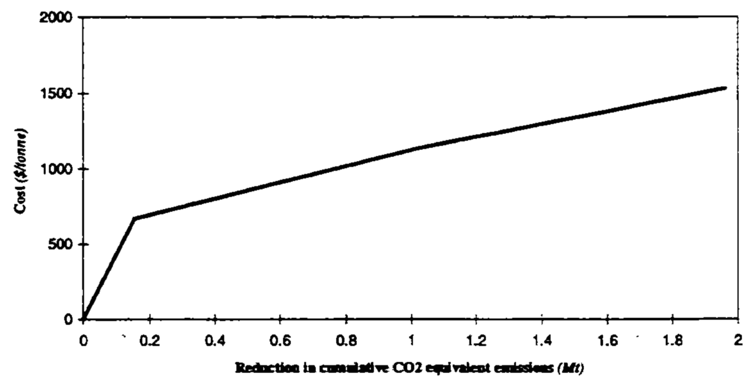
...AT A GLANCE

Greenhouse emissions can be ameliorated by increasing the fuel efficiency of road freight vehicles. An instrument that can be used to achieve this aim is the accelerated retirement (scrappage) from service of the least fuel efficient vehicles.

Key features

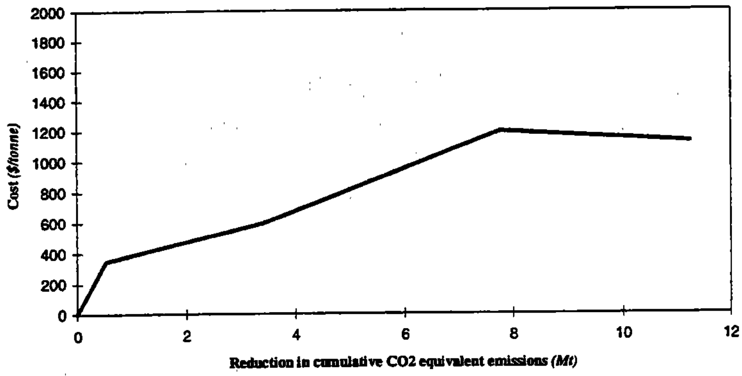
- The accelerated scrappage of older, less efficient, commercial vehicles would not achieve significant reductions in greenhouse gas emissions from commercial vehicles
- Developed specifically by the BTCE for its Greenhouse study, the TRUCKMOD model has been used to assess the effect on the average fuel efficiency of Australia's fleet of commercial vehicles through changes to the age distribution of the fleet.
- BTCE cost estimates suggest that an accelerated scrappage policy is a high cost method of reducing greenhouse gas emissions.
- As far as the BTCE is aware, no similar cost-effectiveness study has been carried out to date with respect to Australian freight vehicles.

FIGURE 4.1 MARGINAL COST OF ACCELERATED SCRAPPAGE POLICY, 2000



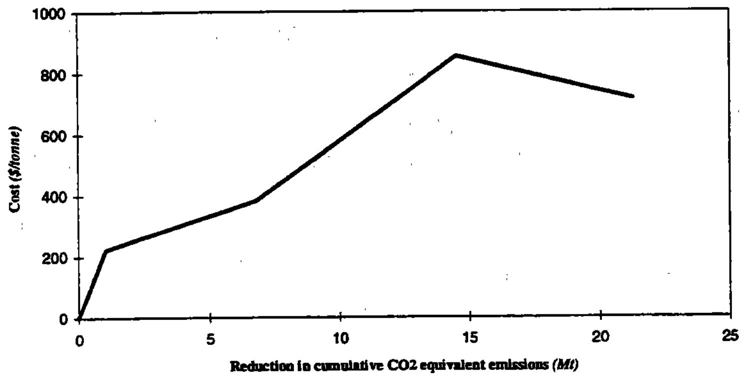
Source BTCE estimates.

FIGURE 4.2 MARGINAL COST OF ACCELERATED SCRAPPAGE POLICY, 2005



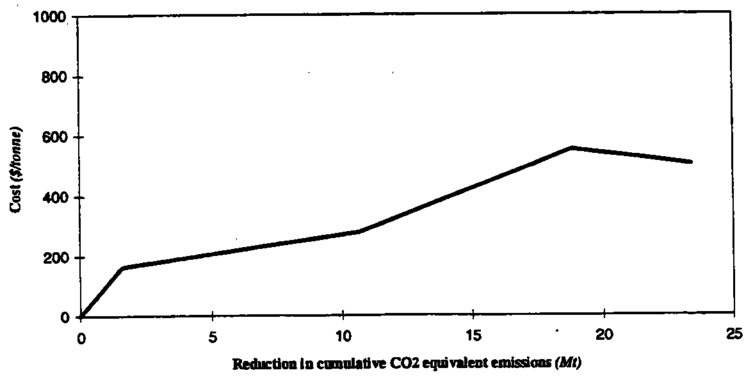
Source BTCE estimates.

FIGURE 4.3 MARGINAL COST OF ACCELERATED SCRAPPAGE POLICY, 2010



Source BTCE estimates.

FIGURE 4.4 MARGINAL COST OF ACCELERATED SCRAPPAGE POLICY, 2015



Source BTCE estimates.

CHAPTER 4 ACCELERATED SCRAPPAGE OF ROAD FREIGHT VEHICLES

BACKGROUND

A number of countries have policies that encourage the early scrappage of passenger vehicles. For example, in Japan the cost of registering vehicles increases substantially with age. The United States has had a number of State based programs in California, Illinios and Delaware, which encourage scrappage of old vehicles through 'cash for clunkers' type schemes, where the government offers cash to owners of high emitting vehicles (Alberini et al. 1994a and Alberini et al. 1994b).

The measure assessed here extends the concept of accelerated scrappage to trucks and LCVs.

An accelerated scrappage policy can be implemented either on the basis of mandatory requirements, or financial inducements can be used to encourage owners to scrap their vehicles earlier than they would otherwise have done. The costs of a mandatory policy are borne in the first instance by vehicle owners, while the taxpayers generally bear the cost of voluntary scrappage schemes.

A voluntary vehicle retirement scheme requires a policy judgement about criteria for scrappage of vehicles in order to ensure that efficient ones are not scrapped along with 'gross polluters'. However, a voluntary scrappage scheme further requires a policy decision on prices to be offered to vehicle owners. Prices must be sufficiently high to attract owners. As the number of vehicles of particular types in the fleet is reduced, prices will rise. Price offer levels would in practice be constrained by government Budget allocations, unless knowledge of vehicle markets were good enough to forecast sufficiently accurately the funds required to acquire a targeted group of vehicles.

The complexities of modelling such a system in the absence of historical experience (from a greenhouse policy perspective) are beyond the capabilities of TRUCKMOD. Primarily for this reason it was decided to assess only the cost-effectiveness of a mandatory scrappage scheme.

Mandatory schemes also require prior specification of criteria for accelerated scrappage.

Total greenhouse vehicle emissions are a product both of vehicle emissions rates and of total vehicle use. Targeting of vehicle usage on the basis of total kilometres travelled would clearly be inefficient as a means of controlling greenhouse emissions. Owners of well tuned vehicles, for example, would be relatively penalised. A scheme based on emission rates would require regular checking of all vehicles, preferably during on road travel rather than just at test centres. Because emission rates depend to a large extent on fuel efficiency (which directly determines CO_2 emissions), it too could be used as a criterion although monitoring would again prove to be a major problem.

A proxy often used for emissions rates or fuel efficiency is the age of the vehicle. A scrappage scheme based on vehicle age would inevitably be inefficient because it would not reward owners who initially purchased more fuel efficient vehicles, it generates a disincentive to maintain vehicles close to the mandatory scrappage age, and vehicle age may bear little relationship in practice to vehicle usage and deterioration.

However, in the absence of more detailed data on emission rates of freight vehicles the accelerated scrappage policy instrument assessed here is based on vehicle age as the criterion for mandatory scrappage. Implementation of such a measure could be made progressively more intense based on age groups such as the following which were used here:

1. all freight vehicles over 30 years of age.
2. all freight vehicles over 20 years of age.
3. all freight vehicles over 18 years of age.
4. all freight vehicles over 15 years of age.
5. all freight vehicles over 12 years of age.

METHODOLOGY

Analysis of the accelerated scrappage of freight vehicles assumed application of the measure from 1996 to 2015.

Implementation of an accelerated scrappage policy would immediately result in a shortfall of road freight vehicles necessary to handle the total road freight task. An immediate result would be a reallocation of vehicles among tasks, a reduction in the underlying scrappage rate for vehicles not affected by the policy, and an increase in the number of new vehicles purchased. It could also lead to an increase in the intensity of vehicle use in terms of average kilometres travelled and an increase in average loads. It was not possible, however, to estimate the magnitude of these effects.

For the purposes of the analysis, the total road freight task was assumed to remain unchanged after imposition of a policy to accelerate scrappage of road freight vehicles. Average kilometres travelled and average loads of vehicles remaining in the fleet were also assumed to remain unchanged. The number of additional new vehicles entering the fleet and the number of vehicles of younger vintages that, if not for the policy, would otherwise have been scrapped, in replacement of those scrapped, was assumed to be just sufficient to transport the unchanged total road freight task. In TRUCKMOD, new vehicles are assumed to carry the same average load as the vehicle they replace, however, average VKT of new vehicles are greater than for older vehicles. The number of additional new vehicles entering the fleet will therefore be significantly less than the number of vehicles scrapped.

