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Assessing Canada's 2025 passenger vehicle greenhouse gas standards: Technology deployment and costs

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Background

This paper is part of a series that reports on an analysis done by the ICCT of Canada-specific technology pathways, costs, and benefits of Canada's 2025 passenger vehicle greenhouse gas standards, as finalized in 2014 (Regulations Amending the Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations, 2014). The analysis compares the standards presently in force to following the Trump Administration's proposal to roll back the 2025 U.S. fuel economy and greenhouse gas emissions standards.

Such a comparison is relevant because Canada's passenger vehicle fuel efficiency regulation is structured in such a way as to tie Canada's standards directly to the U.S. regulation. If Canada maintains its regulatory status quo, its light-duty vehicle (LDV) greenhouse gas standards will automatically retreat to whatever level is the final outcome of the U.S. rulemaking process initiated in August 2018.

The ICCT analysis uses the U.S. Environmental Protection Agency's Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA) version 1.4.56, updated most recently to support the technical assessment for the midterm review (U.S. Environmental Protection Agency [EPA], National Highway Traffic Safety Administration [NHTSA], and California Air Resources Board [CARB], 2016). The model evaluates the relative costs and effectiveness (CO_2 emission reduction) of vehicle technologies and applies them to a defined baseline vehicle fleet to meet a specified CO_2 emissions target.

For a detailed discussion of the Canadian baseline vehicle fleet defined for this project, a description of the OMEGA model and the inputs to the Canada-specific analysis, and an evaluation of consumer benefits and social/environmental benefits of the two regulatory alternatives, see the other papers in this series (Posada, Isenstadt, Sharpe, & German, 2018a, 2018b, 2018c).

Results of OMEGA modeling of the Canadian LDV fleet

This paper presents the core results of the ICCT analysis: the projected technology deployment in the Canadian vehicle fleet, with associated per-vehicle costs, by car and truck class and by vehicle type. (See Appendix I for a brief description of the technologies.)

Two scenarios were studied: maintaining GHG 2025 targets for MY 2021–2025 vehicles, and freezing GHG standards at 2020 targets, beginning with MY 2021. In the first, technology projections and costs were calculated for a Canadian LDV fleet that follows the GHG 2025 standards. The second presents a Canadian LDV fleet that harmonizes with the U.S. MY 2021–2025 targets frozen at 2020 levels.

The analysis shown here illustrates the projected least-cost technology pathway toward compliance. Manufacturers may choose other compliance pathways—including shifting their product mix to vehicles of larger or smaller size than those currently sold, or promoting SUV sales over compact cars—depending on marketing strategies, fuel price variations, local conditions and consumer preferences, and further technology development.

TECHNOLOGY DEPLOYMENT

Figures 1, 2, and 3 show the Canadian fleet-wide shift in technology market adoption rates from the baseline (CY 2016) for a selected group of technologies under the scenarios considered. Figure 1 compares the technology projections using EPA's technology-cost curves as defined in the midterm review evaluation and the projections using ICCT's updated technology-cost curves.

As the figure illustrates, most technologies progress in the same direction under both ICCT and EPA technology assumptions, although to varying levels of penetration. Notable exceptions are turbo-downsizing, stop-start, and mild hybrids. These three technologies are expected to increase in market share under EPA assumptions, but decrease or remain stagnant under ICCT assumptions. This is due, in part, to ICCT assigning greater cost-effectiveness of non-hybrid (naturally aspirated), Atkinson-cycle engines with cooled exhaust gas recirculation (EGR).

The OMEGA model does not consider performance factors that consumers weigh when purchasing a new vehicle. Since turbocharged engines have higher torque at lower engine speeds than naturally aspirated engines, consumers who favor forced induction may be willing to pay more for turbocharged engines. This consumer preference is not factored into the OMEGA model, which projects that naturally aspirated engines will be the least expensive path to compliance under ICCT's technology assumptions. Only 27% of 6-cylinder engines and 4% of 8-cylinder engines are turbocharged, suggesting that there is ample room in Canada's baseline fleet for downsizing engines.

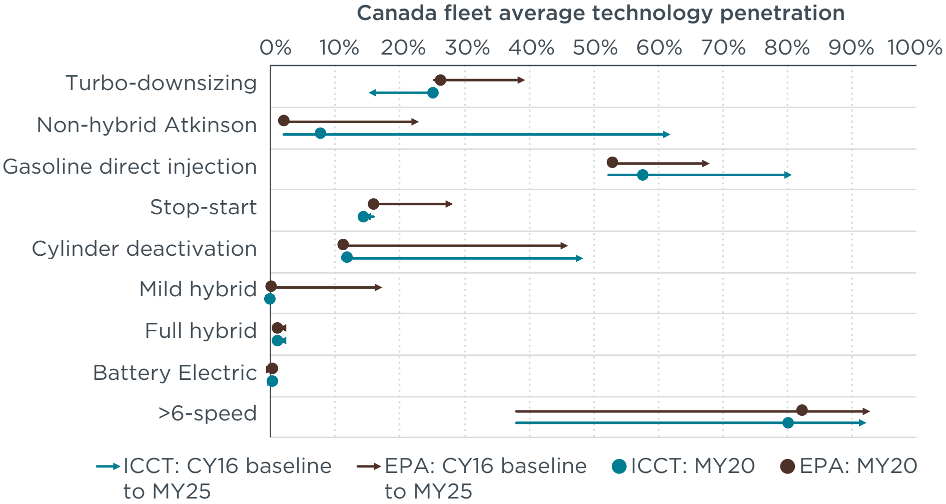

Figure 1. Comparison of projected Canadian LDV fleet average changes in technology penetration under EPA cost-effectiveness assumptions (brown lines), and under ICCT's cost-effectiveness assumptions (blue lines). Baseline (CY 2016) data shown as line start points; MY 2025 values shown as line arrowheads; MY 2020 values shown as dots.

