ENERGY TRANSFORMED: SUSTAINABLE ENERGY SOLUTIONS FOR CLIMATE CHANGE MITIGATION

MODULE C

INTEGRATED APPROACHES TO ENERGY EFFICIENCY AND LOW EMISSIONS ELECTRICITY, TRANSPORT AND DISTRIBUTED ENERGY

This online textbook provides free access to a comprehensive education and training package that brings together the knowledge of how countries, specifically Australia, can achieve at least 60 percent cuts to greenhouse gas emissions by 2050. This resource has been developed in line with the activities of the CSIRO Energy Transformed Flagship research program, which is focused on research that will assist Australia to achieve this target. This training package provides industry, governments, business and households with the knowledge they need to realise at least 30 percent energy efficiency savings in the short term while providing a strong basis for further improvement. It also provides an updated overview of advances in low carbon technologies, renewable energy and sustainable transport to help achieve a sustainable energy future. While this education and training package has an Australian focus, it outlines sustainable energy strategies and provides links to numerous online reports which will assist climate change mitigation efforts globally.

CHAPTER 8: INTEGRATED APPROACHES TO ENERGY EFFICIENCY AND TRANSPORT

LECTURE 8.3: INTEGRATED APPROACHES TO ENERGY EFFICIENCY AND ALTERNATIVE TRANSPORT FUELS - TRUCKING
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The Natural Edge Project (TNEP) is an independent non-profit Sustainability Think-Tank based in Australia. TNEP operates as a partnership for education, research and policy development on innovation for sustainable development. TNEP's mission is to contribute to, and succinctly communicate, leading research, case studies, tools, policies and strategies for achieving sustainable development across government, business and civil society. Driven by a team of early career Australians, the Project receives mentoring and support from a range of experts and leading organisations in Australia and internationally, through a generational exchange model.
The International Energy Agency forecasts that if policies remain unchanged, world energy demand is set to increase by over 50 percent between now and 2030.\(^1\) In Australia, CSIRO has projected that demand for electricity will double by 2020.\(^2\) At the same time, The Intergovernmental Panel on Climate Change (IPCC) has warned since 1988 that nations need to stabilise their concentrations of CO\(_2\) equivalent emissions, requiring significant reductions in the order of 60 percent or more by 2050.\(^3\) This portfolio has been developed in line with the activities of the CSIRO Energy Transformed Flagship research program; ‘the goal of Energy Transformed is to facilitate the development and implementation of stationary and transport technologies so as to halve greenhouse gas emissions, double the efficiency of the nation’s new energy generation, supply and end use, and to position Australia for a future hydrogen economy’.\(^4\) There is now unprecedented global interest in energy efficiency and low carbon technology approaches to achieve rapid reductions to greenhouse gas emissions while providing better energy services to meet industry and society’s needs. More and more companies and governments around the world are seeing the need to play their part in reducing greenhouse gas emissions and are now committing to progressive targets to reduce greenhouse gas emissions. This portfolio, The Sustainable Energy Solutions Portfolio, provides a base capacity-building training program that is supported by various findings from a number of leading publications and reports to prepare engineers/designers/technicians/facilities managers/architects etc. to assist industry and society rapidly mitigate climate change.

The Portfolio is developed in three modules;

**Module A: Understanding, Identifying and Implementing Energy Efficiency Opportunities for Industrial/Commercial Users – By Technology**

**Chapter 1: Climate Change Mitigation in Australia’s Energy Sector**

*Lecture 1.1:* Achieving a 60 percent Reduction in Greenhouse Gas Emissions by 2050

*Lecture 1.2:* Carbon Down, Profits Up – Multiple Benefits for Australia of Energy Efficiency

*Lecture 1.3:* Integrated Approaches to Energy Efficiency and Low Carbon Technologies

*Lecture 1.4:* A Whole Systems Approach to Energy Efficiency in New and Existing Systems

**Chapter 2: Energy Efficiency Opportunities for Commercial Users**

*Lecture 2.1:* The Importance and Benefits of a Front-Loaded Design Process

*Lecture 2.2:* Opportunities for Energy Efficiency in Commercial Buildings

*Lecture 2.3:* Opportunities for Improving the Efficiency of HVAC Systems

**Chapter 3: Energy Efficiency Opportunities for Industrial Users**

*Lecture 3.1:* Opportunities for Improving the Efficiency of Motor Systems

*Lecture 3.2:* Opportunities for Improving the Efficiency of Boiler and Steam Distribution Systems

*Lecture 3.3:* Energy Efficiency Improvements available through Co-Generation

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Module B: Understanding, Identifying and Implementing Energy Efficiency Opportunities for Industrial/Commercial Users – By Sector

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Lecture 4.2: Demand Management Approaches to Reduce Rising ‘Peak Load’ Electricity Demand
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Lecture 4.4: Making Energy Efficiency Opportunities a Win-Win for Customers and the Utility: Decoupling Energy Utility Profits from Electricity Sales

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Module C: Integrated Approaches to Energy Efficiency and Low Emissions Electricity, Transport and Distributed Energy

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Lecture 8.2: Integrated Approaches to Energy Efficiency and Alternative Transport Fuels – Passenger Vehicles
Lecture 8.3: Integrated Approaches to Energy Efficiency and Alternative Transport Fuels - Trucking

Chapter 9: Integrated Approaches to Energy Efficiency and Distributed Energy

Lecture 9.3: Beyond Energy Efficiency and Distributed Energy: Options to Offset Emissions
Integrated Approaches to Energy Efficiency and Transport