It was necessary to make these simplifying assumptions to keep the analysis tractable. One consequence, however, is that the assumption of no change in the total road freight task will tend to understate the actual reduction in the road freight task that would occur as a result of an accelerated scrappage policy. The simulation results using TRUCKMOD will therefore tend to understate the actual reduction in emissions.

In the first year of implementation of an accelerated scrappage policy there will be a large number of old vehicles scrapped. In each subsequent year, where the policy is maintained, only those vehicles that pass the threshold age will be scrapped, so fewer vehicles will be scrapped in subsequent years. As a consequence, the costs of the policy will tend to be highest in 1996 and fall substantially thereafter.

Estimating emission reductions and costs—methodology and data

The cost of an accelerated scrappage policy is equal to the additional resource cost of undertaking the original transport task plus the value of any additional benefits forgone.

The cost is measured here as the sum of:

- the present value of future services that the scrapped vehicles would otherwise have been used to provide, less costs associated with maintaining and running the vehicle; and
- net changes in government tax revenue. Increased sales of new vehicles will increase sales tax receipts, a reduced stock of vehicles will reduce state government vehicle registration receipts, and a fall in demand for automotive fuels will reduce fuel excise receipts.

The number of vehicles to be scrapped is determined directly by the scrappage policy. The displaced freight task (that is the freight task that would have been handled by the vehicles scrapped) is the product of average

VKT and average vehicle loads of those vehicles scrapped, and the number of vehicles scrapped. The additional number of new vehicles necessary to undertake the displaced freight task is derived using average VKT and average vehicle loads of new vehicles. New vehicles are assumed to take up only 10 per cent of the displaced freight task for scrappage of 30-year and older vehicles. This proportion increases with the intensity of the scrappage policy.

Changes in total fuel consumption were calculated as the difference between total fuel consumption before and after implementation of the scrappage policy. Total fuel use is equal to the product of average vehicle fuel efficiency, average VKT, and the number of vehicles.

Estimates of average costs of scrapping vehicles of different ages are based on vehicle costs derived from *Glass's Guide* (1995 and earlier issues). *Glass's Guides* give retail prices obtained by a franchise dealer for a car of a given age in 'guide condition'. For the purpose of this analysis, 'guide condition' generally means that the vehicle is in roadworthy condition and is carrying approximately six months registration. This is important for the purposes of deriving the net value of future services provided by a used vehicle, which is the principal cost of vehicle scrappage.

Glass's Guide gives used vehicle prices only for vehicles up to ten years of age. The policy measures considered include scrappage of vehicles well over 10 years of age. To estimate prices of vehicles over 10 years of age the BTCE constructed a depreciation function for each of LCVs, rigid trucks and articulated trucks. The real depreciation function was estimated on data for the first ten years of a vehicles life, and extrapolated to derive the average price of vehicles up to 30 years of age.

The estimated real depreciation functions are given by the following relationships.

LCVs:

(4.1) $V_t = V_0 . \exp(-0.117t)$

Rigid trucks:

(4.2) $V_t = V_0 . \exp(-0.567 - 0.090t)$

Articulated trucks:

(4.3) $V_t = V_0 . \exp(-0.139t)$

where V_t is the real price of a vehicle at age t; and
V_0 is the real price of a new vehicle.

The average market price of used vehicles of a particular age are derived by applying the appropriate depreciation function to historical records of real prices of new vehicles.

The economic surplus enjoyed by a road freight vehicle owner is equal to the financial return generated by operating the vehicles less total maintenance and operating costs. The market price of a road freight vehicle only gives the net value of the services provided by vehicles at the 'margin'. That is, the value of the services provided by the vehicle are just equal to the value of services in the vehicle's next best alternative use. For used vehicles which are not traded, the value of the services provided must be at least as great as the value of the vehicle in its next best alternative use. So the economic surplus generated by a vehicle used in a particular activity will be at least equal to the market price. The market price therefore is an underestimate of the total economic surplus generated by each of the used vehicles to be scrapped. The cost estimates presented below, therefore, underestimate the cost to vehicle owners of the accelerated scrappage policy.

The market price used to estimate the costs of the scrappage policy is the average market price for vehicles within a particular age group.

The change in tax revenue is equal to the change in new vehicle sales tax receipts and fuel excise receipts. Additional new vehicle sales tax revenue is estimated by taking the average real retail price of a new vehicle and the sales tax rate and multiplying by the number of additional new vehicles purchased. The change in total fuel excise revenue is equal to the change in total fuel used multiplied by the fuel excise rate.

The implementation of an accelerated scrappage policy would result in an increased demand for used vehicles that are not due to be scrapped. This would result in more of these used vehicles remaining on the road than would otherwise have occurred. The additional registration revenue from these vehicles must be added to derive the total social cost.

RESULTS

The number of trucks scrapped would differ according to the severity of the accelerated scrappage policy. In 1996, if all vehicles over the age of 30 years were mandatorily scrapped, this would result in the scrappage of 15 300 LCVs, 11 600 rigid trucks and 1 300 articulated trucks. In 1996, if all vehicles over the age of 12 years were mandatorily scrapped, this would see approximately 218 000 LCVs, 142 300 rigid trucks and 19 500 articulated trucks removed from the fleet.

If the mandatory scrappage policy remained in operation, as previously mentioned, the number of vehicles scrapped in subsequent years will be significantly less than in 1996, the year of implementation.

The reduction in CO_2 equivalent emissions is smallest in 1996, and this reduction steadily increases each year as more new vehicles enter the fleet and greater numbers of older and less fuel efficient vehicles are forced out of the fleet. The greatest reduction in CO_2 equivalent emissions will come from scrappage of LCVs, as there are a greater number of older LCVs remaining on the road. The smallest reduction in CO_2 equivalent emissions is due to scrappage of rigid trucks.

Tables 4.2 and 4.3 show that forced scrappage of freight vehicles would have a minimal impact in terms of reducing emission levels of greenhouse gases. In the short term (up to the year 2000) it would virtually be necessary to scrap all commercial vehicles older than about 18 years to be certain of reducing emissions from road freight vehicles by 1 per cent per annum. Even if all vehicles over 12 years of age were scrapped, the maximum attainable emission reduction would peak in the year 2015 at just over 17 per cent compared to base case emission levels.

Mandatory acceleration of scrapping of freight vehicles therefore represents a limited policy option in terms of reducing greenhouse gas emissions.

Tables 4.4 and 4.5 show the cumulative costs, in constant \$1996, of accelerated scrappage of older commercial in 2000 and 2015. Most of the cost of accelerated scrappage is borne initially by vehicle owners and users of the services provided by them. Loss of revenue from lower levels of fuel excise is not compensated by increased sales taxes, so that government receipts are reduced.

An accelerated vehicle scrappage policy would ideally remove more highly polluting vehicles from the vehicle fleet. This would have benefits for health and possibly safety. Any overall reduction in vehicle numbers is also likely to reduce congestion costs, but as commercial vehicles make up only a small proportion of the vehicle fleet it is likely that any change in congestion costs will be small. Therefore, it is assumed that the change in congestion costs is negligible.

The health and safety benefits associated with accelerated scrappage of old vehicles are measured as the environmental damage by airborne pollutants (BTCE forthcoming). The externality benefits are calculated using an average urban and non-urban driving cycle. The value of the externality benefits presented in tables 4.4 and 4.5 are less than 1 per cent of the total costs.

Table 4.6 shows that the costs of accelerated scrappage increase quickly as the mandatory scrappage age is lowered. On the basis of a 10 per cent discount rate the present value of costs of accelerated scrappage falls with time. This fall is reflected in figures 4.1 to 4.4 which illustrate the steep increase in costs incurred in the short run for every additional tonne of CO_2 equivalent emissions reduced. Marginal abatement costs fall to about half their year 2000 level by the year 2015. They also rise less quickly as the rate of scrappage is increased.

The analysis shows that accelerated scrappage is a high cost policy option, on a per unit reduction in emissions basis.

Further, the policy does not offer significant scope for reducing emissions. This is not surprising as accelerated scrappage does not target the direct cause of the problem, excessive combustion of fossil fuels, and only indirectly influences the efficiency of the on-road vehicle fleet.