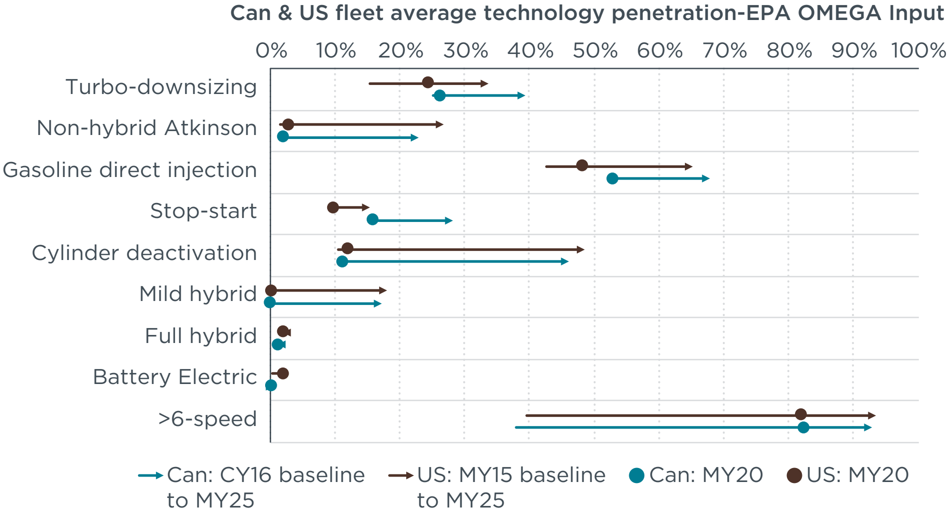

Figure 2. Comparison of estimated technology adoption rates in Canada (blue) and the U.S. (brown) under EPA cost-effectiveness inputs. Baseline (CY 2016 or MY 2015) data are shown as line start points; MY 2025 values are line arrowheads; MY 2020 values are dots.

The differing projections from ICCT and EPA inputs indicate that there are many possible ways in which automakers can both meet GHG standards and consumer performance expectations.

Figure 2 compares the Canadian market projections with those of the United States under EPA cost assumptions. Figure 3 shows the same comparison under ICCT cost assumptions. As noted in our description of the baseline fleet used in this project (Posada et al., 2018a), the Canadian baseline fleet is comprised of MY 2016 and MY 2017 vehicles, whereas the U.S. baseline fleet is comprised of MY 2015 vehicles. Consequently, some of the Canadian baseline vehicles already have more efficient technology than their counterparts in the U.S. baseline. This difference may have a small impact in the final projections, most likely toward lower costs for Canada.

The trends in Figures 2 and 3 mirror one another: the U.S. estimated technology update and related cost-effectiveness work just as well in Canada. In general, technology adoption rates increase as CO_2 targets become more challenging for manufacturers to meet.

The model estimates that almost all vehicles (> 97%) are going to receive least-cost technology options, such as low-rolling resistance tires, improvements to engine friction, electrification of accessories, and aerodynamic improvements.

Across all projections, the 2020 target would require only modest improvements in technology with respect to the Canadian CY 2016 baseline. This would be achieved with least-cost technology options, as listed above, and with improvements in transmissions. A small increase in GDI adoption is also projected. When compared to GHG 2025 targets, this unambitious technology shift would be reflected as small increases in cost and as small, fleet-wide benefits of avoided CO_2.

The OMEGA model also projects that for the average vehicle, most of the efficiency gains are expected to be realized by improvements to conventional technologies, with very little market uptake required for more advanced powertrains, such as those in full hybrids and electric vehicles. In the 2025 time frame, EPA's technology pathways (Figure 2) lead to some 48 volt mild-hybridization (15%–20% market share) and a much lesser role for full-hybrid and battery-electric technologies. The ICCT update of those pathways (Figure 3) results in little hybridization of any kind, due primarily to the lower costs and higher benefits forecasted for conventional technologies.

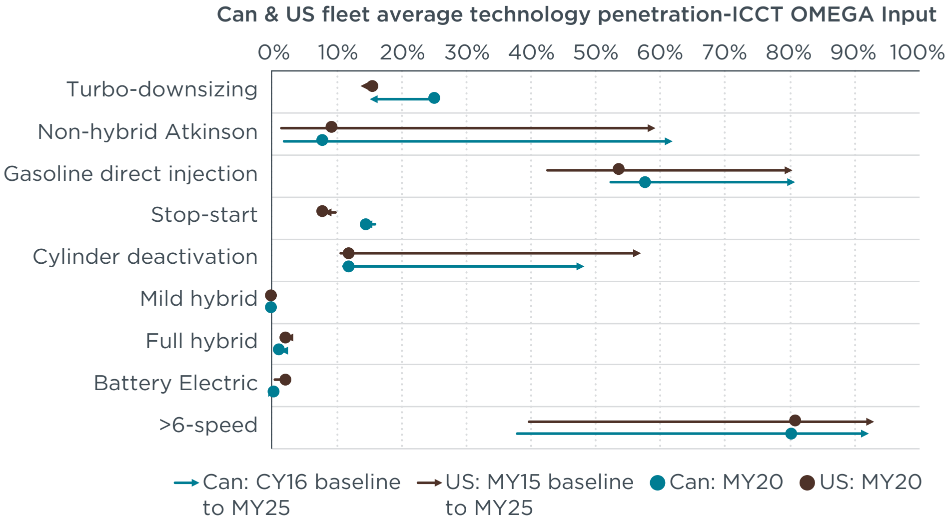

Figure 3. Comparison of estimated technology adoption rates in Canada (blue) and the U.S. (brown) under ICCT cost-effectiveness inputs. Baseline (CY 2016 or MY 2015) data are shown as line start points; MY 2025 values are arrowheads; MY2020 values are dots.

Turbocharged and downsized GDI engines and high-compression Atkinson-cycle engines

A look at the projected fleet wide market share (Figures 2 and 3) shows that the large majority of naturally aspirated engines are projected to be replaced by high-compression, Atkinson-cycle engines or by turbocharged and downsized GDI engines to comply with 2025 targets.

High-compression Atkinson-cycle engines (e.g., Mazda's Skyactiv or Toyota's Dynamic Force gasoline engines) are projected to gain a large market share across Canada's fleet. Note that this type of engine technology is more predominant in the model run using ICCT inputs (Figure 3), as this relatively new technology is opening up a low-cost option to achieve higher efficiency.[1] Lutsey et al. (2017) discuss how the costs and benefits of Atkinson-cycle engines are estimated.

