Historical Case Studies of Energy Technology Innovation

CASE STUDY 8. VEHICLE EFFICIENCY.

AUTOMOBILE FUEL EFFICIENCY STANDARDS

Gregory Nemet
University of Wisconsin

AUTHOR'S SUMMARY

Increasing fuel efficiency standards have affected innovation in automobiles by first, accelerating the adoption of new fuel, engine and, drive train technologies, and second, by shifting the use of improved efficiency between fuel consumption and performance.

In 1975, the US government passed the Federal Automotive Fuel Efficiency Standards, which specified mandatory levels of miles per gallon of gasoline consumed for new vehicles averaged across each manufacturer's vehicle fleet (Greene, 1998). The required Corporate Average Fuel Efficiency (CAFE) standard steadily increased from 18 miles per gallon in 1978 to 27.5 miles per gallon in 1985. The standard was effective in meeting its goals—actual fuel efficiency has only ever fallen below the government requirement by small amounts for short periods. In fact, actual fuel efficiency has almost always exceeded the mandatory level. This over-compliance, combined with the simultaneous rise in the price of gasoline during the period of escalating standards, suggests that fuel prices have played a role in motivating efforts to improve fuel efficiency; change is not attributable to the CAFE standard alone (Davis et al., 2008). The standard for passenger cars in the US remained the same from 1985-2010, while actual efficiency has improved slightly in that period. Standards also exist in Europe, China, Japan, Australia, and Canada. All of these standards are above the US efficiency requirements, by nearly 100% in the case of Japan and the EU.

The past four decades have generated two broad technological responses to the combination of rising standards and rising oil prices: (1) changes in the use of improved engine efficiency—in particular, whether efficiency gains are used to reduce fuel consumption, increase vehicle weight, or increase acceleration; and (2) rapid adoption in certain periods of new technologies including fuel injection, front-wheel drive, and diesel engines.

If referencing this chapter, please cite:
G. Nemet (2012). Automobile Fuel Efficiency Standards. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

1 FUEL EFFICIENCY IN THE US: THE CAFE STANDARD & TECHNOLOGICAL IMPROVEMENTS

Congress passed the Energy Policy and Conservation Act of 1975 in response to the Arab Oil Embargo in 1973 and in recognition of the US's increased dependence on imported liquid fuels. The Act added Title V, "Improving Automotive Efficiency," to the Motor Vehicle Information and Cost Savings Act (DOT, 2002). Title V established the mandatory corporate average fuel economy standards (CAFE), which were based on the sales weighted average fuel economy, expressed in miles per gallon (mpg) of a manufacturer's fleet of passenger cars or light trucks. The original goal of the programme was to double new car fuel economy by model year 1985. The National Highway Traffic Safety Administration (NHTSA) is responsible for establishing and amending the CAFE standards while the Environmental Protection Agency (EPA) is responsible for calculating the average fuel economy for each manufacturer. The standards for model years 1978, 1979, and 1980 were set at 18.0, 19.0, and 20.0 mpg, respectively. The Act required NHTSA to establish CAFE standards for model years 1981, 1982, 1983, and 1984 administratively and to specify the CAFE standards for model years 1985 and thereafter at 27.5 mpg (see Figure 1).

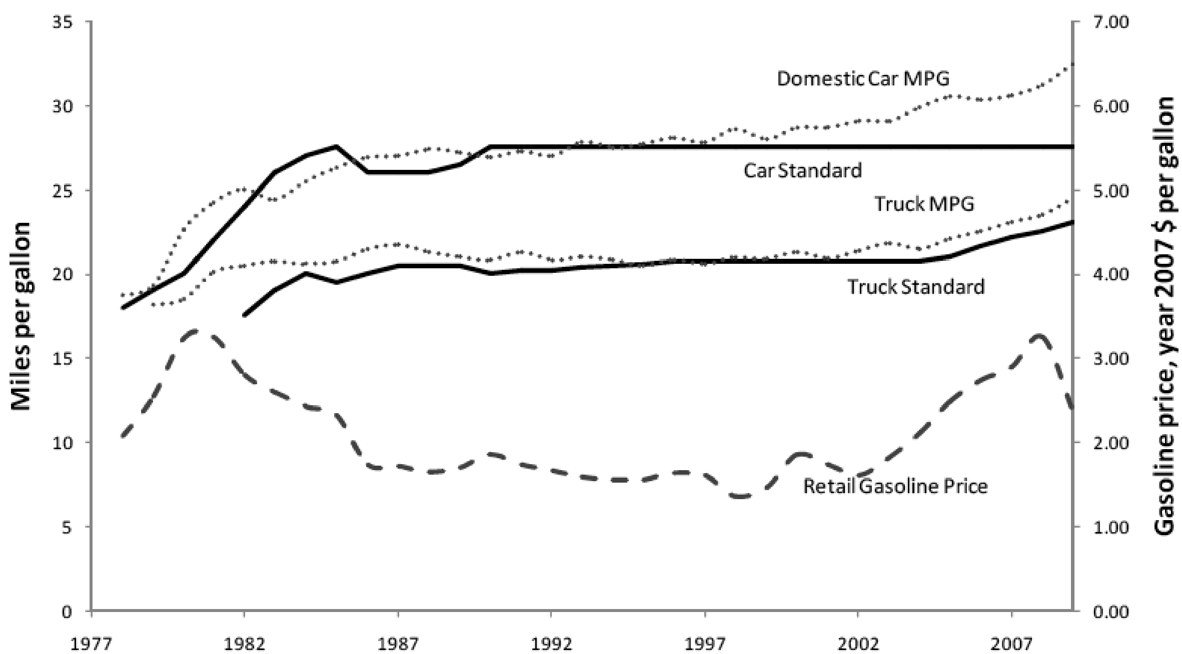

FIGURE 1. GASOLINE PRICES, ACTUAL FUEL EFFICIENCY, AND MANDATED FUEL EFFICIENCY (ANDERSON ET AL., 2010).