TABLE 4.1 TOTAL NUMBER OF VEHICLES SCRAPPED UNDER VARIOUS ACCELERATED SCRAPPAGE REGIMES, 1996 TO 2015

('000 Vehicles)

	Mandatory scrappage restriction				
Year	*Age > 30yrs*	*Age > 20yrs*	*Age > 18yrs*	*Age > 15yrs*	*Age > 12yrs*
1996	28.2	176.0	230.5	301.8	380.6
1997	30.1	192.1	240.4	313.5	386.8
1998	32.3	204.6	251.4	316.0	397.4
1999	34.4	218.1	259.5	317.3	404.4
2000	36.5	227.6	270.9	328.5	406.0
2001	38.3	239.3	283.9	342.3	406.6
2002	40.0	255.1	293.1	346.7	417.8
2003	41.7	267.0	302.2	357.0	425.6
2004	43.3	274.2	320.9	368.7	413.9
2005	44.6	290.2	333.6	366.9	403.4
2006	45.9	307.3	331.0	358.6	405.3
2007	47.4	308.7	326.5	355.3	418.5
2008	48.3	305.5	330.0	360.1	426.6
2009	48.5	310.3	336.2	364.9	462.4
2010	48.5	319.6	336.6	373.3	488.9
2011	48.6	324.6	339.6	399.7	512.8
2012	48.6	327.9	360.8	434.4	544.1
2013	48.4	346.6	380.9	464.1	573.8
2014	48.7	364.2	409.1	492.2	677.7
2015	49.5	390.6	441.4	552.6	695.0

Source BTCE estimates.

TABLE 4.2 TOTAL CO_2 EQUIVALENT EMISSIONS FROM COMMERCIAL VEHICLES UNDER VARIOUS ACCELERATED SCRAPPAGE REGIMES, 1995 TO 2015

(Gigagrams)

		Mandatory scrappage restriction				
Year	*Base case*	*Age > 30yrs*	*Age > 20yrs*	*Age > 18yrs*	*Age > 15yrs*	*Age > 12yrs*
1995	21308	21308	21308	21308	21308	21308
1996	22238	22211	22097	21995	21697	21329
1997	23183	23138	22936	22838	22558	22188
1998	24099	24036	23753	23651	23404	22954
1999	24982	24903	24536	24440	24236	23764
2000	25723	25627	25180	25100	24894	24448
2001	26770	26656	26133	26066	25817	25388
2002	27853	27721	27128	27077	26817	26339
2003	28948	28799	28135	28083	27837	27341
2004	30064	29900	29176	29103	28870	28400
2005	31218	31039	30250	30182	29929	29463
2006	32369	32177	31318	31273	31005	30425
2007	33444	33242	32326	32290	32025	31309
2008	34483	34272	33316	33274	32988	32086
2009	35515	35297	34310	34271	33911	32645
2010	36554	36331	35315	35289	34842	33492
2011	37601	37376	36340	36308	35760	34387
2012	38686	38459	37405	37342	36643	35343
2013	39902	39672	38586	38501	37761	36436
2014	41182	40947	39828	39711	38961	37593
2015	42507	42272	41112	40952	40210	38795

Source BTCE estimates.

TABLE 4.3 PERCENTAGE REDUCTION IN CO_2 EQUIVALENT EMISSIONS FROM COMMERCIAL VEHICLES UNDER VARIOUS ACCELERATED SCRAPPAGE REGIMES, 1996 TO 2015

(per cent)

	Mandatory scrappage restriction				
Year	*Age > 30yrs*	*Age > 20yrs*	*Age > 18yrs*	*Age > 15yrs*	*Age > 12yrs*
1996	0.12	0.63	1.09	2.43	4.09
1997	0.20	1.11	1.55	2.81	4.47
1998	0.28	1.55	2.01	3.12	5.15
1999	0.36	2.01	2.44	3.36	5.48
2000	0.43	2.44	2.80	3.73	5.73
2001	0.52	2.87	3.17	4.29	6.22
2002	0.59	3.26	3.49	4.66	6.81
2003	0.67	3.65	3.89	4.99	7.23
2004	0.74	3.99	4.33	5.37	7.48
2005	0.80	4.35	4.66	5.80	7.89
2006	0.86	4.73	4.93	6.13	8.74
2007	0.91	5.03	5.19	6.38	9.60
2008	0.95	5.25	5.44	6.72	10.78
2009	0.98	5.42	5.59	7.21	12.90
2010	1.00	5.57	5.69	7.70	13.77
2011	1.01	5.67	5.82	8.28	14.45
2012	1.02	5.76	6.04	9.19	15.04
2013	1.03	5.92	6.30	9.63	15.59
2014	1.05	6.09	6.61	9.99	16.14
2015	1.06	6.28	6.99	10.33	16.69

Source BTCE estimates.

TABLE 4.4 TOTAL COSTS OF ACCELERATED SCRAPPAGE BY VEHICLE AGE, 2000

($1996 million)

	Age > 30 yrs.	*Age > 20 yrs.*	*Age > 18 yrs.*	*Age > 15 yrs.*	*Age > 12 yrs.*
Vehicle owners	6.0	81.7	130.0	246.1	460.6
Producer	na	na	na	na	na
Government	4.7	28.0	30.8	44.7	71.1
Externalities	-0.1	-0.5	-0.7	-1.1	-1.7
Total	**10.6**	**109.2**	**160.1**	**289.7**	**529.9**

na Not available.

Source BTCE estimates.

TABLE 4.5 TOTAL COSTS OF ACCELERATED SCRAPPAGE BY VEHICLE AGE, 2015

($1996 million)

	Age > 30 yrs	*Age > 20 yrs*	*Age > 18 yrs*	*Age > 15 yrs*	*Age > 12 yrs*
Vehicle owners	30.0	283.4	415.3	675.0	1169.9
Producer	na	na	na	na	na
Government	7.7	43.4	49.0	64.1	96.5
Externalities	-0.5	-2.8	-3.1	-4.2	-6.4
Total	**37.1**	**323.9**	**461.2**	**734.9**	**1260.0**

na Not available.

Source BTCE estimates.

TABLE 4.6 TOTAL DISCOUNTED NET PRESENT COST OF ACCELERATED SCRAPPAGE, ALL COMMERCIAL VEHICLES, 1996 TO 2015

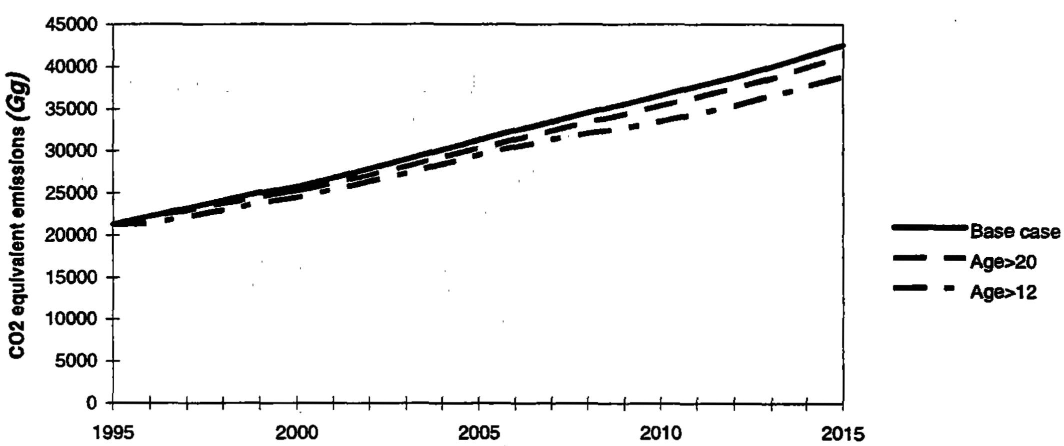
($1996 million)

Year	*Age > 30 yrs.*	*Age > 20 yrs.*	*Age > 18 yrs.*	*Age > 15 yrs.*	*Age > 12 yrs.*
1996	46.0	391.5	649.6	1143.7	1857.6
1997	43.5	384.1	562.1	1014.2	1689.4
1998	41.4	365.0	527.1	899.1	1583.0
1999	39.3	346.8	490.6	790.4	1430.8
2000	37.1	323.9	461.2	734.9	1260.0
2001	34.9	304.4	424.8	699.9	1132.5
2002	32.7	289.8	380.8	630.0	1055.5
2003	30.6	269.4	355.3	574.6	957.1
2004	28.5	245.1	347.9	525.3	806.6
2005	26.4	231.8	319.9	466.1	709.9
2006	24.4	222.2	280.0	408.9	661.7
2007	22.6	200.6	251.8	363.7	662.6
2008	20.8	178.1	233.5	331.7	636.7
2009	18.9	162.8	213.1	308.0	694.6
2010	17.1	151.4	188.4	295.5	670.3
2011	15.6	138.2	171.2	301.2	641.0
2012	14.1	124.6	166.3	315.0	603.2
2013	12.7	117.6	162.7	307.1	569.1
2014	11.5	112.0	159.7	290.6	601.1
2015	10.5	109.2	160.1	289.7	529.9

Note A discount rate of 10 per cent was used to convert costs to $1996.

Source BTCE estimates.

FIGURE 4.5 TOTAL EMISSIONS PROFILE UNDER ALTERNATIVE SCRAPPAGE POLICIES



Source BTCE estimates.

Sensitivity analysis

The sensitivity of the cumulative discounted total costs of an accelerated scrappage policy, in operation for each year from 1996 to 2015, under different discount rates is shown in table 4.7. The results show that using a higher discount rate reduces the present value of future costs, thus reducing the cumulative present value cost of the policy, and vice versa for a lower discount rate.