Stop-start systems

As shown in Figures 2 and 3, stop-start already enjoys greater market share in Canada's baseline than in the United States. The U.S. baseline has about 9.8% of models with stop-start. The Canadian baseline, which is slightly newer, has around 16% of models with stop-start. Thus, the greater market share in Canada is due to the more recent and advanced Canadian baseline fleet, as well as some consumer preference for vehicles that happen to

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[1] The actual future product mix may be affected by possible consumer preferences for the performance of turbocharged engines, which the OMEGA model does not account for.

have stop-start. Using EPA inputs, the stop-start market share is expected to increase nearly 75% by 2025 and make up 28% of the overall fleet. Using ICCT inputs, however, stop-start market share is expected to decrease about 10% by 2025. Again, the ranges of cost-effectiveness of various technologies leads to different projected outcomes by 2025. But these differences signal a wide variety of paths manufacturers can choose from in order to comply with the standards.

Cylinder deactivation

Cylinder deactivation promises to be a very cost-effective technology in general, but especially for large engines that automakers cannot or will not downsize. At low engine loads, deactivating cylinders allows the engine to run as though it were a much smaller engine, saving fuel. EPA's technology inputs assumed that these engines would have a fixed bank of cylinders that would be deactivated. But with more recent technology that allows for dynamic cylinder deactivation, the number and timing of cylinders deactivated is flexible and variable. This dynamic control extends the engine's operating range and further increases its effectiveness. The market share of cylinder deactivation is expected to grow from about 11% in 2016 to around 47% by 2025.

48V mild hybrids

The 48V mild hybrid offers roughly half of the benefits of a full hybrid at only a third of the cost. These vehicles permit acceleration assist and turbo lag reduction, both of which could prove attractive to the Canadian fleet, which, as of CY 2016, is more than 25% turbocharged. Mild hybrids also enable more robust stop-start, regenerative braking, engine downspeeding, sailing, and shifting the burden of some accessories from the engine to the electrical system. Combined, these effects can dramatically reduce urban driving fuel consumption. EPA inputs predict that mild hybrids will occupy 17% of the market by 2025. ICCT inputs, on the other hand, show fleet-wide compliance without the use of any mild hybrids. The difference in projected outcomes is due to ICCT's assumptions that improvements in conventional combustion technologies—like those discussed above—will be more cost-effective than those used in EPA's assumptions.

Table 1. Level of mass reduction/lightweighting in the OMEGA model's GHG 2025 projections for Canada and the United States, using both ICCT and EPA technology cost-benefit inputs. Baseline masses shown for reference.

		Canada	US
EPA Inputs	**Cars**	6.1%	6.0%
	Trucks	9.0%	10.2%
	Fleet	**7.6%**	**8.0%**
ICCT Inputs	**Cars**	6.4%	6.4%
	Trucks	10.2%	11.5%
	Fleet	**8.4%**	**8.8%**
Baseline Mass (kg)	**Cars**	1,480 (-2.6%)	1,520
	Trucks	2,010 (-0.8%)	2,026
	Fleet	**1,757 (+1.2%)**	**1,736**

Electric vehicles

Regardless of the technology cost assumptions, Figures 2 and 3 illustrate that battery-electric vehicles play little, if any, role in meeting the GHG 2025 standards in Canada, as well as in the United States. The standards simply do not require widespread uptake of EVs. Should national-level and local-level governments desire broad adoption of electric vehicles, additional strategies and incentives would be required beyond the CO_2 standards.

Lightweighting

Though not shown in the preceding figures, lightweighting, or weight reduction, is an extremely cost-effective technology for reducing CO_2 emissions. Every 10% reduction in weight is estimated to provide a 5%–7% reduction in CO_2 emissions. And reducing mass with design optimization and some material substitution can lead to net cost savings. Lightweighting results are tabulated in Table 1. The results of the OMEGA modeling are included for comparison.

Under both ICCT and EPA assumptions, the Canadian fleet requires slightly less lightweighting than the U.S. fleet. Part of this slight difference is due to the Canadian baseline vehicles' lower masses (curb weights). The average Canadian car in the CY 2016 baseline is 2.6% lighter than the U.S. car in its MY 2015 baseline. The average truck is 0.8% lighter in Canada than in the United States. The estimated fleet-wide average weight reduction in Canada is 7.5%–8.5% in 2025.

COST PER VEHICLE

When using the ICCT cost-benefit estimates, meeting the 2025 standards costs, on average, $865 (2015 CAD, $651 USD) more per vehicle than meeting the 2020 standards. The costs are higher when using EPA cost-benefit estimates, at $1,368 ($1,029 USD) more per vehicle for meeting the 2020 standards. Table 2 summarizes the results. The summaries include direct manufacturing costs, or the added costs incurred by manufacturers to meet the standards, as well as indirect costs, including overhead, marketing, distribution, warranty, and profit.

Figure 4 compares the total costs incurred by individual manufacturers on a fleet-wide basis for the Canadian fleet, under both ICCT's assumptions and EPA's more conservative assumptions.

In general, the total costs for Canadian manufacturers are quite similar to those incurred by the same manufacturers in the United States, as shown in Figures 5 and 6. Figure 5 shows that six automakers have slightly higher costs of compliance in Canada than in the United States. Most see a decrease in fleet-average costs, while the entire GHG emissions program is estimated to cost $28 less per vehicle in Canada than in the United States.

Table 2. Estimated total costs for the Canadian fleet to meet the 2025 standards compared to the costs of meeting the 2020 standards (2015 CAD).

		Costs to meet 2025 standards in 2025	Costs to meet 2020 standards in 2025	Difference (2025 vs 2020)
EPA inputs	**Cars**	$1,542	$331	$1,211
	Trucks	$1,972	$461	$1,511
	Fleet	**$1,766**	**$399**	**$1,368**
ICCT inputs	**Cars**	$1,045	$260	$784
	Trucks	$1,308	$369	$938
	Fleet	**$1,183**	**$318**	**$865**

The story is much the same under ICCT technology cost-effectiveness inputs, plotted in Figure 6. Six different manufacturers experience slightly higher compliance costs per vehicle in Canada than in the United States, but the majority see a cost decrease. The full fleet is estimated to cost about $8 more per vehicle in Canada than in the United States. As expected, the overall program cost is much lower under the ICCT technology assumptions than under those from the EPA.

The average compliance costs shown in Figures 5 and 6 are, in Canada, within 2% of the average costs in the United States. The slight differences stem largely from the differences in baseline fleet technology penetration and relative share of cars and trucks, which have different compliance costs. The difference in manufacturer car-truck split between the two countries also suggests compliance costs will differ for each manufacturer.