An important aspect of the CAFE standard is its strong enforcement capacity. The penalty for failing to meet CAFE standards is $55 per vehicle for every mile per gallon under the relevant target standard. NHTSA had collected about $786 million in fines for CAFE non-compliance by the end of 2008.

The CAFE standard has affected the rate and direction of technological change in vehicles (NAS, 2002). End-use efficiency has improved, almost continuously for the past thirty years. But the availability of more efficient energy conversion has been used to accomplish different ends during the period of rising

If referencing this chapter, please cite:
G. Nemet (2012). Automobile Fuel Efficiency Standards. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

fuel economy standards (1975-1985) compared to the period of static standards (1986-present). In the first period, efficiency improvement was directed towards improving miles travelled per gallon of gasoline consumed. After 1985, in the second period, almost all of the efficiency improvements were used to increase other vehicle attributes including acceleration, towing capacity, and size.

Energy conversion efficiency has improved in drive trains, engines, drag, and rolling resistance. As shown in Figure 2, drive train and engine energy conversion efficiency has improved from about 15 to 43 ton-miles per gallon between 1975 and 2005. From 1975 to 1985, efficiency improved at the rate of 2-3% per year (Lutsey and Sperling, 2005). After 1985, efficiency improvement slowed to about 1% per year, although that rate has increased since 2000.

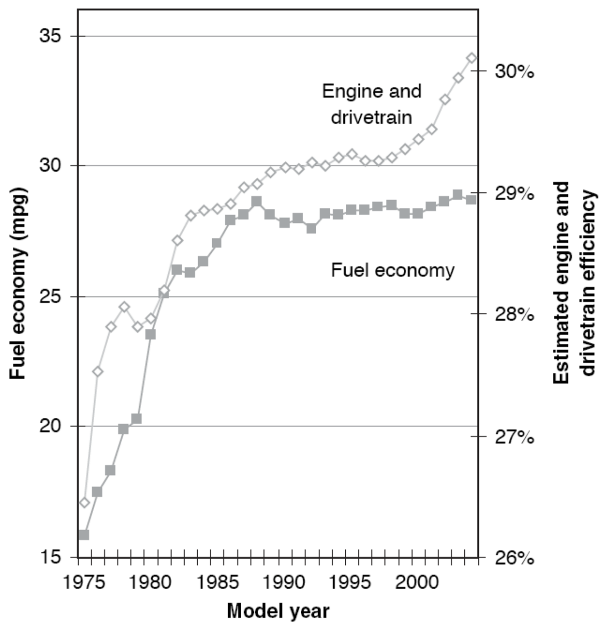

FIGURE 2. FUEL ECONOMY AND EFFICIENCY OF ENGINE AND DRIVE TRAIN (LUTSEY AND SPERLING, 2005)**.**

The continuity of this improvement—spanning the period of rising efficiency standards and then static standards - makes it difficult to attribute to CAFE. However, consideration of what end-use characteristics these efficiency gains were used for is revealing; from 1975 to 1985 vehicle weight dropped by about one-third and acceleration remained the same. After 1985, when CAFE standards stopped rising, efficiency improvements were used to power increasingly heavier vehicles, which could accelerate considerably faster. These trends are clearly shown in Figure 3.

If referencing this chapter, please cite:
G. Nemet (2012). Automobile Fuel Efficiency Standards. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

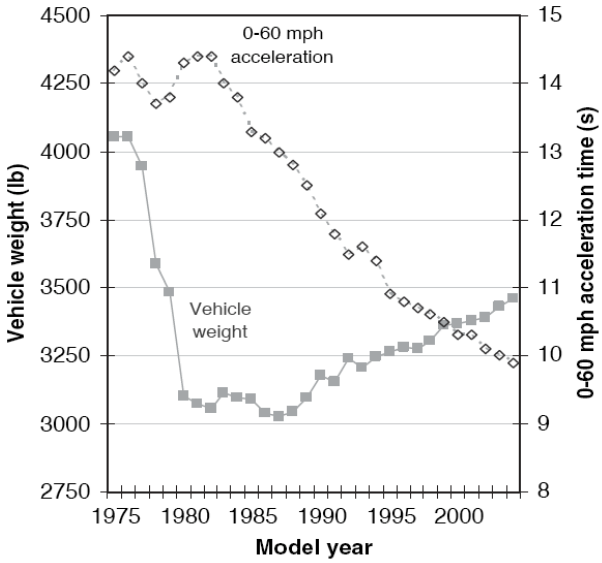

FIGURE 3. VEHICLE WEIGHT AND ACCELERATION (LUTSEY AND SPERLING, 2005)**.**

Although the use of lighter vehicles with stable acceleration characteristics accounts for about half of the miles per gallon improvement from 1975 to 1985, new technology accounts for the other half (Lutsey and Sperling, 2005). Technology adoption in passenger vehicles during and after the period of stringent CAFE standards also shows the effect on the direction of technological change. As shown in Figure 4, the adoption of fuel injection, front-wheel drive, and automatic transmissions with torque converter lock-up each went from installation in less than 10% of new vehicles in 1975 to 100%, 80%, and 60% respectively by 1985. Conversely, the adoption of air conditioning decreased during the same period (Figure 4). Seen over much longer time frames, this is a striking deviation from the long-term trend of technological change (Figure 5).