Lecture 8.3: Integrated Approaches to Energy Efficiency and Alternative Fuels - Trucking

Educational Aim

Globally, trucking is one of the largest contributors to transportation emissions, and this is forecast to more than double over the next 50 years if business-as-usual continues. Transportation contributes 15 percent of Australia’s greenhouse gas emissions, and approximately 15 percent of road transportation emissions come from freight trucks. Greenhouse gas emissions from the trucking sector have risen in Australia by 47 percent between the years 1990 and 2005. The goal of this lecture is to outline ways that greenhouse gas emissions can be cost effectively reduced from the trucking sector. Engineers are being increasingly asked to investigate this as, with rising fuel costs, the costs to business of trucking fleets is rising. In the USA, WalMart has committed to doubling fuel efficiency by 2015, saving the company $US492 million per year by 2020. To get such large increases in fuel efficiency requires a Whole System Design approach to re-optimise the design of the whole truck. This lecture discusses how a Whole System Approach to identifying and implementing fuel efficiency opportunities can greatly reduce greenhouse gas emissions from trucking. This lecture also describes in detail the individual improvements, focussing predominantly on currently available technological improvements. A clear understanding of energy efficiency opportunities will assist engineers and other students of these modules to realise potential energy efficiency improvements in their trucks.

Essential Reading

<table>
<thead>
<tr>
<th>Reference</th>
<th>Page</th>
</tr>
</thead>
</table>

5 Peer review by Geoff Andrews - Director, Genesis Now Pty Ltd.
Learning Points

1. Transportation contributes to 15 percent of Australia’s greenhouse gas emissions, most of which come from road transportation emissions – 75 percent of which comes from cars, 15 percent from freight trucks, and the rest from buses. Emissions from the trucking sector have risen in Australia by 47 percent between the years 1990 and 2005. Hence it is important to find ways to improve fuel efficiency and reduce greenhouse gas emissions from this sector.

2. Engineers are being increasingly asked to investigate this as, with rising fuel costs, the costs of freight trucking fleets is rising. In the USA, WalMart has committed to doubling fuel efficiency by 2015, saving the company 497 million by 2020. To get such large increases in fuel efficiency requires a Whole System Design Approach to re-optimise the design of the whole truck.

3. In a typical, modern, heavy truck, only 7 percent of the input fuel energy contributes to hauling the freight, providing a fuel economy of about 2.3-2.6 km/l.8 The three major energy losses are from the conversion of fuel energy into kinetic energy in the engine, aerodynamic drag and rolling resistance.

4. Rocky Mountain Institute (RMI)9 have demonstrated the potential reduction in heavy truck fuel consumption achievable through a Whole System Design (WSD) approach. RMI’s WSD truck incorporates 20 technological efficiency improvements in the engine and drivetrain, resulting in reduced aerodynamic drag and rolling resistance. These improvements compound to improve fuel economy from around 2.5 km/l to 5km/l at an internal rate of return (IRR) of 60 percent. The unweighted mean average increase in fuel economy of the technology improvements is 4 percent, but through the compounding effect, fuel economy is increased by 101 percent. RMI used a three-step process to determine the sequence of making technology improvements that maximised the overall improvement and cost effectiveness. RMI suggest that additional operational improvements and regulatory changes improvements (in the US) can further improve the WSD truck’s fuel economy to about 6.8 km/l at low cost.

5. Mass: The mass of the truck can be reduced by 2300-3200kg and the mass of the trailer can be reduced by 900kg.10

6. Aerodynamic drag:11 Aerodynamic drag is the result of forces due to pressure imbalances acting on a truck as it moves through air. For highway trucks, reducing aerodynamic drag by 2 percent improves fuel economy by about 1 percent. Aerodynamic drag becomes the most significant contributor to power requirements in a typical truck at speeds faster than about 80 km/h. There are potential modifications to several external truck and trailer components, as well as to the truck-trailer gap, which can reduce turbulence around the truck and hence reduce aerodynamic drag.

7. Rolling resistance: Rolling resistance is the result of internal friction in tyres as they flex during

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motion. Reducing rolling resistance by 3 percent improves fuel economy by about 1 percent. Rolling resistance is the most significant contributor to power requirements in a typical truck at speeds less than about 80 km/h. Every 2 km/h increase in truck speed over 90 km/h decreases fuel economy by 2 percent as a result of increased aerodynamic drag and rolling resistance. There is a proportional relationship between truck mass and rolling resistance. Every 70 kPa (10 psi) of tyre under-inflation decreases fuel economy by 1 percent. Increasing tread wear reduces rolling resistance and hence improves fuel economy by up to 7 percent. Optimal tyre and axle alignment is 0 degrees, or straight ahead.

8. **Engine**. The typical, modern, heavy truck, diesel engine produces about 320kW, at a brake thermal efficiency of about 40-44 percent. Potential improvements on these engines that can improve fuel economy include: oil-free turbo-machinery; displacement on demand technology; variable intake valve timing; variable intake lift piezo-injectors; 42V electrical systems; controllable electric pumps and drives; homogeneous charge compression ignition; internal engine braking; better lubricants; camless diesels; and incorporating hybridisation. For any engine, it is important to incorporate the engine that best suits the most common operating conditions of the truck.