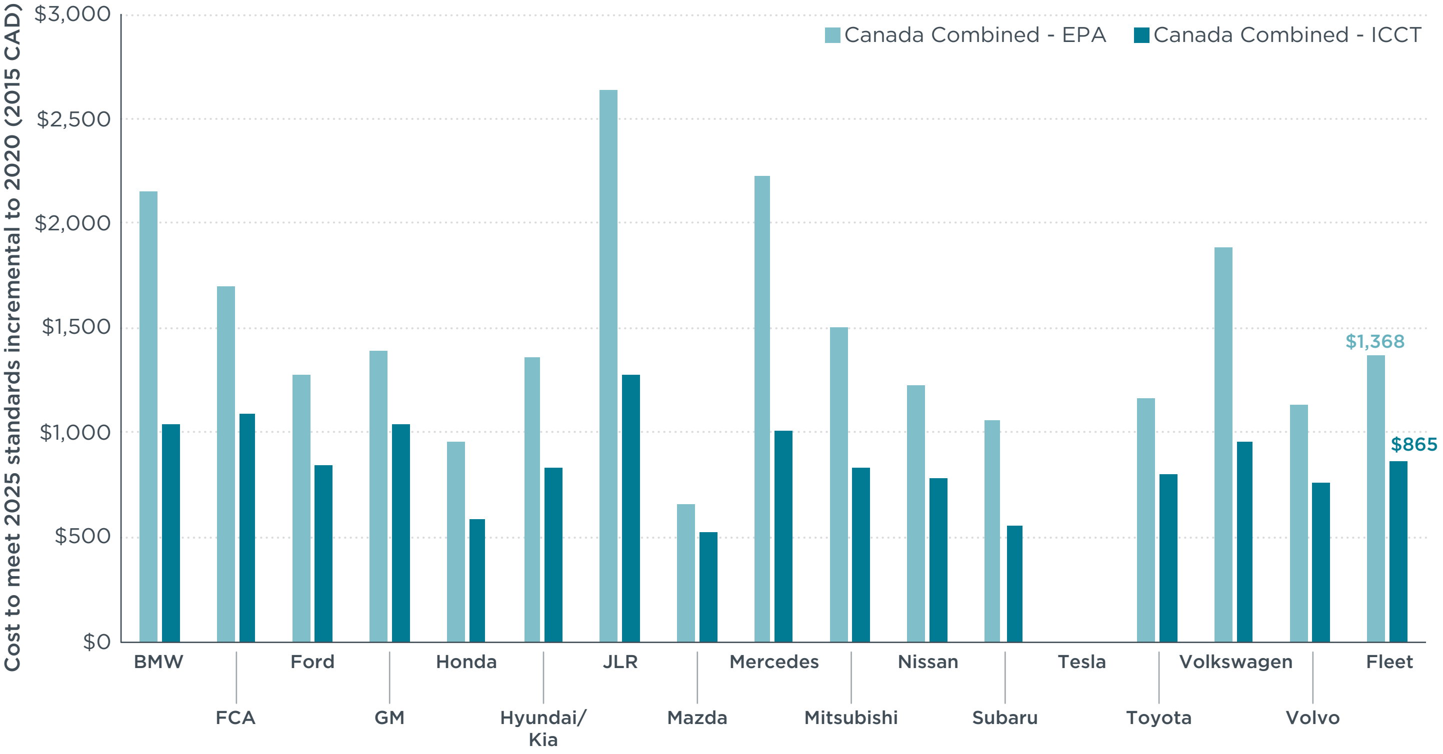

Figure 4. Comparison of manufacturer fleet-average total costs to meet the 2025 standards in Canada under ICCT (dark) and EPA (light) technology inputs compared to meeting the 2020 standards.