If referencing this chapter, please cite:
G. Nemet (2012). Automobile Fuel Efficiency Standards. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

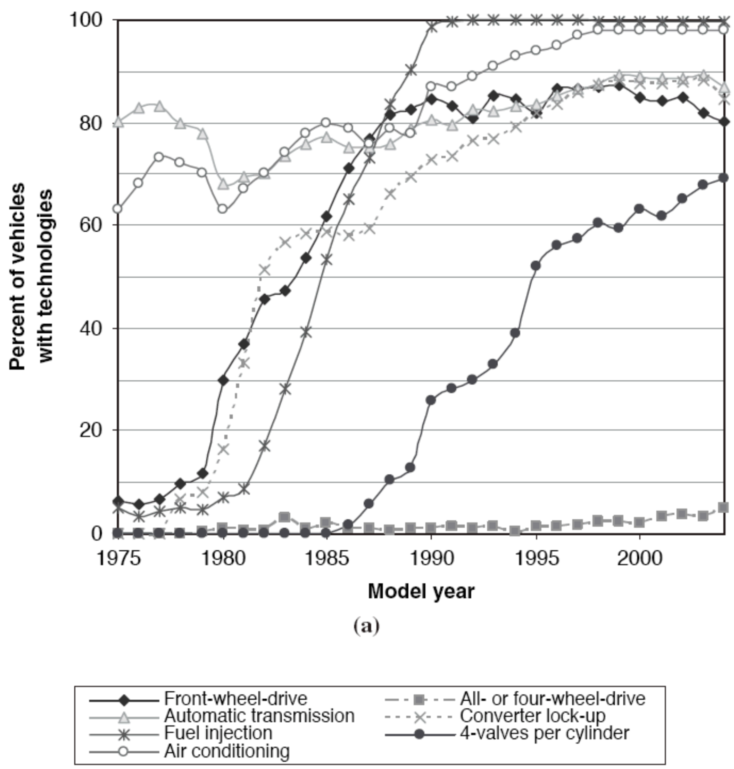

FIGURE 4. DIFFUSION OF PASSENGER VEHICLE TECHNOLOGIES (LUTSEY AND SPERLING, 2005).

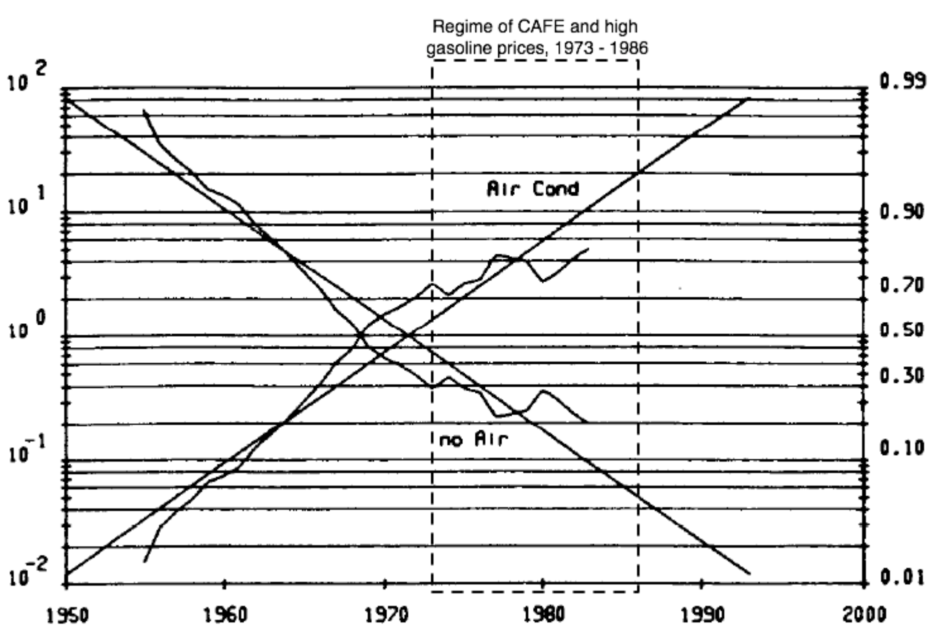

FIGURE 5. DIFFUSION OF AIR CONDITIONING IN VEHICLES. NOTES: THIS FIGURE REPRESENTS SUBSTITUTION OF ONE TECHNOLOGY BY ANOTHER. THE RIGHT HAND Y-AXIS REFERS TO THE MARKET SHARE FOR EACH TECHNOLOGY (F). THE LEFT HAND Y-AXIS IS F/(1-F), WHICH HELPS DEFINE THE LOGISTIC SUBSTITUTION CURVE DESCRIBED BY FISHER AND PRY. SOURCE: NAKICENOVIC, 1986; FISHER AND PRY, 1971.

2 FUEL EFFICIENCY IN EUROPE: VOLUNTARY AGREEMENTS & REGULATION

Until the late 1990s, Europe did not have EU-wide fuel economy regulations. In 1998, the European Commission (EC) and the European automobile manufacturers association, Association des Constructeurs Européens d'Automobiles (ACEA), signed an agreement to voluntarily reduce the CO_2 emission rates of new passenger cars sold in the EU (An and Sauer, 2004a). The Korean & Japanese Automobile Manufacturers Associations (KAMA & JAMA respectively) also signed similar voluntary agreements with the EC soon after. The industry committed to reducing average emission rates to 140 grams of CO_2 per km (gCO_2/km) by 2008 for ACEA and 2009 for KAMA and JAMA from the 1995 average of 187 gCO_2/km, with the possibility of extending the agreement to reduce the average emission rate to 120 gCO_2/km by 2012. The equivalence of these emission standards to fuel efficiency standards are shown in Figure 6.