9. **Lubricant**. Lubricants are used to reduce friction between moving engine components in contact, and hence energy losses and wear as well as transferring heat to the surrounding areas. Optimising the lubricant temperature maximises lubrication, which then assists in optimising the component operating temperature and hence improves fuel economy. Every 15°C decrease in lubricant temperature decreases fuel economy by 1 percent. The two main types of commonly-available lubricants are synthetic lubricants and mineral lubricants. Compared to mineral lubricants, synthetic lubricants are more stable at high temperatures, more fluid at low temperatures and more resistant to oxidation, but are also more costly. Synthetic lubricants are more cost effective in drivetrain components such as axles and transmissions rather than engines.

10. **Transmission**. Transmissions comprise a set of gears that transmit the engine output to the truck driveline. Using a non-optimal transmission can reduce fuel economy by up to 10-15 percent. Optimising the transmission includes selecting the gear ratios and number of gears to suit the most common truck load and travel terrain.

11. **Cooling system**. Truck engines are cooled by a cooling system, which provides convective cooling by fan and conductive cooling by coolant. In a typical, heavy, highway truck, the fan is active about 10 percent of the travel time and contributes substantially to truck power requirements. Unnecessary fan activity can be minimised by ensuring that all relevant controls...
operate correctly and by regular maintenance. Engine coolant assists in optimising the engine operating temperature. Optimising the coolant temperature optimises cooling and maximises fuel economy. Every 15°C decrease in coolant temperature decreases fuel economy by 0.4 percent.

12. **Operational:** There are several operational improvements that can further improve truck fuel economy, including: reducing out-of-route distance, which contribute about 3-10 percent of all distance travelled; introducing dashboard indicators, which may improve fuel economy by 1-5 percent; and improving driver behaviour, which can account for 20-30 percent variation in fuel economy.  

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Brief Background Information

Globally the trucking sector contributes significantly to transportation emissions. Emissions from this sector are forecast to rise over the next 50 years as demand for freight transport continues to rise.

Figure 8.3.1. Projected freight transport activity by region from 2000-2050.


Figure 8.3.2. Projected freight transport by mode from 2000-2050.


In Australia emissions from the freight trucking sector have increased by 47 percent from 1990-2005 and make up roughly 15 percent of emissions from the transportation sector. Hence it is important to identify and implement fuel efficiency opportunities in this sector to reduce greenhouse gas emissions.

25 Ibid.
Identifying Fuel Efficiency Opportunities in Trucking

The vast majority of fuel energy in trucks is lost during tasks other than hauling the freight. Equation 8.3.1 and Table 8.3.1 show the fuel energy losses in road vehicles.

\[
B_e = \frac{1}{c_o d} \int [(mC_d g \cos \alpha + \frac{\rho}{2} C_d A v^2) + m(a + g \sin \alpha) + B_r] v dt
\]

Equation 8.3.1: Fuel consumption per unit of distance for road vehicles

Source: Robert Bosch GmbH (2004)\textsuperscript{26}

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_e)</td>
<td>Consumption per unit of distance</td>
<td>g/m</td>
<td>(C_d)</td>
</tr>
<tr>
<td>(\eta_d)</td>
<td>Transmission efficiency of drivetrain</td>
<td>-</td>
<td>A</td>
</tr>
<tr>
<td>m</td>
<td>Vehicle mass</td>
<td>kg</td>
<td>(v)</td>
</tr>
<tr>
<td>(C_r)</td>
<td>Coefficient of rolling resistance</td>
<td>-</td>
<td>(a)</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration</td>
<td>m/s(^2)</td>
<td>(B_r)</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Angle of ascent</td>
<td>°</td>
<td>t</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Air density</td>
<td>kg/m(^3)</td>
<td>(b_e)</td>
</tr>
</tbody>
</table>

Source: Robert Bosch GmbH (2004)\textsuperscript{27}

Figure 8.3.3 below shows that in a typical, modern, heavy truck for every unit of fuel energy (black): 7 percent is lost in idle (dark grey); 68 percent of the remaining energy is lost in the engine and drivetrain (hatch); 63 percent of the next remaining energy is lost to aerodynamic drag (light grey); and 43 percent of the remaining energy is lost to rolling resistance (spotted); leaving less than 7 percent of the original fuel energy to haul the freight (white). This fuel economy equates to about 2.3-

\textsuperscript{27} Ibid.
2.6 km/l.\textsuperscript{28} Of course, these are only typical figures, and the actual figure will vary markedly depending on the freight task, the route, the vehicle, the driver, maintenance, road and traffic conditions, and weather, including wind – all of which vary themselves.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure833.png}
\caption{The component energy losses in a typical, modern, heavy truck}
\end{figure}

\textit{Source: DOE (2000)\textsuperscript{29}}

The three major energy losses are from the conversion of fuel energy into kinetic energy in the engine, aerodynamic drag and rolling resistance. Common combustion engine technologies, having been in development for over 100 years and undergone many incremental efficiency improvements, are a relatively mature technology compared to other truck technologies. Consequently, additional improvements in engine efficiency are likely to be among the least cost effective. On the other hand, efficiency improvements in aerodynamic drag and rolling resistance can now be accelerated through innovations in basic technologies.

For example, computer based modelling allows for complex and accurate optimisation of aerodynamic body features and tyre tread design, which has a large impact on rolling resistance. In addition, high performance materials allow the truck mass, which also has a large impact on rolling resistance, to be reduced while strength, toughness and durability are maintained. High performance materials also allow tyres that run with lower rolling resistance to be developed. Efficiency improvements in aerodynamic drag and rolling resistance, alone, can have a large impact on fuel consumption. Figure 8.3.4 shows that reducing aerodynamic drag and rolling resistance by 50 percent, plus reducing idle time by 80 percent, can reduce fuel consumption by over 50 percent.