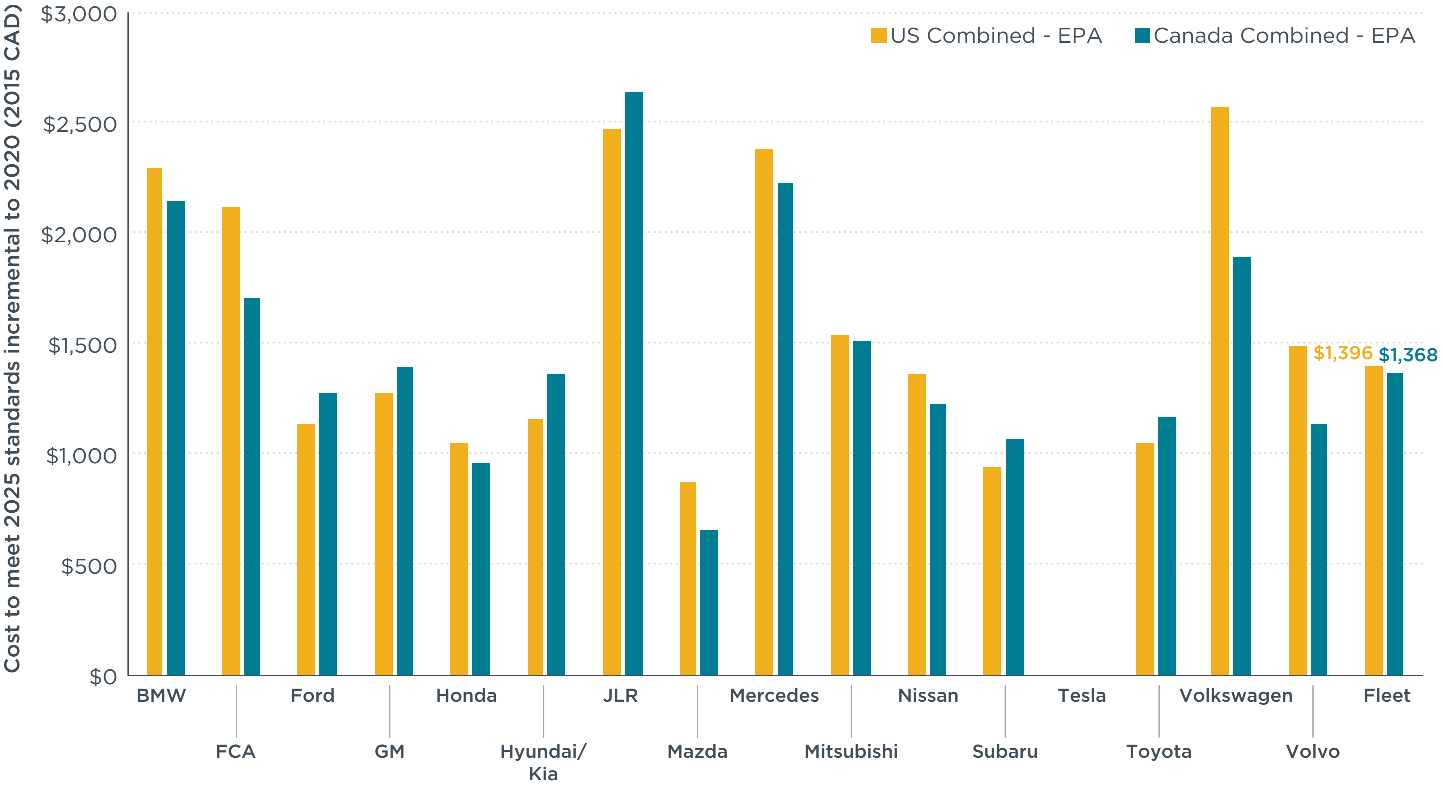

Figure 5. Comparison of manufacturer total costs to meet the 2025 standards in the United States (yellow) and in Canada (blue) under EPA's technology cost-effectiveness inputs when compared to meeting the 2020 standards.

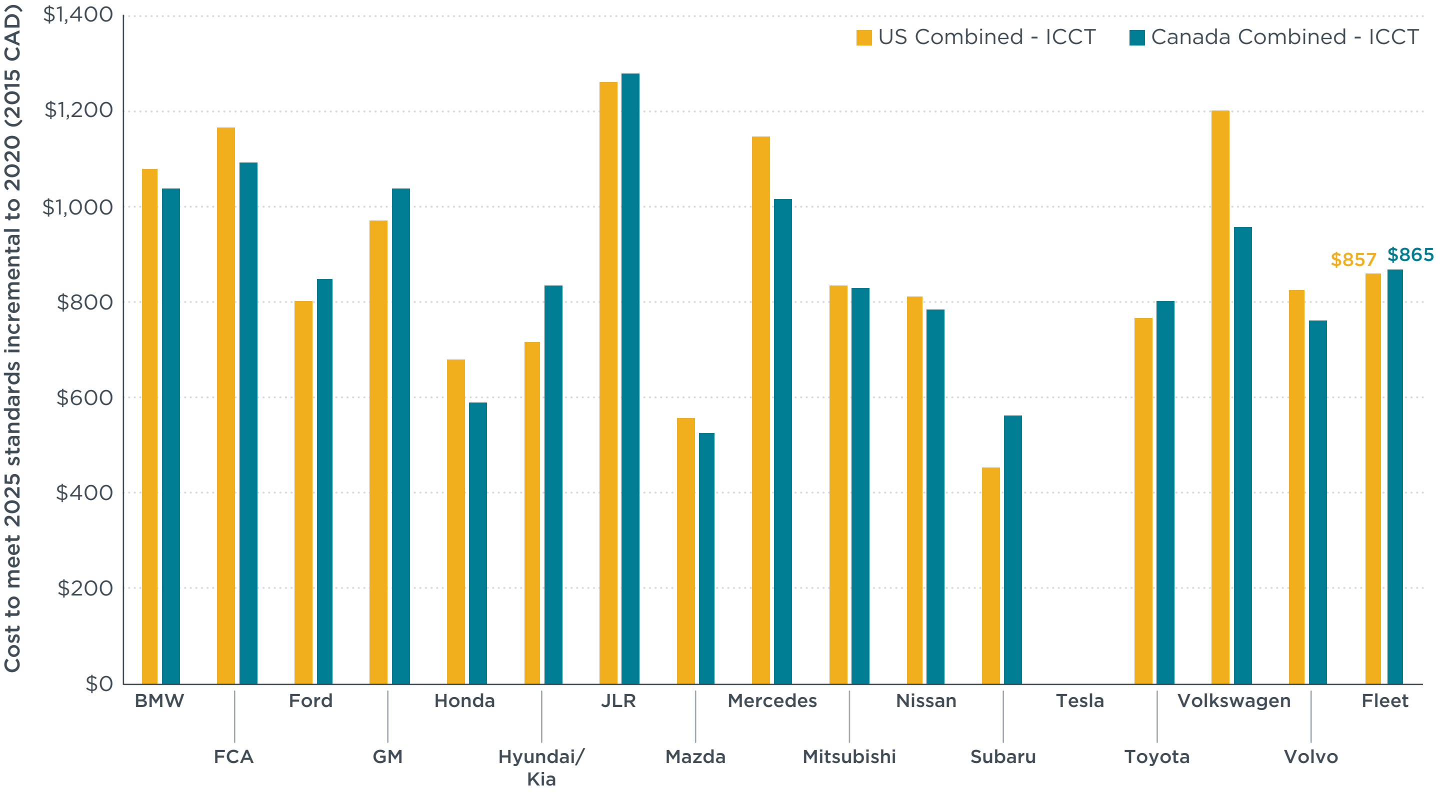

Figure 6. Comparison of manufacturer total costs to meet the 2025 standards in the United States (yellow) and in Canada (blue) under ICCT's technology cost-effectiveness inputs when compared to meeting the 2020 standards.

SUMMARY OF TECHNOLOGY DEPLOYMENT AND COST PER VEHICLE DISCUSSION

Table 3 summarizes the costs and technologies required to meet the 2025 standards in Canada by MY 2025. Both EPA and ICCT inputs lead to the straightforward conclusion that improvements to conventional powertrains make up the vast majority of technology required to meet the GHG standards in 2025. Such improvements—termed "advanced combustion" in Table 3—include Atkinson-cycle and Miller-cycle engines, cylinder deactivation, turbo-downsizing, and a suite of technologies that allow more precise control over engine and transmission operation. Furthermore, automakers have recently announced plans for additional advanced combustion efficiency technologies that were not incorporated into either EPA's or ICCT's inputs to the OMEGA model.[2] Although electrification and full hybridization are not necessary to comply with Canada's 2025 GHG standards, the popularity of plug-in hybrids and fully electric vehicles will likely grow as battery technology improves and costs decline. Many automakers have publicly committed to offering fully electric vehicles. Such commitments serve as further indication that manufacturers have many possible pathways in which to improve the efficiency of their fleets and meet future GHG emissions standards.

Table 3. Technologies and costs (2015 CAD) needed to meet the 2025 GHG standards for the Canadian fleet.