Until 2007, the EC's strategy of reducing auto emissions was primarily based on three pillars: voluntary agreements with auto manufacturers; increased consumer awareness regarding fuel economy of cars, and market-oriented measures aimed at influencing motorists' choice. (Further details of the pre-2007 strategy can be found on the EC's Climate Action webpages). In December 2007, the EC adopted a proposal for reducing the average emission rates and eliminating the voluntary agreements with the industry asserting that the previous strategy had only brought limited progress toward the 120 gCO_2/km target for 2012. In December 2008, the EC established a new regulation to reduce the fleet average emission to 130 gCO_2/km through technology improvement related to vehicle efficiency and a further 10 gCO_2/km reduction through complementary measures (ICCT, 2010). These complementary measures can broadly be classified into two categories. The first category includes improvements in car components that have the highest impact on fuel consumption, such as efficient tires and air conditioners, tire pressure-monitoring systems and gearshift indicators. The second category includes measures to gradually reduce the carbon content of the fuel itself through increased use of bio-fuels and other alternative fuels (Amin, 2009; ICCT, 2010).

As indicated by Figure 6, along with Japan, Europe has the most stringent fuel economy standards in the world and as a result has the most fuel-efficient passenger vehicle fleet. The fuel economy standard has played a vital role in significantly reducing the average fuel consumption of passenger vehicles in Europe since 1995 (Zachariadis, 2006). Technologically, the main driver of the fuel efficiency improvement in Europe has been the rapid adoption of advanced technologies that have reduced vehicle mass and enhanced thermodynamic engine efficiency. The second driver is the widespread penetration of diesel vehicles. The share of diesel cars as a share of all new cars sold in Europe has increased significantly in the last decade - from about a quarter of new vehicles sold to over half (Figure 7). However, like the US case, it is difficult to ascertain what portion of this diesel vehicle penetration was due to fuel economy regulation. Apart from its combustion efficiency, other factors that have contributed to the rising share of diesel vehicles in Europe are fuel tax differentiation favouring diesel in most European nations and advancements in diesel vehicle technology (Pock, 2010).