Figure 8.3.4. The impact of reducing aerodynamic drag and rolling resistance by 50 percent, plus reducing idle time by 80 percent, on fuel consumption in a typical, modern, heavy truck. 

*Source: DOE (2000)*

Over the course of one year, the economic savings of even modestly reduced fuel consumption are substantial. Table 8.3.2 shows the dollar and percentage cost savings over 100,000 km (about one year of travel) for various increments of improvement. Some line haul trucks will travel four times this distance every year.

**Table 8.3.2:** The dollar and percentage cost savings over 100,000 km for various increments of improvement in truck fuel economy

<table>
<thead>
<tr>
<th>Improved fuel economy (km/l)</th>
<th>2.3</th>
<th>2.6</th>
<th>2.9</th>
<th>3.2</th>
<th>3.5</th>
<th>3.8</th>
<th>5.3</th>
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<tbody>
<tr>
<td><strong>Current fuel economy (km/l)</strong></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$8,478</td>
<td>$15,000</td>
<td>$20,172</td>
<td>$24,375</td>
<td>$27,857</td>
<td>$30,789</td>
<td>$40,472</td>
</tr>
<tr>
<td>-</td>
<td>13%</td>
<td>23%</td>
<td>31%</td>
<td>38%</td>
<td>43%</td>
<td>47%</td>
<td>62%</td>
</tr>
<tr>
<td>2.3</td>
<td>-</td>
<td>$6,522</td>
<td>$11,694</td>
<td>$15,897</td>
<td>$19,379</td>
<td>$22,311</td>
<td>$31,993</td>
</tr>
<tr>
<td>-</td>
<td>12%</td>
<td>21%</td>
<td>28%</td>
<td>34%</td>
<td>39%</td>
<td>57%</td>
<td></td>
</tr>
<tr>
<td>2.6</td>
<td>-</td>
<td>-</td>
<td>$5,172</td>
<td>$9,375</td>
<td>$12,857</td>
<td>$15,789</td>
<td>$25,472</td>
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<tr>
<td>-</td>
<td>10%</td>
<td>19%</td>
<td>26%</td>
<td>32%</td>
<td>51%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$4,203</td>
<td>$7,685</td>
<td>$10,617</td>
<td>$20,299</td>
</tr>
<tr>
<td>-</td>
<td>9%</td>
<td>17%</td>
<td>24%</td>
<td>45%</td>
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<td>-</td>
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<td>3.5</td>
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<td>$2,932</td>
<td>$12,615</td>
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<td>34%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N.B. Numbers are based on 100,000 km of travel and fuel at an average cost of US$1.30 per litre.

*Source: Adapted from Kenworth Truck Company (2006)* p 1

Whole System Design (WSD) Approach

There are several factors that affect truck fuel economy, as shown in Figure 8.3.5. There is potential for each factor to directly improve energy efficiency and lead to improved fuel economy. Many of these factors also affect other factors, so there is potential for additional, indirect improvements in fuel economy. Acting on potential indirect improvements has a compounding effect that delivers an overall improvement that is greater than the sum of the individual improvements.

![Figure 8.3.5. The factors affecting fuel economy in trucks. Source: Kenworth Truck Company (2006) p 8](image)

Rocky Mountain Institute (RMI) have demonstrated the potential reduction in heavy truck fuel consumption achievable through a Whole System Design approach. RMI’s WSD truck incorporates technological efficiency improvements in the engine and drivetrain, resulting in reduced aerodynamic drag and rolling resistance, using a combination of off-the-shelf technologies and technologies that are expected to be near market maturity by 2025. These improvements compound to improve fuel economy from about 2.5 km/l to 5km/l at an internal rate of return (IRR) of 60 percent. Table 8.3.3 shows the compounding effect of the efficiency improvements in the WSD truck (but also includes an initial mass reduction step, and starts at a higher baseline fuel consumption).

Note that the unweighted mean average increase in fuel economy of the technology improvements is 4 percent, but through the compounding effect fuel economy is increased by 101 percent. The total net capital cost, which incorporates the cost saving from using a smaller engine, is AU$17,903 and Table 8.3.2 shows that the fuel cost saving are AU$25,472 per 100,000 km (about one year of travel). These numbers indicate that the additional capital costs of a WSD truck can be recovered through fuel cost savings in about eight months.

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Table 8.3.3: The cost and impact of technology improvements on overall fuel economy in the Whole System Design truck