Area	Technology	EPA inputs	ICCT inputs
Advanced combustion	High compression ratio Atkinson/Miller	23.9%	61.8%
	Turbocharged and downsized	39.3%	15.1%
	Cylinder deactivation	46.1%	48.3%
Non-hybrid and non-electric		80.8%	97.8%
Hybrid	Mild hybrid	17.2%	0.0%
	Full hybrid	1.2%	1.2%
Electric	Plug-in hybrid electric	0.3%	0.3%
	Battery electric	0.5%	0.7%
Incremental technology cost from 2020 standards		$1,368	$865
Incremental technology cost from Baseline (CY2016)		$1,766	$1,183

Note that engines can have several advanced combustion technologies, as well as some level of hybridization or electrification. Very little hybridization is required to meet GHG 2025 standards. They can be met with a fleet that is comprised mainly of non-electric vehicles with advanced combustion engines (81% under EPA cost assumptions and 98% under ICCT cost assumptions).

Although the GHG 2025 standards by themselves will not significantly increase the number of zero-emission vehicles (ZEVs), ZEVs can help Canada achieve this goal. The ZEV standard in Québec serves as an example of mandatory requirements for automakers to sell or lease a minimum number of ZEVs per year.

Technology cost impact and sensitivity analysis of a bifurcated market

A bifurcated LDV market in North America would occur if Canada maintained its 2025 targets, along with California and the Section 177 states, while the remainder of the U.S. market kept GHG targets at 2020 levels out to 2025. Under this scenario, approximately 40% of the combined Canadian-U.S. market would be subject to 2025 targets by MY 2025, and the remaining 60% would be covered under 2020 targets until MY 2025.

The cost impacts of such a market were estimated by looking at the changes in production volumes and adoption rates for key fuel-efficiency technologies. The cost of producing technologies decreases as volume increases. Unit costs decrease as manufacturers refine their production processes, use less expensive materials, and simplify or improve component parts. When the standards of the combined market first splits in MY 2021, it is possible that the rate at which unit costs decrease will slow due to less production volume.

The ICCT made use of the individual technology cost reduction-by-learning curves developed by EPA and estimated the cost impact assuming potential volume sales reductions driven by a bifurcated North American market. Those technology cost-learning curves were developed by EPA for the 2012 and the 2016 regulatory impact assessment analysis (EPA, NHTSA, CARB, 2016), and were adopted for all the technology cost analysis included in the OMEGA model. For instance, the EPA estimates that in 2020, non-hybrid, Atkinson-cycle engines and cylinder deactivation will fall to about 90% of their cost the year they were first introduced—a 10% cost reduction by learning. By 2025, the cost of those two technologies will have fallen to about 85% of their original costs—a 15% reduction by learning (see Appendix II). Similarly, EPA estimates that by 2020, stop-start costs will fall to about 75% of their original value and, by 2025, drop to about 64% of their original value.

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[2] For example, Mazda will introduce a gasoline compression ignition engine in 2019, FCA's 2019 RAM pickup has a 48v hybrid system standard on the base V6 engine, and Infiniti's 2019 QX50 has a variable compression ratio, turbocharged engine.

To assess the impact of Canada's fleet belonging to a smaller market with a slower production volume rate, the ICCT estimated the cumulative production rate of technology adoption for 2020 and 2025, and then estimated how the slower production would affect the incremental cost of the technology. Each technology exhibits a particular cost impact for changes in production rates because each technology has different levels of complexity and is currently at different levels of market adoption levels. For example, stop-start costs, which, under the full-learning rate would reach about 64% of original cost by 2025, could fall to 70% of the original cost under a slower learning rate. This corresponds to a 9.2% increase in cost for stop-start in a split market. See appendix II for further details, along with a sensitivity analysis under higher and lower rates of learning.

Assuming that the learning rates decelerate according to the market split, under a 60% reduction in learning rate (i.e., only 40% of the market requires additional technologies) the majority of technologies experience a cost increase of 3% to 5%. Averaging the percent increases, weighted by estimated 2025 market share (figure 1) leads to an overall cost increase of 4.7%–4.9%, or $41–$67 (based on Table 3). The reason costs are affected so marginally if the market splits is that the most important technologies to meet the 2025 targets are well-known, broadly applied improvements to conventional vehicles.

A sensitivity analysis was applied to assess the impact of potential market size variations on technology costs. The market sizes were defined as retaining the GHG 2025 targets, and were evaluated from 0% to 100% of the total North American market.

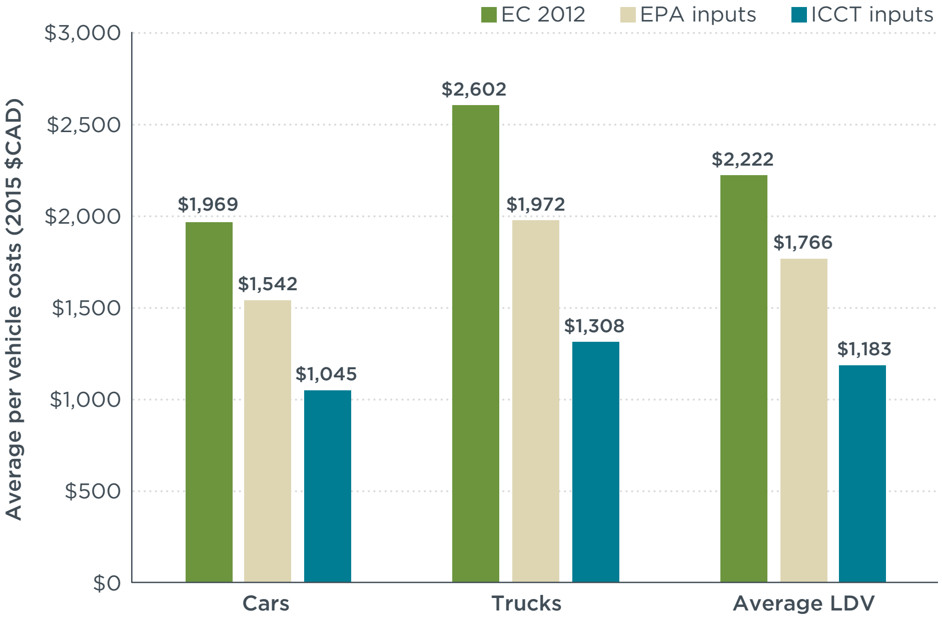

Figure 7. Comparison of 2012 Environment Canada (EC) estimated manufacturer total costs (corrected to 2015 CAD) to the updated EPA's and ICCT's technology cost-effectiveness inputs.