TABLE 4.7 SENSITIVITY ANALYSIS—CUMULATIVE DISCOUNTED TOTAL COSTS OF ACCELERATED SCRAPPAGE OF COMMERCIAL VEHICLES UNDER VARIOUS DISCOUNT RATE SCENARIOS

($1996 million)

Discount rate (per cent)	*Age > 30 yrs.*	*Age > 20 yrs.*	*Age > 18 yrs.*	*Age > 15 yrs.*	*Age > 12 yrs.*
5	759.3	6741.9	9293.7	15255.9	27239.7
10	528.6	4668.3	6506.1	10689.8	18752.6
15	396.1	3484.7	4913.4	8107.6	14030.2

Source BTCE estimates.

EQUITY ISSUES

An accelerated scrappage policy, requiring mandatory retirement of vehicles on the basis of age, will place the cost largely on existing owners of vehicles that are due to be scrapped. Forced scrappage of vehicles would obviously affect owner operators, many of whom operate on low margins. Any significant reduction of operators could increase concentration in the industry.

Other effects of introducing an accelerated scrappage policy include:

- an increase in the short term in the value of vehicles that are not scrapped immediately, representing a transfer of wealth to remaining used vehicle owners;
- an increase in the price of new vehicles, an increased cost for new vehicle purchasers;
- an increase in the price of freight transport services, representing a transfer from consumers to suppliers of freight transport services. This will tend to increase the cost of goods for whom transport is a necessary input before final sale.

These effects are largely a transfer of wealth between different agents in the economy.

To the extent that governments sought to raise taxation receipts or to reduce expenditure to make up for the short fall caused by loss of fuel excise, taxpayers in general would also suffer a loss in welfare.

CHAPTER 5 CONCLUDING REMARKS

BTCE TRUCKMOD is a vintage-specific model of the aggregate Australian truck fleet. As such, it is ideal for the analysis of policies on issues that involve altering or examining the flows of new vehicles into the fleet and old vehicles out of the fleet. It has been used to examine two possible policies for reducing greenhouse gas emissions from the Australian trucking sector.

The first policy involved setting more rigorous standards for the adoption of fuel-saving technology in new trucks. The standards were presumed to involve incremental changes to currently (or imminently) available technology, not radical redesigns, and were seen as possible to implement in the short term. However, because the policy affects only new trucks, it does not offer short-term solutions, given the slow replacement of older vehicles. But, in the long run, a policy of technology standards for new vehicles promises significant reductions from base case emissions growth (though not absolute reductions) at a fairly low cost.

The second policy simulated involved forced scrappage of older trucks. Because the policy was not adequately targeted (using only age as a criterion) it turned out to be a high cost policy that also offered little scope for emissions reduction.

BTCE TRUCKMOD will be useful in analysing many other policies. For example, future use in analysing the growth of trucking's contribution to urban pollution and congestion is a logical extension, where the model can be used in conjunction with urban area models.

APPENDIX I MATHEMATICAL DESCRIPTION OF TRUCKMOD

This section gives a mathematical description of TRUCKMOD.

Variable abbreviations:

tkm_t = total tonne-kilometres *(t.km/year)*

ts^i = task split by vehicle type *(per cent)*

tkm_t^i = total tonne-kilometres by vehicle type *(t.km/year)*

$\bar{t}_t^i$ = average load *(t/vehicle.km)*

$\overline{vkt}_t^i$ = average vehicle kilometres travelled *(km/vehicle.year)*

N_t^i = number of vehicles *(vehicles)*

$\hat{N}_t^i$ = estimated number of vehicles *(vehicles)*

$\hat{N}_t^{i,v}$ = estimated number of vehicles by vehicle age, or vintage *(vehicles)*

$\hat{S}_t^{i,v}$ = estimated number of vehicles scrapped by vehicle age between year *t* and *t+1 (vehicles)*

$p^{i,v}$ = scrappage proportion by vehicle age *(per cent)*

$\overline{fe}_t^{i,v}$ = average fleet fuel efficiency in year *t (litres/km)*

fc_t^i = total fuel consumption in year *t* *(litres)*

$pvkt^{i,v}$ = proportion of vehicle kilometres travelled by vehicle age *(per cent)*

$pfl_t^{i,s}$ = proportion of fuel used by fuel type by vehicle type in year *t (per cent)*

η^s = energy density of fuel type *s (J/Ml)*

$E_t^{i,s}$ = energy used by vehicle type *i* using fuel type *s*, in year *t (PJ)*

E_t^i = total energy used by vehicle type *i* in year *t (PJ)*

θ^s = emissions factor for fuel type *s (Gg/PJ)*

e_t^i = emissions of CO_2 by vehicle type in year *t (Gg)*

where

i = vehicle type (eg. LCV, rigid truck, articulated truck);

t = time period (year);

v = vehicle age (also referred to as vehicle vintage or cohort); and

s = fuel type.

TASK/SPLIT SUB-MODEL

Equation (I.1) is the econometric relationship that determines the total road freight task.

$$\text{(I.1)} \quad \ln(tkm_t) = \ln(\text{TOTFRT}) = -4.46 + 1.058 \ln(\text{RGDP}) - 0.923 \ln(\text{RROADLH})$$

(-3.6) (14.9) (-12.8)

where

ln(TOTFRT)	log of total road freight task (measured in *t.km*);
ln(RGDP)	log of real expenditure on gross domestic product; and
ln(RROADLH)	log of the real road freight rate for long haul road freight.

The split of the task by vehicle type is given by:

$$\text{(I.2)} \quad tkm_t^i = ts^i . tkm_t, \qquad \text{where } \sum_{i=1}^{3} ts^i = 1$$

VEHICLE STOCK SUB-MODEL

Average vehicle kilometres travelled, by vehicle type *i* in year *t* is :

$$\text{(I.3)} \quad \overline{vkt}_t^i = \frac{\sum_v vkt_t^{i,v}}{N_t^i}$$

The estimated number of vehicles required to undertake the total road freight task is determined by the total freight task, average VKT and average load factor:

$$\text{(I.4)} \quad \hat{N}_t^i = \frac{tkm_t^i}{\bar{t}_t^i . \overline{vkt}_t^i}$$

VINTAGE DISTRIBUTION SUB-MODEL

The number of vehicles in the vehicle stock, by vehicle age, is given in 1991. The estimated number of vehicles scrapped in any year, by vehicle age, is given by:

$$\text{(I.5)} \quad \hat{S}_t^{i,v} = \hat{N}_t^{i,v} . p^{i,v}$$

The number of vehicles remaining in the fleet in year *t*, by vehicle age *v*, are given by:

$$\text{(I.6)} \quad \hat{N}_t^{i,v} = \hat{N}_{t-1}^{i,v} - \hat{S}_{t-1}^{i,v-1}$$

The estimated number of new vehicles in year t is given by:

(I.7) $\hat{N}_t^{i,0} = N_t^i - \sum_{v \neq 0} \hat{N}_t^{i,v}$

VINTAGE EFFICIENCY SUB-MODEL

Total fuel consumption in year t by vehicles of vintage v is given by:

(I.8) $fc_t^{i,v} = \overline{fe}_t^{i,v} . \left(pvkt^{i,v} . \overline{vkt}_t^i \right)$

where

(I.9) $pvkt^{i,v} = \dfrac{vkt^{i,v}}{\sum_v vkt^{i,v}}$

for the purposes of this model $pvkt^{i,v}$ is assumed to be a linear function of vehicle age, constant with respect to the time period. This function is based on observation of the proportion of *VKT* travelled by vehicles in the 1991 SMVU, and is assumed to be the same for all future years.

Total fuel consumption in year t is the sum of fuel consumed by different aged vehicles:

(I.10) $fc_t^i = \sum_{v=0}^{20} fc_t^{i,v}$

FUEL AND ENERGY CONSUMPTION SUB-MODEL

Total energy use by vehicle type i of fuel type s in year t is given by apportioning total fuel consumption to one of three different fuel types and multiplying by the appropriate energy density factor, given by equation (11). Total energy consumption is given by equation (12).

(I.11) $E_t^{i,s} = fc_t^i . pfl_t^{i,s} . \eta^s$

(I.12) $E_t^i = \sum_s E_t^{i,s}$

TOTAL EMISSIONS SUB-MODEL

Total emissions from vehicle type i in period t is given by equation (I.13):

(I.13) $e_t^i = \sum_s fc_t^i . pfl_t^{i,s} . \eta^s . \theta^s$

APPENDIX II SCRAPPAGE AND VEHICLE VINTAGE SURVIVAL RATES

The scrappage functions used in the model were estimated using data obtained from the ABS *Motor Vehicle Census* (MVC) database (ABS, 1993 and earlier issues). The functional form posited for the survival of vehicles of a particular vintage within the fleet was the logistic functional form. This implies a reverse S-shaped survival curve for each vintage. The estimated survival function has the form:

(II.1) $$y_t = k - \frac{k}{1+e^{-(\alpha+\beta t)}}$$

This implies that the conditional scrappage function will have the form:

(II.2) $$\rho_t = \frac{\beta}{1+e^{-(\alpha+\beta t)}}$$

The parameter estimates are given in tables II.1 to II.3. The estimated conditional scrappage rates and the survival rates for LCVs, rigid trucks and articulated trucks are given in tables II.4 and II.5. Figure II.1 shows the estimated survival functions for each vehicle type by vehicle age, and figure II.2 shows the estimated scrappage rate for each vehicle type by vehicle age. Note that the conditional scrappage rate is defined as the number of vehicles scrapped as a proportion of the number of vehicles remaining in the fleet at any particular time, for any particular vintage (cohort).