<table>
<thead>
<tr>
<th>Order</th>
<th>Component</th>
<th>Technology improvement</th>
<th>Fuel economy increase (%)</th>
<th>Gross capital cost (US$/truck)</th>
<th>Net capital cost (US$/truck)</th>
<th>Post-install fuel economy (km/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mass</td>
<td>Mass reduction</td>
<td>10.0</td>
<td>2000</td>
<td>1449</td>
<td>2.90</td>
</tr>
<tr>
<td>2</td>
<td>Aero</td>
<td>Truck boat-tail</td>
<td>4.9</td>
<td>500</td>
<td>-512</td>
<td>3.03</td>
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<tr>
<td>3</td>
<td>Aero</td>
<td>Cross-flow vortex trap device</td>
<td>5.0</td>
<td>500</td>
<td>-533</td>
<td>3.16</td>
</tr>
<tr>
<td>4</td>
<td>Tires</td>
<td>Super singles</td>
<td>2.7</td>
<td>466</td>
<td>-76</td>
<td>3.23</td>
</tr>
<tr>
<td>5</td>
<td>Tires</td>
<td>Low roll resistance</td>
<td>1.0</td>
<td>181</td>
<td>59</td>
<td>3.25</td>
</tr>
<tr>
<td>6</td>
<td>Aero</td>
<td>Cab deflector/ sloping hood/cab side flares</td>
<td>2.8</td>
<td>1000</td>
<td>422</td>
<td>3.33</td>
</tr>
<tr>
<td>7</td>
<td>Aero</td>
<td>Leading/trailing edge + vortex strake device</td>
<td>2.0</td>
<td>750</td>
<td>337</td>
<td>3.38</td>
</tr>
<tr>
<td>8</td>
<td>Aero</td>
<td>Pneumatic blowing</td>
<td>15.0</td>
<td>3000</td>
<td>3000</td>
<td>3.78</td>
</tr>
<tr>
<td>9</td>
<td>Tires</td>
<td>Pneumatic blowing</td>
<td>1.2</td>
<td>500</td>
<td>378</td>
<td>3.81</td>
</tr>
<tr>
<td>10</td>
<td>Aero</td>
<td>Tractor-trailer gap/ wheel wells/ baffles/ bumper</td>
<td>0.5</td>
<td>300</td>
<td>197</td>
<td>3.82</td>
</tr>
<tr>
<td>11</td>
<td>Aero</td>
<td>Underbody diffusion + enclosure &amp; undercarriage flow</td>
<td>3.3</td>
<td>2500</td>
<td>1818</td>
<td>3.91</td>
</tr>
<tr>
<td>12</td>
<td>Aero</td>
<td>Electronic vision system</td>
<td>1.0</td>
<td>1000</td>
<td>793</td>
<td>3.93</td>
</tr>
<tr>
<td>13</td>
<td>Electrical</td>
<td>AUX power related</td>
<td>1.0</td>
<td>324</td>
<td>223</td>
<td>3.96</td>
</tr>
<tr>
<td>14</td>
<td>Electrical</td>
<td>Fuel cell aux power</td>
<td>1.8</td>
<td>461</td>
<td>461</td>
<td>4.01</td>
</tr>
<tr>
<td>16</td>
<td>Engine</td>
<td>Improved injection &amp; combustion including HCCI</td>
<td>8.0</td>
<td>1500</td>
<td>1500</td>
<td>4.76</td>
</tr>
<tr>
<td>17</td>
<td>Engine</td>
<td>Internal friction, lubes &amp; bearings</td>
<td>3.0</td>
<td>600</td>
<td>600</td>
<td>4.90</td>
</tr>
<tr>
<td>18</td>
<td>Engine</td>
<td>Higher cylinder pressure</td>
<td>4.0</td>
<td>1000</td>
<td>1000</td>
<td>5.10</td>
</tr>
<tr>
<td>19</td>
<td>Engine</td>
<td>Displacement on demand</td>
<td>2.0</td>
<td>1000</td>
<td>1000</td>
<td>5.20</td>
</tr>
<tr>
<td>20</td>
<td>Trans</td>
<td>Transmission-related (lock-up, electronic controls, reduced friction)</td>
<td>2.0</td>
<td>1000</td>
<td>1000</td>
<td>5.31</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td></td>
<td></td>
<td>20,582</td>
<td>15,116</td>
<td>5.31 km/l (compound)</td>
</tr>
</tbody>
</table>

Source: Adapted from Lovins, A.B. et al (2004) p 26

RMI suggest that additional operational improvements and regulatory changes improvements (in the US) can further improve WSD truck fuel economy to about 6.8 km/l at low cost. Operational improvements include reducing wasted miles via GPS navigation, and improving driver behaviour by providing feedback through dashboard fuel economy indicators and load-sensing cruise control. Regulatory changes include increasing the maximum number of axles for trucks (in the US).

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The sequence in which the WSD truck improvements were made was not arbitrary, but instead specially determined to maximise the overall improvement and cost effectiveness. RMI used a three-step process:36

1. Make a technology improvement that directly reduces mass, aerodynamic drag or rolling resistance. Choose the improvement with the greatest cost effectiveness, measured as lowest pre-install cost per improved truck fuel economy. Note that making an improvement may change the cost effectiveness of the remaining improvements.

2. Re-size the engine to match the new required capacity. Go back to Step 1 until Step 1 improvements are no longer cost effective.

3. Make technology improvements that directly improve the engine and drivetrain until the improvements are no longer cost effective. At any time, choose the improvement with the greatest cost effectiveness, measured as the lowest pre-install cost per improved truck fuel economy. RMI’s cost effectiveness limit was US$1/gal (about AU$0.26/l).

RMI conservatively followed this sequence once and state that to optimise the system would require iterating through the sequence until no further technology improvements were cost effective. The remainder of this lecture describes in detail the individual improvements that can be made to improve truck fuel economy, focussing predominantly on currently-available technological improvements.

**Mass**

The mass of both the truck and trailer can be reduced substantially.37 The mass of the truck can be reduced by 2300-3200kg through measures such as eliminating two differentials, using aluminium for differential housing, eliminating 6-inch spacer blocks and using super singles tyres rather than pairs of tyres. The mass of the trailer can be reduced by 900kg through measures such as using alternative floor materials and eliminating excess steel in the frame.