Even under the (highly unrealistic) worst case, in which technology costs no longer decrease after MY 2020, the average 2025 per-vehicle technology cost would only be about 8% higher than under full-scale learning. See appendix II for further details.

Comparison to Environment Canada's 2012 technology cost assessment

In December 2012, Environment Canada staff presented the results of a technical analysis supporting the proposal for harmonization with EPA's GHG rule covering MY 2017–2025, and consistent with the authority set by the Canadian Environmental Protection Act of 1999. The impact assessment team used the 2012 version of the OMEGA model to estimate the cost to comply for vehicles sold in Canada. The total incremental cost, in 2011 CAD, to comply with the MY 2025 targets (from MY 2016) was estimated by EC staff as $1,856 CAD for cars, $2,453 CAD for trucks, and $2,095 CAD for the average Canadian LDV (Regulations Amending the Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations, 2012). Figure 7 compares these original 2012 costs with the cost values found in this analysis. Note that the original EC 2012 values, in 2011 CAD, were corrected for inflation and converted to 2015 CAD (CPI = 1.0608).[3]

Improved technology cost-effectiveness inputs have significantly reduced the estimated cost of compliance with the MY 2025 standards in Canada. The 2016 EPA cost-effectiveness inputs bring EC's 2012 costs down by about 21% on average. When compared to the most cost-effective inputs from the ICCT analysis, the EC 2012 costs dip more than 47%.

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[3] Bank of Canada, Inflation calculator. Accessed on Sep 4th, 2018. https://www.bankofcanada.ca/rates/related/inflation-calculator/

Appendix I Vehicle efficiency technologies

Table 4. Technologies projected by the OMEGA model. Source: (EPA, NHTSA, CARB, 2016).

Technology	Code	Description
Turbocharging and downsizing	TDS 18 / TDS 24 / TDS 27	Turbocharging increases the specific power level, allowing a reduced engine size while maintaining performance. The OMEGA model considers three levels of boosting, 18-bar brake mean effective pressure (BMEP), 24-bar BMEP and 27-bar BMEP, as well as four levels of downsizing, from four cylinders (I4) to smaller I4 or I3, from V6 to I4 and from V8 to V6 and I4. Cooled EGR is also used for the 24-bar and 27-bar systems and the 27-bar system uses a 2-stage turbocharger. An 18-bar BMEP is applied with 33 percent downsizing, 24-bar BMEP is applied with 50 percent downsizing and 27-bar BMEP is applied with 56 percent downsizing. In addition to the efficiency benefits, turbocharging improves performance, especially in steep and high-altitude conditions.
Gasoline direct injection	DI	Gasoline direct injection injects fuel at high pressure directly into the combustion chamber. This provides evaporative cooling of the air/fuel charge within the cylinder, which allows for higher compression ratios and increased thermodynamic efficiency. GDI is generally paired with TDS to further support engine downsizing for improved efficiency.
Automatic transmissions	AT6 / AT8	A conventional AT is optimized by adding additional gears, which reduces gear ratio spacing and increases the overall gear ratio spread. This enables the engine to operate more efficiently over a broader range of vehicle operating conditions, with options for six and eight gears. In addition to the efficiency benefits, the higher number of gears improves performance, especially in steep and high-altitude conditions.
Manual transmission	MT	Improvements to MTs include six-speed manual transmissions, offering an additional gear ratio, often with a higher overdrive gear ratio, compared to the baseline five-speed manual transmission.
Advanced transmissions and dual clutch transmission	DCT6 / DCT8	DCTs are similar in construction to a manual transmission, but the vehicle's computer controls shifting and launch functions, instead of the driver. A dual-clutch automated shift manual transmission uses separate clutches for even-numbered and odd-numbered gears, so the next expected gear is pre-selected, which allows for faster, smoother shifting.
Advanced diesel	DSL	Diesel engines have good fuel-efficiency due to reduced pumping losses and a combustion cycle that operates at a high compression ratio, with a very lean air-fuel mixture. This technology requires the addition of relatively costly emissions control equipment, including NO_x after-treatment and diesel particulate filters (DPFs).
Start-stop system, 12 V	SS	Also known as idle-stop or 12V micro-hybrid and commonly implemented as a 12-volt, belt-driven integrated starter-generator, this is the most basic hybrid system that facilitates idle-stop capability. This system replaces a common alternator with an enhanced power starter-alternator, both belt-driven, and a revised accessory drive system.
Mild-hybrid electric vehicle	MHEV	MHEVs provide regenerative braking and acceleration assist capacity, in addition to idle-stop capability. A higher voltage battery is used, 48 V, with increased energy capacity compared to baseline automotive batteries. The higher voltage allows the use of a smaller, more powerful electric motor and reduces the weight of the motor, inverter, and battery wiring harnesses. This system replaces a standard alternator with an enhanced power, higher voltage, higher efficiency, belt-driven starter. The battery capacity is smaller compared to HEV batteries.
Hybrid electric vehicle	HEV	A full hybrid vehicle has larger capacity electric motors and batteries, enabling higher rates of regenerative braking energy and acceleration assist, as well as limited operation on the electric motor alone. An example of a hybrid vehicle is the Toyota Prius.
Plug-in hybrid electric vehicle	PHEV	PHEVs are hybrid electric vehicles with the means to charge their battery packs from an outside source of electricity (usually the electric grid). These vehicles have larger battery packs than non-plug-in hybrid electric vehicles with more energy storage and a greater capability to be discharged.
Electric vehicle	EV	EVs are vehicles with all drive and other systems powered by energy-optimized batteries charged primarily from grid electricity. EVs with 75-mile, 100-mile and 150-mile ranges have been included as potential technologies by the OMEGA model.
Low-rolling resistance tires	LRRT2	The second generation of low rolling resistance tires further reduce frictional losses associated with the energy dissipated in the deformation of the tires under load, compared to the now common LRRT available on baseline vehicles. LRRTs tend to be stiffer than conventional tires, giving them more resistance to rough roads.