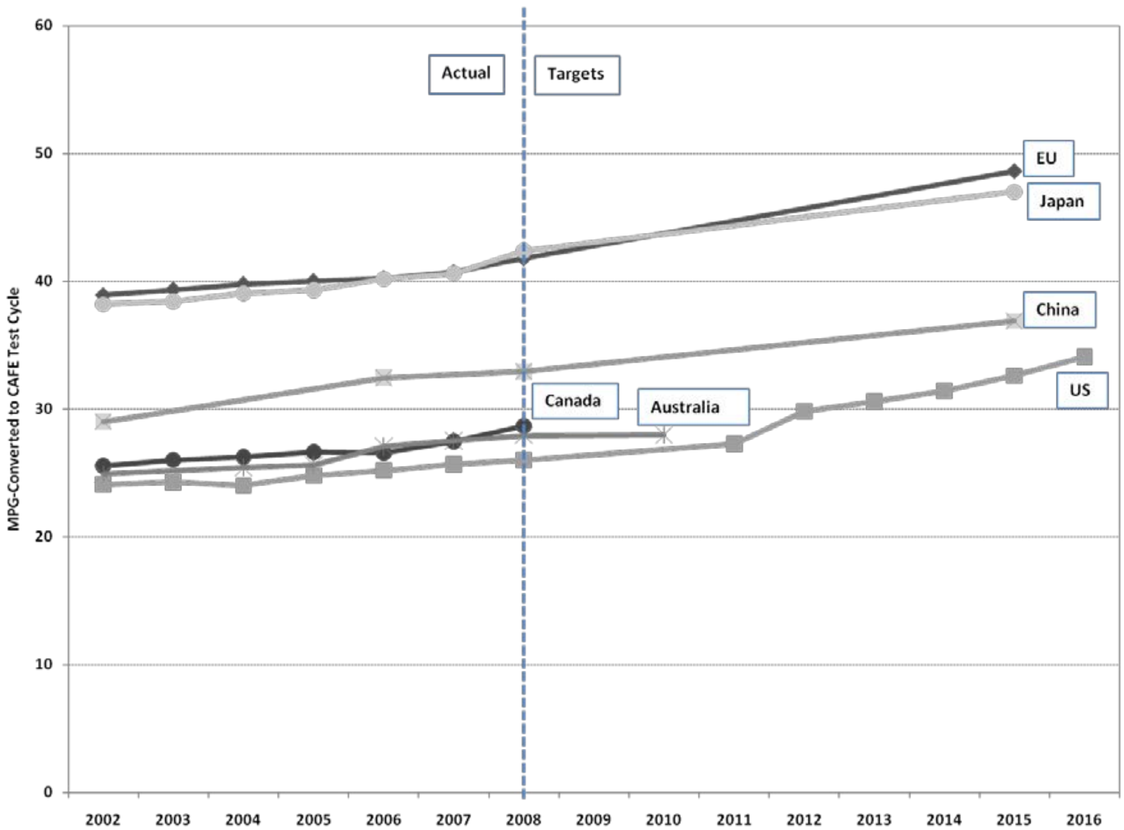

FIGURE 6. FUEL ECONOMY: HISTORICAL AND FUTURE TARGETS FOR 6 COUNTRIES (ICCT, 2010)**.**

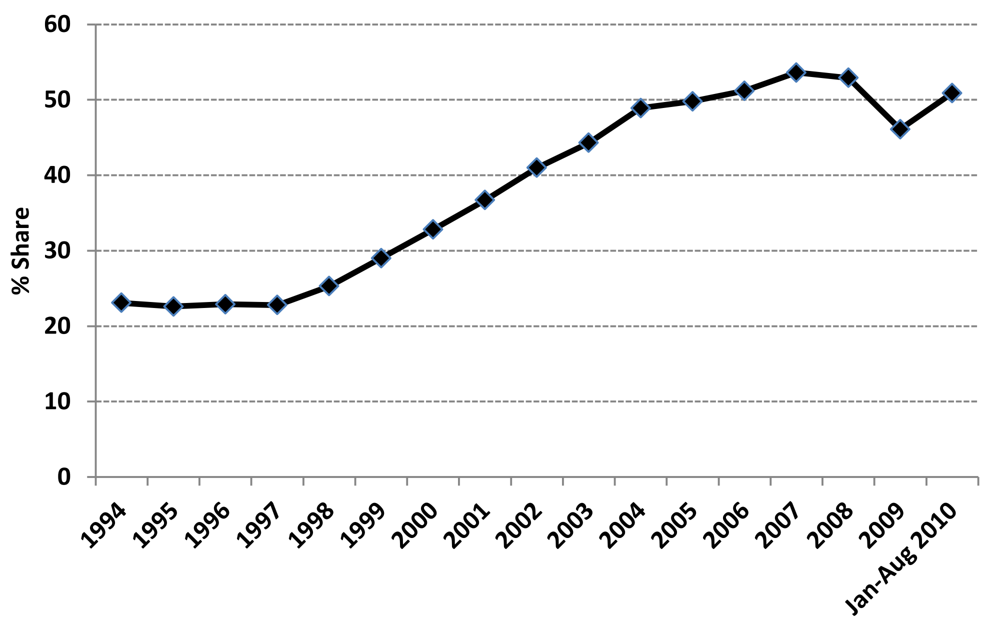

FIGURE 7. DIESELS AS A SHARE OF NEW PASSENGER CAR REGISTRATIONS IN THE EU-15 (ACEA). NOTE: THE EU-15 WAS THE 15 MEMBER STATE EU FROM JANUARY 1995 TO APRIL 2004. CURRENTLY THE EU HAS 27 MEMBER STATES.

If referencing this chapter, please cite:
G. Nemet (2012). Automobile Fuel Efficiency Standards. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

3 FUEL EFFICIENCY IN CHINA: RAPID IMPROVEMENTS & FLEXIBILITY ISSUES

China began regulating vehicle fuel economy relatively recently. Its first national fuel economy standard for new passenger vehicles based on weight category was issued in September 2004. This standard was to be implemented in two phases, taking effect in July 2005 (Phase 1) and January 2008 (Phase 2) respectively. The main goals of this regulation were to reduce China's increasing dependence on foreign oil, to encourage foreign automakers to introduce more advanced and fuel-efficient vehicle technologies, and to encourage domestic automakers to improve their standard (Oliver et al., 2009). China is finalizing the third phase of its fuel economy standard, which is expected to be officially issued by the Chinese government during 2011 and will be fully effective by 2015 (Wang et al., 2010; An et al., 2011).

Phase 1 of the Chinese fuel economy standard was established for passenger vehicles based on their weight by dividing them into sixteen categories (Oliver et al., 2009). Phase 1 standards were effective from July 2005 and July 2006 for new models and existing models respectively (Wang et al., 2010). Phase 2, which tightened the standards by about 10% and had only 15 weight classes, became effective on January 2008 and January 2009 for new and existing models, respectively. In addition to weight classification, vehicles were further classified either as "normal structure" or "standard structure" vehicles. Vehicles that had automatic transmission or at least three rows of seats were classified as "special structure" vehicles. Vehicles in this category were subject to less stringent standards than those falling in the "normal structure" category.

The fuel economy standards have brought about some impressive outcomes in the Chinese automotive market with respect to average fuel consumption and technology advancement (see Figure 6). Between 2002 and 2006, the normal structure vehicles and special structure vehicles reduced their average fuel consumption by 7-17% and 10-20% respectively (Oliver et al., 2009). The sales weighted corporate average fuel consumption (CAFC) for 34 companies that accounted for almost 90% of the passenger vehicle market decreased by almost 12% from 2002 to 2006.

The results of these standards from a technological perspective are noteworthy as well. About 800 highly inefficient domestic vehicle models were eliminated and inefficient technologies such as three-gear transmission and two-valve engines were phased out (Wang et al., 2010). The economy standards also increased penetration of vehicles with advanced technologies such as variable valves and multi-valve camshafts, electronic throttle control, multi-gear transmission, and parts made from lighter materials.

Similar to the case of Japan, the effectiveness of the fuel economy standards in China has been complemented well by fiscal policies. As shown in Figure 8, China has revised the excise tax levied on automakers on multiple occasions to encourage the manufacture of smaller engine vehicles and discourage the manufacture of larger ones (ICCT, 2007).