The parameter estimates for the survival function were estimated by non-linear least squares, using MVC data (ABS 1993, and earlier issues). All estimation was performed using the SHAZAM econometrics program.

TABLE II.1 LCV SCRAPPAGE FUNCTION PARAMETER ESTIMATES

Dependent variable:	Number of LCVs remaining in the fleet		
Vintage:	1976		
Estimation method:	Non-linear least squares		
Log-likelihood:	-31.28		
No. of iterations:	38		
Parameter	*Estimate*	*Standard error*	*t-ratio*
α	2.575	0.044	58.6
β	-0.176	0.025	-71.2
k	102850	525.730	195.6

Source BTCE estimates.

TABLE II.2 RIGID TRUCK SCRAPPAGE FUNCTION PARAMETER ESTIMATES

Dependent variable:	Number of rigid trucks remaining in the fleet		
Vintage:	1975		
Estimation method:	Non-linear least squares		
Log-likelihood:	-39.12		
No. of iterations:	41		
Parameter	*Estimate*	*Standard error*	*t-ratio*
α	3.091	0.165	7.9
β	-0.171	0.009	-7.1
k	31564	367.16	37.9

Source BTCE estimates.

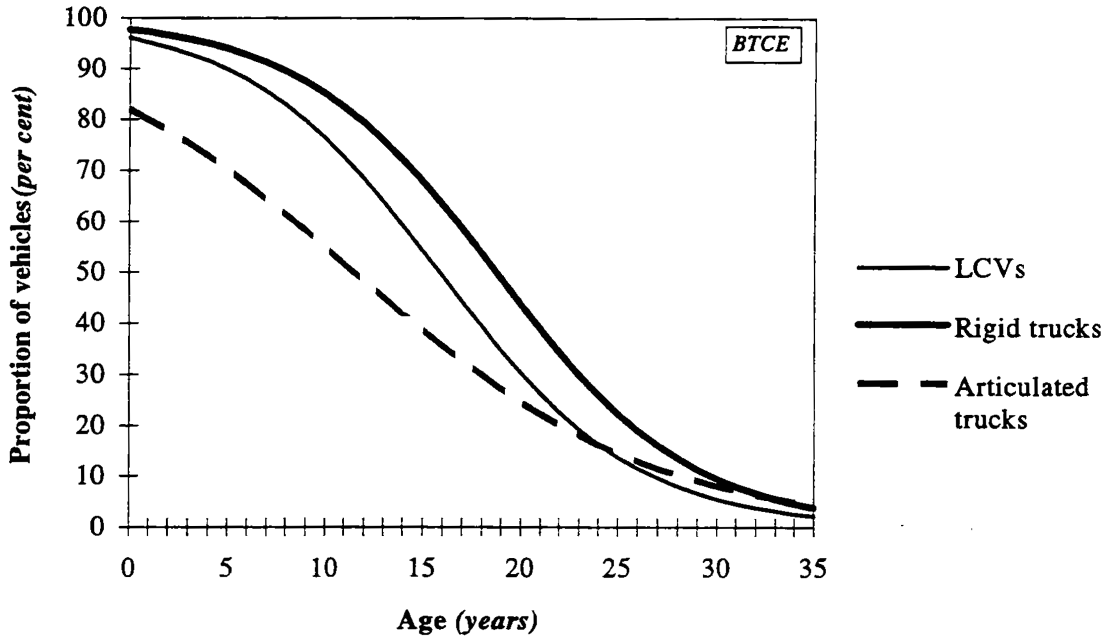
TABLE II.3 ARTICULATED TRUCK SCRAPPAGE FUNCTION PARAMETER ESTIMATES

Dependent variable:	Number of articulated trucks remaining in the fleet		
Vintage:	Pooled 1974-81 vintages		
Estimation method:	Non-linear least squares		
Log-likelihood:	-220.97		
No. of iterations:	67		
Parameter	*Estimate*	*Standard error*	*t-ratio*
α	1.525	0.176	8.7
β	-0.132	0.009	-15.5

Source BTCE estimates.

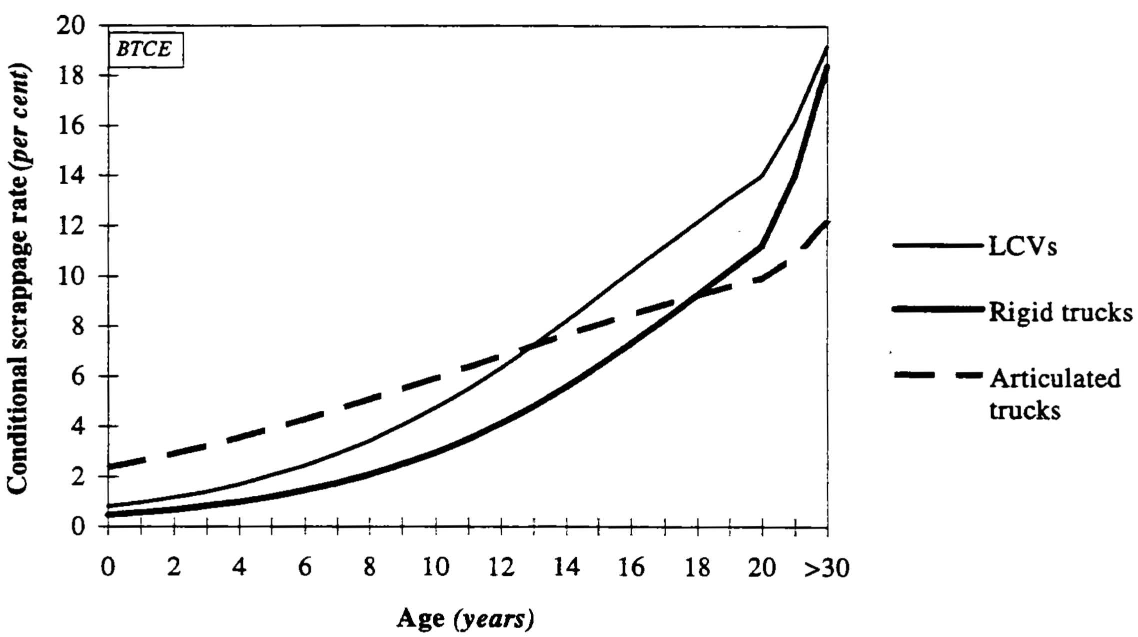
The empirical estimates suggest that about 5 per cent of rigid and articulated trucks still remain in the fleet at 35 years of age. For LCVs, the estimated survival curves suggest that only 2 per cent of vehicles remain in the fleet at about 35 years. The average half life of a particular vintage (that is the time till half the original number of vehicles of a particular vintage remain in the fleet) is about 16 years for LCVs, 19 years for rigid trucks, and approximately 11 years for articulated trucks.

FIGURE II.1 ESTIMATED SURVIVAL FUNCTIONS BY VEHICLE TYPE



Source BTCE estimates.

FIGURE II.2 ESTIMATED CONDITIONAL SCRAPPAGE RATES BY VEHICLE TYPE



Source BTCE estimates.

TABLE II.4 ESTIMATED SCRAPPAGE RATES USED IN TRUCKMOD BY COMMERCIAL VEHICLE TYPE

	Scrappage rates (per cent)		
Age (years)	*LCVs*	*Rigid trucks*	*Articulated trucks*
0	0.63	0.40	2.35
1	0.77	0.48	2.60
2	0.94	0.58	2.87
3	1.15	0.70	3.16
4	1.40	0.84	3.46
5	1.70	1.01	3.79
6	2.05	1.22	4.13
7	2.48	1.46	4.48
8	2.97	1.74	4.85
9	3.55	2.07	5.23
10	4.21	2.46	5.62
11	4.97	2.90	6.01
12	5.80	3.41	6.41
13	6.73	3.99	6.80
14	7.72	4.64	7.20
15	8.77	5.36	7.58
16	9.85	6.14	7.95
17	10.95	6.98	8.31
18	12.04	7.87	8.66
19	13.10	8.79	8.99
20	14.10	9.72	9.31
21-30	16.66	12.45	10.14
>30	20.02	17.33	11.56

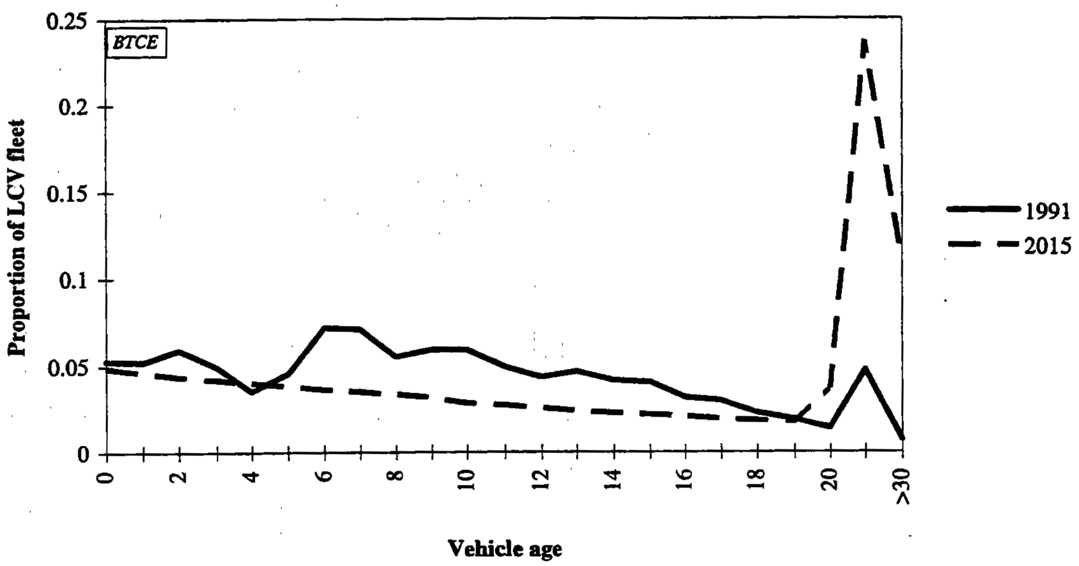
Source BTCE estimates.