**Aerodynamic Drag**

Aerodynamic drag is the result of forces acting on a truck as it moves through the air due to pressure imbalances.38 The magnitude of aerodynamic drag depends on truck speed, frontal area and external shape, as in Equation 3.7.1. The aerodynamic performance of trucks has improved throughout the past few decades. Heavy trucks of the 1970s had aerodynamic drag coefficients of about 1.0,39 but now their aerodynamic drag coefficients are closer to 0.6-0.7, mainly due to improvements in the leading surfaces of the truck.40 Compared to the trucks of the 1970s, modern trucks experience about 30 percent lower aerodynamic drag and have about 15 percent better fuel economy when under steady 100 km/h wind tunnel conditions, and experience about 20 percent lower aerodynamic drag with about 10 percent better fuel economy when travelling at 100 km/h in a typical operating environment.41 The upper theoretical limit for heavy truck aerodynamic drag is

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coefficients is about 0.13-0.19. Figure 8.3.6 shows the impact of aerodynamic aid on fuel economy in trucks. For highway trucks travelling interstate, reducing aerodynamic drag by 2 percent improves fuel economy by about 1 percent. The impact on trucks that travel faster is more significant because the power required to overcome aerodynamic drag increases with the cube of truck speed, as in Equation 3.7.1, while energy increases with the square of truck speed (the difference is because the journey is completed in less time).

Figure 8.3.6. The impact of aerodynamic aid on fuel economy in trucks.

Source: Cummins (2006) p 4

Figure 8.3.7 compares the power requirements of a truck with (a) no aerodynamic aid, and (b) 20 percent aerodynamic aid. At 100 km/h, the aerodynamic drag in truck (a) is 20 percent lower and the overall power requirement is 10 percent lower than those in truck (b). Figure 8.3.7 also shows that aerodynamic drag becomes the most significant contributor to power requirements in a typical truck at speeds faster than about 80 km/h. Modifications to several external components can reduce turbulence around the truck and hence reduce aerodynamic drag, as shown in Figure 8.3.8(a).

These modifications include: full roof deflector (5-10 percent reduction), chassis fairing (1-3 percent reduction), sloped hood (2 percent reduction), round corners, aero bumper (2 percent reduction), air dam, flush headlights (0.5 percent reduction), slanted windshield, curved windshield, side extenders (1-7 percent reduction), skirts, under-hood air cleaners (1-4 percent reduction), concealed exhaust system, recessed door hinges, grab handles, aerodynamic mirrors (1-2 percent reduction), and truck vision systems to replace mirrors (currently are in development) (3-4 percent reduction). The impact of these modifications depends on the mass, trailer type, and truck speed.

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Figure 8.3.7. Comparing the power requirements of a truck with (a) no aero dynamic aid, and (b) 20 percent aero dynamic aid, as a function of speed.

Source: Cummins (2006), pp 5-7

The truck-trailer air gap introduces aerodynamic drag in a crosswind environment, as shown in Figure 8.3.8(b), and is also a source of turbulence, as shown in Figure 8.3.8(a). Every 250 mm increase in truck-trailer air gap beyond about 750 mm, increases aerodynamic drag by about 2

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percent. Aerodynamic drag can be reduced by minimising the truck-trailer gap or using aeroskirts to reduce turbulence.

![Diagram of truck with Worse and Better Fuel Economy]

**Figure 8.3.8.** Air turbulence around a moving truck as a result of (a) various truck components, and (b) the truck-trailer gap.


The trailer shape has an impact on aerodynamic drag. Table 8.3.4 shows the increase in aerodynamic drag due to trailers of various types and shapes. Of the typical trailer types, smooth-side van trailers with rounded leading corners provide the least aerodynamic drag. In addition, increasing the number of trailers increases the aerodynamic drag.

**Table 8.3.4:** Increase in aerodynamic drag for various trailer types

<table>
<thead>
<tr>
<th>Trailer Type</th>
<th>Increase in Aerodynamic Drag (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth-side van trailer with rounded leading corners</td>
<td>Baseline</td>
</tr>
<tr>
<td>Square corner/ vertical rib</td>
<td>5-10</td>
</tr>
<tr>
<td>Drop decks/ flat top with irregular shaped loads</td>
<td>10-30</td>
</tr>
<tr>
<td>Stock crates</td>
<td>10-30</td>
</tr>
<tr>
<td>Car carriers</td>
<td>10-30</td>
</tr>
</tbody>
</table>