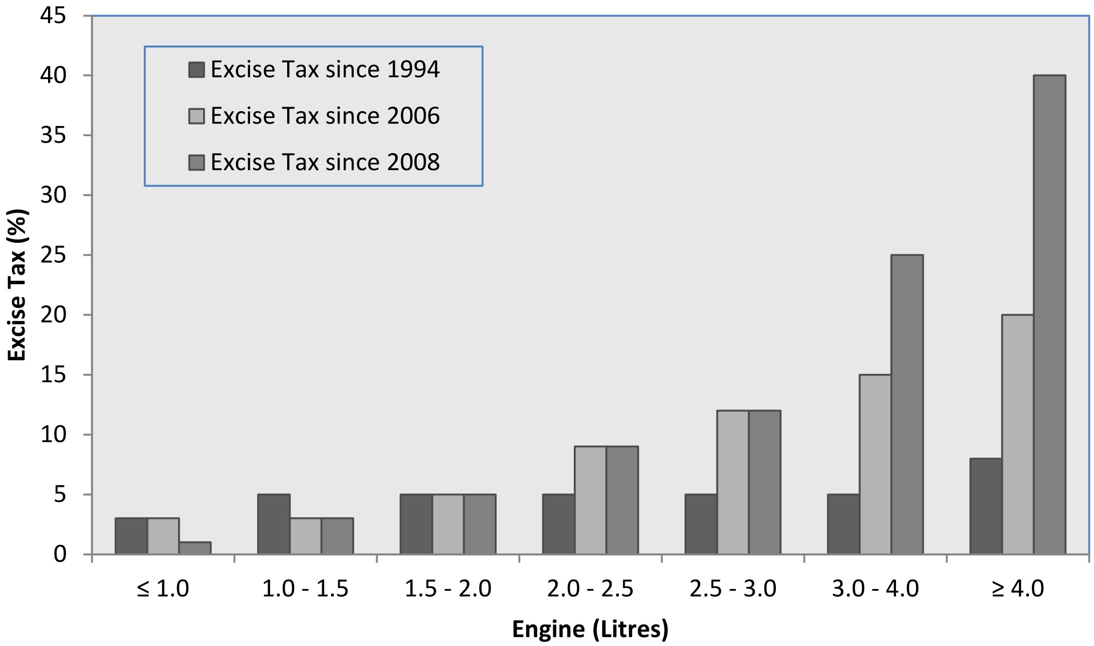

FIGURE 8. EXCISE TAX RATE IN CHINA BASED ON THE ENGINE SIZE OF THE VEHICLE (ZHANG, 2010)**.**

It is important to note that even though China's standards have been generally successful in meeting their goals, there are some shortcomings that need to be addressed. One is the lack of flexibility. Vehicles that fail to meet the standards for their weight class are to be eliminated from the market. Other countries set standards based on average fuel economy of the entire fleet, not a particular model. This flexibility allows for lower efficiency vehicles that may be important for some users, provided that above-standard vehicles offset these. In addition, unlike other nations, the Chinese standard does not include special provisions for alternative fuels. The Phase 3 standards are expected to be based on corporate average fuel consumption targets, which are more flexible. It is important to note that the inflexibility in the first two phases resulted in elimination of about 800 inefficient domestic vehicle models. In essence, the inflexibility achieved one of the main goals that a differential incentive-based system aims for: it gets the dirtiest vehicles off the road (Greene et al., 2005). This feature may be attractive for concerns such as local air pollution for which damages may be disproportionately caused by a small number of high polluting sources.

4 FUEL EFFICIENCY IN OTHER COUNTRIES

Japan, Canada, and Australia also have fuel efficiency standards for automobiles. Japan's are well in excess of the US standards while Canada and Australia have standards only slightly higher than those of the US (see Figure 6).

4.1 Japan

Japan established fuel economy standards for gasoline and diesel powered light-duty passenger and commercial vehicles in 1999. The weight-based Japanese standards were set using the "Top Runner" programme (discussed in detail in the *End-Use Efficiency (Japan)* case study). Under this programme, the target for each vehicle in a particular weight class is based on the performance of the most efficient vehicle in that weight class in the national market and a range of other factors (Onoda, 2008). Originally, there were a total of nine weight classes. The targets for diesel and gasoline vehicles were to be met by 2005 and 2010 respectively (An and Sauer, 2004b). The initial regulation was revised in 2001 to let the automakers accumulate credits in one weight class and use them in another weight class with certain limitations. In December of 2006, the fuel economy targets were revised upward to be met by 2015 and the weight classes were expanded from nine to sixteen (ICCT, 2007). This upward revision of the targets resulted because most of the vehicles sold in Japan by 2002 already met the standards set for 2010. The 2015 targets are expected to improve the average fleet fuel economy of new passenger vehicles from 13.6 km/L (or 32.0 mpg) in 2004 to 16.8 km/L (or 39.5 mpg) in 2015. Figure 9 shows the Japanese fuel economy targets for 2015 for each weight class (Onoda, 2008).

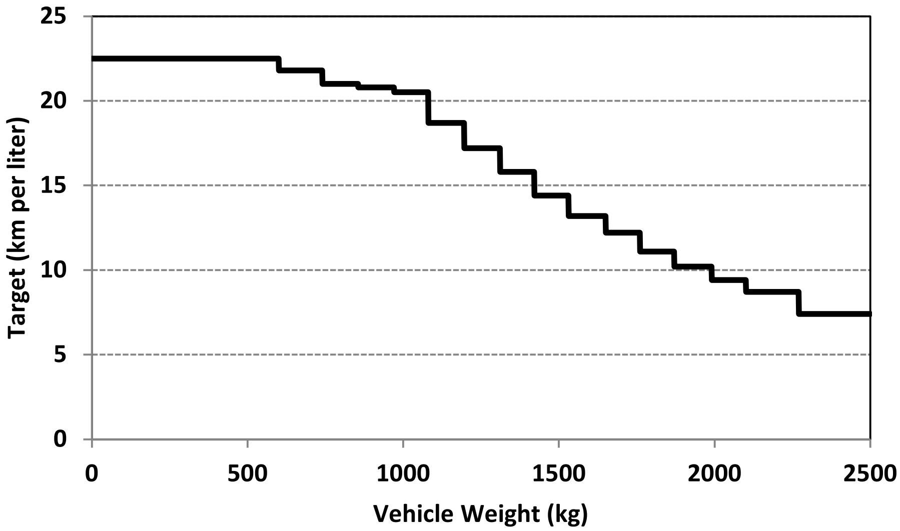

FIGURE 9. JAPANESE FUEL ECONOMY STANDARDS BY WEIGHT FOR 2015. NOTE: 1 KM/L = 2.35 MPG.