TABLE II.5 ESTIMATED PROPORTION OF VEHICLES SURVIVING IN THE FLEET BY COMMERCIAL VEHICLE TYPE

	Survival rates (per cent)		
Age (years)	*LCVs*	*Rigid trucks*	*Articulated trucks*
0	96.03	97.70	82.13
1	95.18	97.20	80.11
2	94.18	96.60	77.92
3	92.97	95.88	75.57
4	91.54	95.02	73.05
5	89.84	93.98	70.37
6	87.86	92.74	67.55
7	85.54	91.28	64.59
8	82.88	89.55	61.51
9	79.83	87.52	58.35
10	76.40	85.17	55.11
11	72.59	82.46	51.82
12	68.42	79.38	48.53
13	63.92	75.91	45.24
14	59.17	72.07	41.99
15	54.24	67.87	38.82
16	49.23	63.37	35.73
17	44.23	58.61	32.76
18	39.34	53.69	29.92
19	34.66	48.70	27.23
20	30.26	43.73	24.69
21	26.19	38.89	22.32
22	22.50	34.25	20.12
23	19.19	29.90	18.08
24	16.26	25.88	16.21
25	13.71	22.24	14.49
26	11.50	18.97	12.93
27	9.60	16.08	11.52
28	8.00	13.56	10.24
29	6.64	11.39	9.09
30	5.49	9.52	8.05
31	4.54	7.93	7.13
32	3.74	6.59	6.30
33	3.08	5.46	5.57
34	2.54	4.51	4.91
35	2.08	3.73	4.33

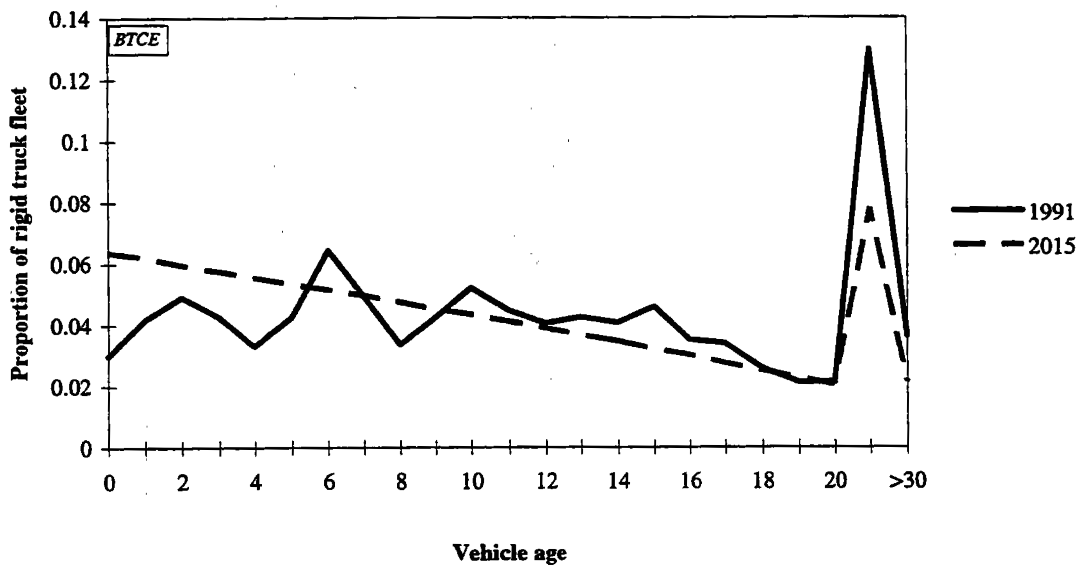
Source BTCE estimates.

FIGURE II.3 AGE DISTRIBUTION OF LCV FLEET, 1991 AND 2015



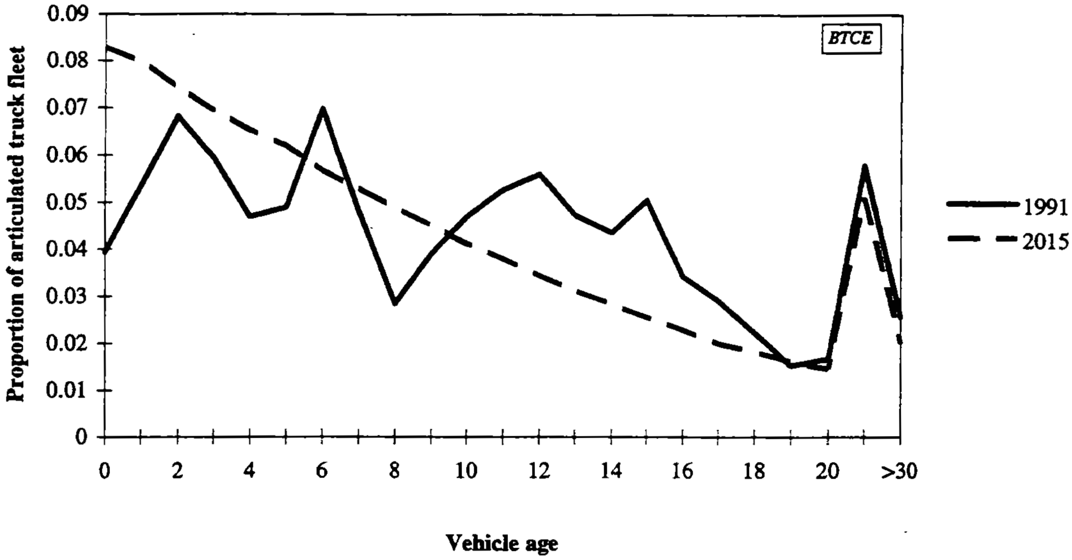
Source BTCE estimates

FIGURE II.4 AGE DISTRIBUTION OF RIGID TRUCK FLEET, 1991 AND 2015



Source BTCE estimates.

FIGURE II.5 AGE DISTRIBUTION OF ARTICULATED TRUCK FLEET, 1991 AND 2015



Source BTCE estimates.

APPENDIX III SUPPORTING DATA

TABLE III.1 ACTUAL AND PROJECTED TOTAL ROAD FREIGHT TASK BY VEHICLE TYPE, 1971 TO 2015

(billion tonne-kms)

Year	*LCVs*	*Rigid trucks*	*Articulated trucks*	*All commercial vehicles*
1971	1.37	10.62	15.20	27.19
1972	1.44	10.60	16.61	28.65
1973	1.53	10.66	17.79	29.98
1974	1.69	10.95	19.05	31.69
1975	1.83	11.22	20.74	33.79
1976	1.99	11.67	23.04	36.70
1977	2.20	12.12	25.24	39.56
1978	2.42	12.71	27.22	42.35
1979	2.60	13.65	31.90	48.15
1980	2.58	14.52	35.21	52.31
1981	2.70	15.20	36.51	54.41
1982	2.87	16.25	40.25	59.37
1983	2.86	15.56	41.36	59.78
1984	3.14	16.50	46.16	65.80
1985	3.52	18.12	52.67	74.31
1986	3.75	18.58	54.05	76.38
1987	4.12	19.47	56.17	79.76
1988	4.68	21.13	59.73	85.54
1989	4.73	21.66	63.67	90.06
1990	4.72	21.99	64.61	91.32
1991	4.75	20.55	62.91	88.21
1992	4.87	21.43	66.96	93.26
1993	5.07	22.64	70.82	98.53
1994	5.39	23.40	71.01	99.80
1995	5.74	24.18	74.09	104.01
1996	6.40	26.23	80.99	113.62
1997	6.82	27.13	84.38	118.34
1998	7.23	27.99	87.52	122.73
1999	7.70	28.99	91.34	128.04
2000	8.20	29.94	95.12	133.26
2001	8.72	30.95	99.08	138.75
2002	9.27	31.98	103.14	144.38
2003	9.86	33.04	107.37	150.26
2004	10.49	34.16	111.90	156.55
2005	11.15	35.29	116.47	162.91

2006	11.74	36.12	120.17	168.03
2007	12.49	37.32	125.07	174.88
2008	13.28	38.57	130.23	182.08
2009	14.12	39.85	135.44	189.41
2010	15.03	41.21	141.27	197.51
2011	15.96	42.54	146.81	205.31
2012	16.98	43.95	152.67	213.60
2013	18.06	45.44	158.94	222.43
2014	19.23	46.99	165.66	231.88
2015	20.42	48.49	172.05	240.96

Source BTCE estimates.