Source: Adapted from Cummins (2006) p 12

**Rolling Resistance**

Rolling resistance is the result of internal friction in tyres as they flex during motion. Friction converts kinetic energy into heat energy, which is lost to the surroundings. Consequently, tyres that run cooler provide higher fuel economy than tyres that run hotter. Recent innovations in complex rubber compounds, casing construction and tread design have lead to the development of modern tyres that increase truck fuel economy by up to 0.2 km/l. Rolling resistance contributes about one-third of the power requirement in a typical truck. Consequently, in these conditions, reducing rolling resistance...
Rolling resistance by 3 percent improves fuel economy by about 1 percent. Rolling resistance of trailer tyres has a greater impact on fuel economy than rolling resistance of truck tyres.\textsuperscript{52} Decreasing the truck speed\textsuperscript{53} decreases tyre flexing and hence rolling resistance. The rolling resistance is the most significant contributor to power requirements in a typical truck at speeds less than about 80 km/h. Every 2 km/h increase in truck speed over 90 km/h decreases fuel economy by 2 percent as a result of increased aerodynamic drag and rolling resistance. Higher speeds also cause tyre treads to wear 10-30 percent faster with respect to distance travelled.\textsuperscript{54} Decreasing the truck mass decreases tyre flexing and hence rolling resistance.\textsuperscript{55} There is a proportional relationship between truck mass and rolling resistance, as in Equation 3.7.1. Rolling resistance of any tyre can be minimised by optimising the inflation pressure. Under-inflated tyres increase rolling resistance and hence reduce fuel economy. They also increase tyre wear, create irregular tread wear and reduces casing durability.\textsuperscript{56} Figure 8.3.9 shows the impact of tyre inflation pressure for various truck axles on truck fuel economy. Every 70 kPa (10 psi) of tyre under-inflation decreases fuel economy by 1 percent. Under-inflation of trailer tyres (medium grey) has a greater impact on fuel economy than under-inflation of truck tyres (black and dark grey). Over-inflated tyres decrease rolling resistance and hence increase fuel economy, but also increase tyre wear.\textsuperscript{57}

![Figure 8.3.9. The impact of tyre inflation pressure for various truck axles on truck fuel economy.](source: Cummins (2006) p 22)\textsuperscript{58}

\textsuperscript{56} Ibid, p 22.
Tyre tread contributes 60-70 percent of tire rolling resistance. Figure 8.3.10 shows the impact of tyre tread wear and type on truck fuel economy. Increasing tread wear reduces rolling resistance and hence improves fuel economy by up to 7 percent. The break-in period for tyres is up to 50,000 km. Rib tyres have lower rolling resistance than lug tyres because they have lower tread depth and thus experience less flexing.

![Figure 8.3.10](image)

**Figure 8.3.10.** The impact of tyre tread wear and type on truck fuel economy.

*Source: Cummins (2006) p 17*

Figure 8.3.11 shows the impact of tyre and axle alignment on truck fuel economy. The optimal alignment is 0 degrees, or straight ahead. A tyre that is misaligned by only ¼ degree will try to travel 2-3 m sideways per km travelled, which not only reduces truck fuel economy, but also increases tyre wear.

![Figure 8.3.11](image)

**Figure 8.3.11.** The impact of tyre and axle alignment on truck fuel economy.

*Source: Cummins (2006) p 21*
**Engine**

The diesel engine from a typical, modern, heavy truck produces about 320kW, at a brake thermal efficiency of about 40-44 percent.\(^{63}\)

RMI describes the potential improvements on these engines and their various components:

- **Engine turbomachinery:** ‘Oil-Free turbomachinery is defined as high-speed rotating equipment, such as turbine engines, that operate without oil-lubricated rotor supports, i.e., bearings, dampers and air/oil seals. We expect advances towards an oil-free turbomachinery to have some impact on the fuel economy gain in heavy trucks. By how much is uncertain, but it is known that relative to state-of-the-art oil lubricated systems, oil-free turbomachinery technology can offer significant system level benefits.’ \(^{64}\)

- **Displacement on demand:** ‘Displacement on demand (DOD) technology deploys only the number of cylinders required to serve the current load, thus shifting the locus of engine operation to a region of higher thermal brake efficiency. The gain in a light-truck fuel economy can be very high, as much as 6% to 8%.’ \(^{65}\)

- **Variable intake valve timing (VVT):** ‘Electronic control of the camshaft enables selection of optimum location for various engine operating conditions, maximizing torque and horsepower outputs, as well as significant emissions benefits from the engine’s precise valve control.’ \(^{66}\)

- **Variable intake lift, piezo-injectors, 42V electrical systems:** ‘Variable intake lift, piezo-injectors, and increased voltage of electrical systems to 42V are at this point essentially part of standard modern system designs.’ \(^{67}\)

- **Controllable electric pumps and drives:** ‘Moving hydraulic and mechanical pump systems to controllable electric pumps and drives will have significant efficiency benefits.’ \(^{68}\)

- **Homogeneous charge compression ignition:** ‘Homogeneous Charge Compression Ignition (HCCI) is a new combustion process that has the potential to be both highly efficient and produce very low emissions. HCCI is currently at the research stage. It is a lean combustion process and enables the combustion to take place spontaneously and homogeneously without flame propagation, eliminating heterogeneous air/fuel mixture regions, translating to a lower local flame temperature that reduces the amounts of Nitric Oxide (\(NO_x\)) and particulate matter emitted. HCCI can provide high, diesel-like efficiencies using gasoline, diesel fuel, and most alternative fuels. HCCI may incorporate the best features of both spark ignition (SI) engines and direct injection (DI) diesel engines. Like an SI engine the charge is well mixed which minimizes particulate emissions, and like a diesel engine it is compression ignited and has no throttling losses, which leads to high efficiency.’ \(^{69}\)

RMI also suggest that fuel economy can also be improved by: introducing internal engine braking; transitioning to better lubricants, such as from 15W40 to 5W30; developing camless diesels; and incorporating hybridisation.\(^{70}\) Engine models have unique torque, power and fuel consumption

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\(^{64}\) Ibid, p 11.

\(^{65}\) Ibid, p 12.

\(^{66}\) Ibid, p 12.

\(^{67}\) Ibid, p 12.

\(^{68}\) Ibid, p 12.

\(^{69}\) Ibid, p 13.