As indicated by Figure 6, Japan has the second most stringent fuel economy standards in the world. As a result of these standards, the fuel economy performance of vehicles in Japan has been impressive. Fiscal policies in Japan complement these standards, enhancing their effectiveness. A progressive tax system based on gross vehicle weight and engine displacement during purchase and registration of vehicles, encourages the purchase of lighter vehicles with smaller engines (ICCT, 2007). Additionally in 2004, Japan implemented the vehicle fuel efficiency certification programme to stimulate consumer interest in fuel efficiency performance and to encourage adoption of fuel efficient vehicles (Onoda, 2008). Under this programme, vehicles are certified in one of four categories, based on whether they meet the target or levels exceeding the target by 5%, 10% and 20%. Manufacturers can attach the certified stickers that indicate vehicles' fuel efficiency performance.

4.2 Canada

Canada's Company Average Fuel Consumption (CAFC) programme was introduced in 1976 to reduce the fuel consumption of the new passenger vehicle fleet. This CAFC programme is similar to the US CAFE programme. Two important differences, however, are that Canada's CAFC programme does not distinguish between domestic and imported vehicles, and compliance is voluntary unlike the US's CAFE standard (ICCT, 2007). The Canadian target has continued to match the US standard each year, with the Canadian vehicle fleet consistently outperforming the US vehicle fleet. This difference is primarily due to variation in tax provisions for fuel and vehicles, as well as to a variation on the ownership mix of vehicles in the two countries (An et al., 2007). For example, the ratio of passenger cars to light trucks is higher in Canada than in the US. The CAFC programme is complemented well by other measures taken by the Canadian federal and provincial governments. In 2007, the Canadian government introduced a programme called Vehicle Efficiency Incentive (VEI), which contained a rebate and a tax component based on vehicle fuel efficiency (ICCT, 2007). The rebate programme offers up to $2,000 for the purchase of an eligible fuel-efficient vehicle. The new excise tax, called the "Green Levy", is applied to new passenger vehicles with average fuel efficiency ratings of 18 mpg or less. In April 2010, the Canadian government issued a draft regulation to limit CO_2 emissions from passenger cars and light trucks. The regulation, which applies to models from 2011 to 2016, is expected to result in an average CO_2 emission rate of 153 gCO_2/km, a 20% reduction compared to the new vehicle fleet sold in Canada in 2007 (ICCT, 2010).

4.3 Australia

The Australian Federal Chamber of Automotive Industries (FCAI) has established several voluntary codes of practice for reducing fuel consumption of new passenger cars over the past several years (An and Sauer, 2004b). The first code was in effect between 1978 and 1987 and even though the industry reduced vehicle fuel consumption significantly, it still narrowly missed the voluntary target. The second code was enacted in 1996 and the FCAI members agreed to reduce average fuel consumption of passenger cars nationally to about 29 mpg by 2000. In 2003, a third voluntary agreement between FCAI and the government was enacted. This agreement requires the industry to reduce the fleet average fuel consumption for passenger cars by 18 percent in 2010 compared to the 2002 level. The actual average fuel consumption has been slightly higher than the target under all three agreements. This is mainly due to the fact that there are no specific enforcement mechanisms or non-compliance penalties. Australia introduced a mandatory fuel consumption labelling scheme in 2001, which required a fuel consumption label to be placed on the windscreen of all new cars (Onoda, 2008). These labels are required to show the vehicle's fuel efficiency and CO_2 emissions per km.

5 CONCLUSION

5.1 Efficiency, performance, and technological change

Automobiles are far more efficient in 2010 than they were in the 1970s - perhaps by a factor of three. However, automobile manufacturers have not used all of this efficiency improvement to reduce fuel consumption per distance travelled; they have used much of the gain in efficiency to satisfy other user preferences, notably for acceleration and for large and heavy vehicles. The allocation of efficiency improvements between reduced fuel consumption and enhanced performance characteristics has varied over time, across countries, and, of course, among vehicle types within countries and periods. Government policies have almost certainly influenced this allocation decision - both in vehicle design and in consumer choice among models. Rising fuel efficiency standards and fuel taxes have, in certain times and geographies, directed technological change toward reducing fuel consumption. However, rising affluence, consumer preferences, and low after-tax fuel prices have at times influenced technological change in the direction of improved performance.

When they are rising, and supported by taxation and rising market prices for fuels, fuel efficiency standards have also led to the adoption of lighter vehicles, as well as to the diffusion of important technologies in vehicle design. In the US, the CAFE standards had a real effect on technological change. The improvement in miles per gallon was accomplished not only by a shift to lighter, less powerful vehicles, but also by the adoption of new energy efficient technologies. Important examples include front-wheel drive and fuel injection in the 1970s. Attribution of these changes to the regulations, rather than gasoline prices, is less clear since the two are so well correlated. The effectiveness of CAFE may actually have been more important after 1985 when it served as a fuel economy floor in the face of persistently low gasoline prices.