TABLE III.2 ACTUAL AND PROJECTED AVERAGE LOAD BY VEHICLE TYPE, 1971 TO 2015

(tonnes/vehicle.km)

Year	*LCVs*	*Rigid trucks*	*Articulated trucks*
1971	0.139	2.33	8.840
1972	0.140	2.35	9.380
1973	0.141	2.37	9.930
1974	0.143	2.38	10.47
1975	0.144	2.40	11.01
1976	0.146	2.42	11.49
1977	0.147	2.57	11.74
1978	0.150	2.74	11.98
1979	0.151	2.92	12.23
1980	0.153	2.76	12.62
1981	0.155	2.61	13.05
1982	0.156	2.41	13.42
1983	0.158	2.59	13.82
1984	0.160	2.78	14.29
1985	0.163	2.97	14.68
1986	0.175	3.11	15.01
1987	0.188	3.23	15.26
1988	0.201	3.29	15.57
1989	0.200	3.35	15.69
1990	0.206	3.36	15.78
1991	0.208	3.36	15.89
1992	0.210	3.36	15.97
1993	0.210	3.36	16.03
1994	0.214	3.39	16.15
1995	0.218	3.42	16.26
1996	0.222	3.46	16.38
1997	0.226	3.49	16.49
1998	0.230	3.53	16.61
1999	0.235	3.56	16.72
2000	0.239	3.60	16.84
2001	0.244	3.63	16.96
2002	0.248	3.67	17.08
2003	0.253	3.71	17.20
2004	0.258	3.74	17.32
2005	0.263	3.78	17.44
2006	0.268	3.82	17.57
2007	0.273	3.86	17.69
2008	0.278	3.90	17.81
2009	0.283	3.94	17.94
2010	0.289	3.98	18.07
2011	0.294	4.01	18.19
2012	0.299	4.05	18.32
2013	0.305	4.10	18.45
2014	0.311	4.14	18.58
2015	0.317	4.18	18.71

Source BTCE estimates.

TABLE III.3 ACTUAL AND PROJECTED AVERAGE VKT BY VEHICLE TYPE, 1971 TO 2015

('000 kms/vehicle)

Year	*LCVs*	*Rigid trucks*	*Articulated trucks*
1971	16.09	15.89	53.75
1972	15.92	15.70	53.38
1973	16.25	15.87	53.34
1974	16.31	15.57	49.69
1975	16.41	15.47	48.31
1976	16.98	15.97	50.46
1977	16.74	15.78	51.44
1978	17.01	16.21	53.56
1979	16.96	16.81	59.32
1980	16.68	17.77	62.42
1981	16.70	18.26	62.09
1982	16.88	19.10	64.41
1983	15.93	17.82	64.74
1984	16.62	17.42	66.86
1985	17.71	17.89	72.28
1986	17.22	17.79	72.37
1987	17.44	18.41	76.32
1988	18.52	19.76	78.73
1989	18.28	19.61	80.99
1990	17.42	19.90	80.37
1991	16.94	18.48	75.98
1992	16.42	19.21	81.09
1993	16.68	20.19	84.93
1994	16.68	20.19	84.93
1995	16.68	20.19	84.93
1996	16.72	20.19	84.93
1997	16.76	20.19	84.93
1998	16.80	20.19	84.93
1999	16.85	20.19	84.93
2000	16.89	20.19	84.93
2001	16.93	20.19	84.93
2002	16.97	20.19	84.93
2003	17.01	20.19	84.93
2004	17.06	20.19	84.93
2005	17.10	20.19	84.93
2006	17.10	20.19	84.93
2007	17.10	20.19	84.93
2008	17.10	20.19	84.93
2009	17.10	20.19	84.93
2010	17.10	20.19	84.93
2011	17.10	20.19	84.93
2012	17.10	20.19	84.93
2013	17.10	20.19	84.93
2014	17.10	20.19	84.93
2015	17.10	20.19	84.93

Source BTCE estimates.

TABLE III.4 PROJECTED BASE CASE NEW VEHICLE AVERAGE FUEL INTENSITY BY VEHICLE TYPE

(litres/100km)

	LCVs	*Rigid trucks*	*Articulated trucks*
1991	13.60	26.50	48.11
1992	13.48	26.50	47.68
1993	13.36	26.50	47.25
1994	13.24	26.30	46.82
1995	13.12	26.11	46.40
1996	13.04	25.85	45.91
1997	12.95	25.59	45.42
1998	12.87	25.33	44.94
1999	12.79	25.08	44.46
2000	12.71	24.83	43.99
2001	12.63	24.58	43.52
2002	12.55	24.33	43.06
2003	12.48	24.09	42.60
2004	12.40	23.84	42.15
2005	12.32	23.60	41.70
2006	12.01	23.23	41.55
2007	11.70	22.87	41.41
2008	11.40	22.51	41.26
2009	11.11	22.16	41.11
2010	10.83	21.81	40.97
2011	10.81	21.77	40.84
2012	10.79	21.73	40.72
2013	10.77	21.69	40.59
2014	10.75	21.65	40.47
2015	10.73	21.61	40.35

Note The base case new vehicle average fuel efficiency figures given in this table reflect BTCE estimates of the most likely trend in new vehicle fuel efficiency over the period to 2015.

Source BTCE estimates.

TABLE III.5 DETERIORATION FACTOR OF FLEET AVERAGE FUEL INTENSITY BY AGE, ALL COMMERCIAL VEHICLES

(index)

Age (years)	*Deterioration factor*
0	1.010
1	1.020
2	1.030
3	1.041
4	1.051
5	1.062
6	1.072
7	1.083
8	1.094
9	1.105
10	1.116
11	1.121
12	1.127
13	1.132
14	1.138
15	1.132
16	1.127
17	1.121
18	1.116
19	1.105
20	1.105
21-30	1.138
>30	1.200

Source BTCE estimates.

TABLE III.6 PROPORTION OF AGE SPECIFIC AVERAGE VKT TO FLEET AVERAGE VKT, BY VEHICLE TYPE

Age	*LCVs*	*Rigid trucks*	*Articulated trucks*
0	1.443	1.742	1.862
1	1.393	1.705	1.747
2	1.343	1.668	1.632
3	1.293	1.632	1.518
4	1.243	1.595	1.403
5	1.198	1.528	1.318
6	1.153	1.460	1.233
7	1.107	1.393	1.149
8	1.062	1.325	1.064
9	1.017	1.258	0.979
10	0.967	1.157	0.892
11	0.918	1.056	0.805
12	0.868	0.955	0.718
13	0.819	0.854	0.631
14	0.769	0.753	0.544
15	0.745	0.687	0.488
16	0.720	0.620	0.432
17	0.696	0.554	0.376
18	0.671	0.487	0.320
19	0.647	0.421	0.264
20	0.623	0.355	0.208
20-30	0.350	0.185	0.160
>30	0.250	0.150	0.130

Source BTCE estimates, ABS (1993 and earlier issues).

TABLE III.7 PROPORTION OF TOTAL FUEL CONSUMPTION BY FUEL TYPE, 1991

Fuel type	*LCVs*	*Rigid trucks*	*Articulated trucks*
Petrol	0.728	0.108	0.001
Diesel	0.198	0.857	0.996
LPG	0.074	0.036	0.003
LNG	0.000	0.000	0.000
Total	1.000	1.000	1.000

Source BTCE estimates.

TABLE III.8 NON-CO_2 EXHAUST EMISSION FACTORS BY COMMERCIAL VEHICLE TYPE

(grams/km)

	Emission					
Fuel type	*CH_4*	*N_2O*	*NO_x*	*CO*	*NMVOCs*	*SO_x*
Light trucks						
Petrol	0.14	0.012	1.76	23.58	1.97	0.05
Diesel	0.01	0.014	1.18	1.11	0.53	0.394
LPG	0.089	0.008	1.98	21.99	1.72	0.035
Medium trucks						
Petrol	0.174	0.006	4.65	57.80	4.13	0.094
Diesel	0.02	0.017	3.10	1.82	0.99	0.633
LPG	0.13	0.011	2.82	24.00	2.46	0.050
Heavy trucks						
Petrol	0.21	0.009	4.66	121.3	6.09	0.153
Diesel	0.07	0.025	15.29	7.86	2.78	1.412
LPG	0.22	0.020	4.83	24.00	4.21	0.085

Note These average emission factors relate to dynamometer drive cycles used to test compliance with Australian vehicle regulatory standards. The classification as light, medium and heavy trucks does not exactly match the ABS classification of LCV, rigid and articulated trucks, but is sufficiently close so that the emission factors for light trucks are applied to LCVs, those for medium trucks are applied to rigid trucks, and heavy trucks are used for articulated trucks.

Source BTCE (1995, p. 182).