\(^{70}\) Ibid, p 11.
characteristics that vary with engine speed. It is important to incorporate the engine that best suits the most common operating conditions of the truck. For example, if the most common operating is highway cruising then the engine should operate at its optimal speed when the truck is travelling at 100 km/h.\textsuperscript{71} In another example, an engine with too much power encourages drivers to accelerate rapidly, drive faster and then have to brake more often, while an engine with too little power reduces gradeability, can reduce speed upgrade and dissatisfy the driver.\textsuperscript{72}

**Lubricants\textsuperscript{73}**

Lubricants (usually lube oil) are used to reduce friction between moving engine components in contact, and hence energy losses and wear as well as transferring heat to the surrounding areas. Engine lubricants assist in optimising the engine operating temperature. Optimising the lubricant temperature maximises lubrication, which then assists in optimising the engine operating temperature and hence improves fuel economy. If the temperature is too low the lubricant is too viscous and thus requires more pumping energy to move it around the engine. If the temperature is too high the lubricant is too fluid to lubricate effectively. Typical lubricant system operating temperatures are above 105°C, and every 15°C decrease in lubricant temperature decreases fuel economy by 1 percent. The two main types of commonly-available lubricants are synthetic lubricants and mineral lubricants. Figure 8.3.12 shows the impact of both synthetic lubricants and mineral lubricants on fuel economy for various truck components. Compared to mineral lubricants, synthetic lubricants are more stable at high temperatures, more fluid at low temperatures and more resistant to oxidisation, but are also more costly.

![Figure 8.3.12.](image)

*Figure 8.3.12. The impact of synthetic lubricants and mineral lubricants on fuel economy for (a) a truck engine oil sump, (b) truck axle lubrication, and (c) truck transmission.*

*Source: Cummins (2006) pp 14-15\textsuperscript{74}*


\textsuperscript{72} Ibid, p 13.

\textsuperscript{73} Ibid, pp 14-15, 18, 20.
Using synthetic lubricants in engines reduces pumping energy losses and oil churning losses at low ambient temperatures, but performance is similar at normal operating temperatures. In addition, the performance of any engine lubricant is degraded by combustion by-products. Consequently, the additional economic investment in synthetic lubricant may only be cost effective for extreme engine operating temperature conditions. Synthetic lubricants are more cost effective in drivetrain components such as axles and transmissions, which frequently operate at extreme temperatures and rarely suffer from internal contaminants. The synthetic lubricant’s greater resistance to oxidation can increase its effective life, which can offset the additional economic investment.

**Transmission (Gear Box)**

Transmissions comprise a set of gears that transmit the engine output to the truck driveline. They are a major contributor to whether the engine operates at the optimum speed during the most common operating conditions. Using a non-optimal transmission can reduce fuel economy by up to 10–15 percent. Optimising the transmission includes selecting the gear ratios and number of gears to suit the most common truck load and travel terrain. Generally, operating fast gears and slow engines improves fuel economy. Automated transmissions are now available for trucks. They incorporate computer controlled shift logic to determine the optimal gear changes for maximum fuel economy. However, automated transmissions may not be as accurate at manual gear changes in some conditions, such as during frequent ascents and descents.

**Cooling System**

Truck engines are cooled by a cooling system, which provides convective cooling by fan and conductive cooling by coolant. In a typical, heavy, highway truck, the fan is active about 10 percent of the travel time and contributes substantially to truck power requirements, as shown in Table 8.3.5. The fan automatically activates in response to high cooling system temperatures, high intake manifold (boost) air temperatures and the air conditioner Freon compressor activating.

<table>
<thead>
<tr>
<th>Engine speed (RPM)</th>
<th>1100</th>
<th>1300</th>
<th>1500</th>
<th>1700</th>
<th>1900</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine: Cummins ISM (kW)</td>
<td>7</td>
<td>10</td>
<td>16</td>
<td>24</td>
<td>34</td>
<td>46</td>
</tr>
<tr>
<td>Engine: Cummins ISX/SIG (kW)</td>
<td>8</td>
<td>13</td>
<td>19</td>
<td>28</td>
<td>39</td>
<td>52</td>
</tr>
</tbody>
</table>

*Source: Adapted from Cummins (2006) p 20*

Unnecessary fan activity can be minimised by ensuring that the fan clutch and thermostatic switch operate effectively, and by maintaining a clean charge air cooler and the appropriate coolant level. The air conditioner Freon compressor contributes about 50 percent of fan activity. Excessive fan activity can be from an overcharged system, defective or incorrect head pressure switches, or poor condenser efficiency.

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**Operational**

There are several operational improvements that can further improve truck fuel economy:

- Out-of-route distance contributes about 3-10 percent of all distance travelled.\(^7^8\) Out-of-route distance can be reduced by using technologies such as GPS navigation.

- Dashboard indicators\(^7^9\) that assist drivers to monitor parameters related to fuel economy are in development. There are digital fuel economy displays that monitor instantaneous fuel consumption and average trip fuel economy, which may improve fuel economy by 1-5 percent.

- Driver behaviour\(^8^0\) can account for 20-30 percent variation in fuel economy. Behaviours include control of truck idle time, control of truck speed, acceleration and braking techniques and gear shifting techniques.

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\(^7^9\) Ibid.

Optional Reading


Key Words for Searching Online

Truck fuel economy, truck energy efficiency, aerodynamic drag, rolling resistance, oil-free turbomachinery, displacement on demand (DOD), homogeneous charge compression ignition (HCCI), internal engine braking, automated transmission.