5.2 Outlook

As of 2011, the outlook for fuel efficiency and technological change in the US looks more dynamic than it has been since the 1970s; still policy details and outcomes remain unsettled. In 2010, the National Highway Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA) issued a joint final rule that established a new National Program to improve fuel economy and reduce greenhouse gas emissions from passenger cars and light trucks from model year 2012 to 2016. The implementation of this new rule was primarily driven by the Energy Independence and Security Act of 2007 and further administrative action in 2009 (Anderson et al., 2010). Light duty vehicles must have an estimated combined average fuel economy of 29.7 and 34.1 mpg in 2012 and 2016 respectively. These standards, although more stringent, are more flexible. Automakers can earn credits by over complying and these credits can be traded with other manufacturers, banked for future compliance, or transferred between car and light truck fleets. In August 2011 the White House released its plan for even tighter fuel efficiency standards, developed in conjunction with US automakers and labor groups. However, these standards remain contentious and their eventual passage into legislation remains uncertain. Similarly, expectations of future fuel prices are also unclear. The steady and substantial rise in gasoline prices in the mid-2000s was followed by a period of exceptionally high price volatility, including a rapid decline with multiple years of lower prices, and a more recent rise.

The situation in Europe, China, and Japan is much different. Standards are higher and expectations for the next several years provide a much clearer view to increasingly more stringent fuel efficiency standards. One important source of difference is that concern about climate change provides a sustained source of support for fuel economy measures in these countries. Conversely in the US, climate change ranks low in polls of social priorities, and the dominant motivation for fuel efficiency legislation is energy security which tends to oscillate with crises and fuel prices.

Taxation of fuels and vehicles outside the US also supports the establishment of more stringent fuel economy standards. Technological outcomes are evident. One sees the dramatically higher adoption of diesel vehicles in Europe, but also efficiency improvements to tires and air conditioners, as well as gear shift indicators and tire pressure monitoring. In China, adoption of lighter materials, variable valves, electronic throttles, and improved transmissions have helped meet the more stringent standards.

6 FURTHER READING

For more background see Anderson et al., 2010; Greene, 1998; Lutsey and Sperling, 2005.

7 REFERENCES

Amin, A. T. M. N., 2009. *Reducing Emissions from Private Cars: Incentive measures for behavioural change*, Economics and Trade Branch, Division of Technology, Industry and Economics, United Nations Environment Programme.

An, F., Daniel, S. & James, S. C., 2007. International Comparison of Policies to Reduce Greenhouse Gas Emissions from Passenger Vehicles. *Driving Climate Change.* Burlington: Academic Press.

An, F., Earley, R. & Green-Weiskel, L., 2011. *Global Overview on Fuel Efficiency and Motor Vehicle Emission Standards: Policy Options and Perspectives for International Cooperation,* New York, United Nations Department of Economic and Social Affairs.

An, F. & Sauer, A., 2004a. *Comparison of Passenger Vehicle Fuel Economy and Greenhouse Gas Emission Standards Around the World,* Arlington, VA, Pew Center on Global Climate Change.

An, F. & Sauer, A., 2004b. *Comparison of Passenger Vehicle Fuel Economy and Greenhouse Gas Emission Standards Around the World.,* Arlington, VA., Pew Center on Global Climate Change.

Anderson, S. T., Fischer, C., Parry, I. & Sallee, J. M., 2010. Automobile Fuel Economy Standards: Impacts, Efficiency, and Alternatives. *National Bureau of Economic Research Working Paper Series,* **No. 16370**.

Davis, S., Diegel, S. & Boundy, R., 2008. *Transportation Energy Data Book,* Oak Ridge, TN, U.S. Department of Energy.

DOT, 2002. *Effects of the Alternative Motor Fuels Act CAFE Incentives Policy,* Washington, U.S. Department of Transportation (DOT); U.S. Department of Energy; U.S. Environmental Protection Agency.

Fisher, J. C. & Pry, R. H., 1971. Simple substitution model of technological change. *Technological Forecasting and Social Change,* **3**(1): 75-88.

Greene, D. L., 1998. Why CAFE worked. *Energy Policy,* **26**(8): 595-613.

Greene, D. L., Patterson, P. D., Singh, M. & Li, J., 2005. Feebates, rebates and gas-guzzler taxes: a study of incentives for increased fuel economy. *Energy Policy,* **33**(6): 757-775.

ICCT, 2007. *Passenger Vehicle Greenhouse Gas and Fuel Economy Standards: A Global Update.* , International Council on Clean Transportation.

ICCT, 2010. *Global passenger vehicle fuel economy and GHG emissions standards: April 2010 update.*, International Council on Clean Transportation.

Lutsey, N. & Sperling, D., 2005. Energy efficiency, fuel economy, and policy implications. *In*, 2005. 8-17.

Nakicenovic, N., 1986. The automobile road to technological change : Diffusion of the automobile as a process of technological substitution. *Technological Forecasting and Social Change,* **29**(4): 309-340.

NAS, 2002. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards,* Washington DC, The National Academies Press.

Oliver, H. H., Gallagher, K. S., Tian, D. & Zhang, J., 2009. China's fuel economy standards for passenger vehicles: Rationale, policy process, and impacts. *Energy Policy,* **37**(11): 4720-4729.

Onoda, T., 2008. *Review of International Policies for Vehicle Fuel Efficiency*, International Energy Agency (IEA).

Pock, M., 2010. Gasoline demand in Europe: New insights. *Energy Economics,* **32**: 54-62.

Wang, Z., Jin, Y., Wang, M. & Wei, W., 2010. New fuel consumption standards for Chinese passenger vehicles and their effects on reductions of oil use and CO2 emissions of the Chinese passenger vehicle fleet. *Energy Policy,* **38**(9): 5242-5250.

Zachariadis, T., 2006. On the baseline evolution of automobile fuel economy in Europe. *Energy Policy,* **34**: 1773-1785.

Zhang, Z., 2010. Is it fair to treat China as a Christmas tree to hang everybody's complaints? Putting its own energy saving into perspective. *Energy Economics,* **32**: S47-S56.

8 ACKNOWLEDGEMENTS

Thanks to Bickey Rimal and Peter Braden for excellent research assistance.