TABLE III.9 GLOBAL WARMING POTENTIAL OF SPECIFIC EMISSIONS RELATIVE TO CO_2

Time horizon	Emission					
(years)	*CO_2*	*CH_4*	*N_2O*	*CO*	*NO_x*	*NMVOCs*
20	1	62.0	290	5	30	28
100	1	24.5	320	1	8	8
500	1	7.5	180	0	3	3

Source BTCE (1995, p. 144).

TABLE III.10 ENERGY DENSITY BY FUEL TYPE

(megajoules/litre)

Fuel type	*Energy Density*
Petrol	34.2
Diesel	38.6
LPG	25.7
LNG	..

.. Not applicable.

Source BTCE (1995, p. 181).

TABLE III.11 CO_2 EMISSION FACTORS BY FUEL TYPE

(grams/megajoule)

Fuel type	*Emission factor*
Petrol	66.0
Diesel	69.7
LPG	59.4
LNG	51.3

Source BTCE (1995, p. 181).

APPENDIX IV MODEL CALIBRATION

Calculation of aggregate emissions relies principally on using total fuel use and given emissions factors. TRUCKMOD essentially disaggregates the aggregate data, performs multiplicative operations on the disaggregated data, and then re-aggregates the data. Depending on the type of operation performed on the disaggregated data discrepancies with the aggregate results may occur.

Total fuel consumed in a year is the sum of fuel consumption by each vehicle within that year. In theory, this would be measured by summing the total fuel consumed by each vehicle.

In the model total fuel consumption is calculated by taking the average rate of fuel consumption by vehicle type, multiplied by average kilometres travelled and the total number of vehicles. This is given in equation (IV.1).

(IV.1) $fc_t = \overline{fe}_t . \overline{vkt}_t . N_t$

Average fuel efficiency is measured as total fuel consumption divided by the number of kilometres travelled by all vehicles.

(IV.2) $\overline{fe}_t = \dfrac{fc_t}{vkt_t}$

(IV.3) $\overline{vkt}_t = \dfrac{vkt_t}{N_t}$

The principal reason for the development of TRUCKMOD is to trace the effects of policy measures across different vehicle vintages. The mechanism for doing this in TRUCKMOD still has some shortcomings.

Average fuel efficiency by vehicle vintage is calculated by taking average fuel efficiency and allocating it across different vintages. However, vintage specific average fuel efficiency is not directly available. The vintage specific average fuel efficiency therefore had to be derived from the average fleet fuel efficiency and total fuel consumption. The vintage specific average fuel efficiencies used in the model are an estimate of the true value. The extent to which the estimates of the vintage specific average fuel efficiency differ from the true distribution will affect the extent to which the model produces aggregate results for total fuel consumption that differ from actual total fuel consumption.

Similarly, for vintage specific average VKT, the true values are not available for each vintage, so that the distribution of vintage specific average VKT had to be estimated from fleet average VKT and some grouped vintage specific average VKT estimates. Again, the extent to which the estimates of vintage specific average VKT differ from the true values will affect the extent to which the model correctly estimates total fuel consumption.

Equation (IV.4) gives the actual total fuel consumption for vehicle type i, in year t. Equation (IV.5) describes how TRUCKMOD calculates total fuel consumption. The difference between equations (IV.4) and (IV.5) is that estimates of vintage specific average fuel efficiency and average VKT are used in (IV.5), as opposed to true values in (IV.4).

(IV.4) $fc_t^i = \sum_v \overline{fe}_t^{i,v} . \overline{vkt}_t^{i,v} . N_t^{i,v}$

(IV.5) $\hat{fc}_t^i = \sum_v \hat{fe}_t^{i,v} . \hat{vkt}_t^{i,v} . N_t^{i,v}$

To ensure that TRUCKMOD produces results that are in line with aggregate fuel consumption, the model contains an 'aggregate fuel consumption adjustment factor'.

'Aggregate fuel consumption adjustment factor':

Age distribution = *f*(vehicle fleet size * fuel efficiency * average VKT).

This check gives an estimate of the factor by which this distributional model either under or over estimates the aggregate fuel consumption estimates. Because the model takes aggregate estimates of vehicle fleet, fuel consumption and VKT, disaggregates these estimates to derive age distributions for each, multiplies the age distribution estimates, and then aggregates these results, there are likely to be discrepancies between the 'aggregate' and 'disaggregated-aggregate' results. The adjustment factor result gives the magnitude of these discrepancies.

GLOSSARY

Adiabatic: compression or expansion of a gas without heat flow to the surrounding material.

Brake thermal efficiency: ratio of the measured output of an engine to the heat supplied to the engine as fuel (Goodsell 1989).

Cam: revolving lobe, usually of eccentric shape, fixed on a shaft and able to convert rotary motion to reciprocating or oscillating motion for a component held against it. Spring pressure is normally used to keep the reciprocating component in contact with the cam. Cams are employed to operate the valves of a four-stroke engine.

Ceramics: technology involving the use of porcelain and other vitreous materials in manufactured goods. Ceramic materials are brittle, low in weight and highly resistant to chemical action. They have great surface hardness, with good frictional and wear properties, low thermal conductivity but low resistance to thermal shock. Car manufacturers employ ceramic materials for some engine components to improve the frictional properties or reduce the heat loss through low thermal conductivity. An insulating ceramic layer in the combustion chamber prevents the loss of heat to the engine block and cooling system. One disadvantage of ceramic material is that it cannot be machined in the conventional way, and must be shaped by expensive production processes, such as hand grinding.

Charge: the quantity or mass of fuel (or air and fuel) entering the cylinder of an engine on each stroke (Goodsell 1989).

Diesel fuel: special light oil formulated for use in diesel engines. The process of distillation places hydrocarbon molecules in groups according to their chemical and physical makeup. During refining the hydrocarbons are separated into 'fractions' according to boiling point range. The first and second lightest fractions form the basis of petroleum. The next fractions are used for kerosene. The next heaviest fraction forms the basis of diesel fuel. Also called automotive diesel oil and distillate (see also petroleum).

Fuel intensity: is the inverse of fuel efficiency, and refers to the *intensity of fuel use* for road vehicles. It is typically measured in litres per 100 kilometers.

Intercooler: system for reducing the temperature of air entering a turbocharged engine. Cooling is done by an air-to-air radiator system or by using a watercooled heat exchanger unit between the turbo compressor and inlet manifold system. The lower temperature increases the air density, allowing more mixture to enter the engine, increasing the efficiency and reducing the tendency to knock due to excessive compression temperatures. The main advantages of such a system are it can increase power output by as much as 20 per cent, and it reduces wear and tear on the engine because the cooler blast mixture helps lower the general temperature of the engine.

Low-heat-rejection engine: an engine system in which the combustion heat loss to the coolant is minimised. This results in a greater proportion of the thermal value of the fuel being converted to useful work. Low-heat-rejection engines are also commonly referred to as 'adiabatic engines' (Goodsell 1989.)

Petroleum: also known as petrol, gas and automotive gasoline. Automotive fuel derived from oil bearing shale rock (see also diesel fuel).

Pumping loss: engine power output can be decomposed to recognise engine energy losses. There are two general types of engine energy losses: (i) thermodynamic efficiency and heat recovery, and (ii) engine friction both mechanical and aerodynamic. The phrase 'pumping loss' refers to aerodynamic engine friction (NELA 1991).

Rolling resistance: the set of internal forces tending to slow down a moving vehicle. Rolling resistance forces include the friction within the axles, wheel bearing friction and friction between the tyres and the road (Goodsell 1989).

Specific fuel consumption: fuel consumed per unit of power output, usually expressed as mass or volume per unit power per unit time (Goodsell 1989).

Supercharging: engine driven compressor that forces fuel mixture into the cylinders at greater than atmospheric pressure. Three main advantages: (i) it enables a relatively small engine to produce high power; (ii) it does so without adding substantially to the weight of the engine; and (iii) it does not add appreciably to overall fuel consumption unless the additional power is used.

Turbocharging: compressor unit driven by a small turbine rotated at high speed by the engine's exhaust gases. The turbine is used to compress the fuel mixture to achieve the same effects as supercharging.

Turbocompounding: exhaust gas driven second or 'compound' turbine, usually downstream of the turbocharger, which is connected to the crankshaft via a hydraulic coupling and reduction gearing.

Volumetric efficiency: extent to which the cylinder of an engine is completely filled by the incoming charge following an exhaust stroke. A measure of the ability of an engine to breathe freely. Note that the volumetric efficiency is a ratio of masses, not of volumes (Goodsell 1989).

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NELA	Nelson English, Loxton & Andrews Pty Ltd
BTCE	Bureau of Transport and Communications Economics

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ABBREVIATIONS

ABS	Australian Bureau of Statistics
BTCE	Bureau of Transport and Communications Economics
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CVT	Continuously variable transmission
GDP	Gross Domestic Product
GDP(E)	Gross Domestic Product (Expenditure)
Gg	Gigagrams (10^9 grams)
GWP	Global warming potential
km	kilometre
LCV	Light commercial vehicle
LNG	Liquid natural gas
LPG	Liquid petroleum gas
MJ	Megajoules (10^6 joules)
MVC	Motor Vehicle Census
NMVOCs	Non-methane volatile organic compounds
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
SMVU	Survey of Motor Vehicle Use
TKM	tonne-kilometres
VKT	Vehicle kilometres travelled