High-efficiency gearbox	HEG	Includes continuous improvement in seals, bearings and clutches, super finishing of gearbox parts, and development in the area of lubrication, all aimed at reducing frictional and other parasitic load in the system for an automatic, DCT or manual type transmission
Improved accessories	IACC2	Second-generation improved accessories include high-efficiency alternators, electrically driven (i.e., on-demand) water pumps and cooling systems and alternator regenerative braking. This excludes other electrical accessories such as electric oil pumps and electrically driven air conditioner compressors.
Engine friction reduction	EFR2	The second generation of components to reduce engine friction includes low-tension piston rings, roller cam followers, improved material coatings, more optimal thermal management, piston surface treatments, and other improvements in the design of engine components and subsystems that improve engine operation.
Cooled exhaust gas recirculation	EGR	Adopted with boost, cooled EGR increases the exhaust-gas recirculation rate used in the combustion process to increase thermal efficiency and reduce pumping losses. Levels of exhaust gas recirculation approach 25% by volume in the highly boosted engines modeled.
Active aerodynamics	AERO	Reducing the aerodynamic drag of a vehicle reduces fuel consumption. The OMEGA model considers two levels of aerodynamic improvements. The first one considers changes to vehicle shape, which is constrained primarily by design considerations and should have zero implementation cost. The second option covers active aerodynamics technologies. One example of active aerodynamic technologies is active grill-shutters. Active grill shutters close off the area behind the front grill under highway driving conditions, reducing the vehicle aerodynamic drag and thus, fuel consumption.
High compression Atkinson-cycle engine	ATK	An Atkinson-cycle engine trades off decreased power for increased efficiency. Essentially, the intake valve remains open for a longer duration on the intake stroke and closes during the normal compression stroke. This results in an effective compression ratio that is less than the expansion ratio during the power stroke, and increases the geometric compression ratio. This allows more work to be extracted per volume of fuel as compared to a typical Otto-cycle engine. However, due to a smaller amount of trapped air mass (a consequence of air being forced out of the cylinder through the intake valve early in the compression stroke), the power density in the Atkinson cycle is lower than that of the Otto cycle. Increasing the compression ratio can partially compensate for this drawback.
Weight reduction	WR	Vehicle weight reduction, also referred to as lightweighting, reduces the energy needed to overcome inertial forces, thus yielding lower fuel consumption and GHG emissions. Lightweighting was modeled in OMEGA assuming per-vehicle changes of 0%, 5%, 10%, 15% and 20%. The maximum, 20%, was applied only to 2025 vehicles.

Appendix II Potential technology cost effects of a bifurcated North American market: Discussion

If Canada, California, and the Section 177 U.S. states maintain the GHG standards unchanged, approximately 40% of the combined Canadian-U.S. market would be subject to 2025 targets, while 60% would remain under the 2020 target through MY 2025.

In this situation, it is possible that rates of decrease in unit production costs will slow, due to slowed accumulated production volume. Typically, as cumulative production volumes increase, unit costs decrease as manufacturers learn to improve processes, use less expensive materials, and simplify or improve component parts. Generally, the newer the technology, the lower the cumulative production, and the less experience manufacturers have with it.

Through numerous studies contained in, and since, the initial 2012 rulemaking for the U.S. 2017–2025 greenhouse gas standards, the EPA refined its learning curves and where technologies lie on these curves (EPA, NHTSA, CARB, 2016).

Figure 8 illustrates this concept with key fuel-efficiency technologies required to meet the 2025 targets. The solid blue curve represents a technology that is already fully learned out by manufacturers. The cost in the year it is introduced (100%) does not change dramatically over many years, and it decreases by about 1.5% annually. The solid brown curve illustrates a technology that undergoes more learning after its introduction. Its costs decrease rapidly at first, then the rate of decrease slows to about the same rate as a fully learned technology.

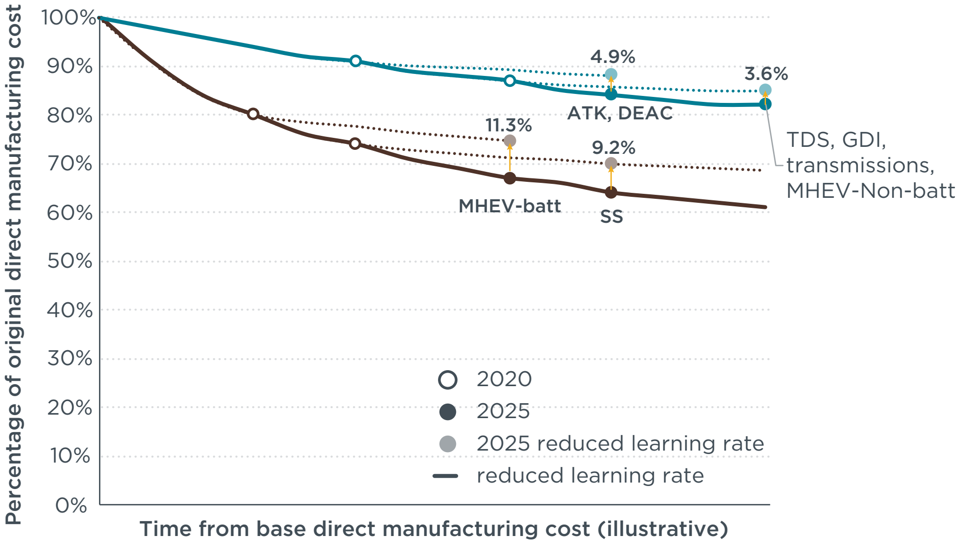

Figure 8. Full learning rates and reduced learning rates of fuel-efficiency technologies

Table 5. Percent increase in technology cost due to a North American market split

Technology	Percent change in cost in 2025	OMEGA estimated 2025 penetration, EPA assumptions	OMEGA estimated 2025 penetration, ICCT assumptions
Turbo-downsizing	3.6%	39.3%	15.1%
Atkinson cycle	4.9%	23.0%	61.8%
GDI	3.6%	67.9%	80.8%
Stop-start	9.2%	28.3%	14.3%
Cylinder deactivation	4.9%	46.1%	48.3%
MHEV*	6.4%	17.2%	0.0%
Transmissions	3.6%	92.8%	92.3%
Mass reduction	5.8%	7.6% MR fleet-wide	8.4% MR fleet-wide
Weighted average cost change		**4.9%**	**4.7%**

* MHEV costs are a weighted average of battery and non-battery component costs. (EPA, NHTSA, CARB 2016) estimates battery costs to be 36% of total MHEV costs.

Several technologies are located on the curves based on EPA's assumed rate of learning. For instance, EPA estimates that, in 2020, non-hybrid, Atkinson-cycle engines and cylinder deactivation will fall on the blue curve at about 90% of their original cost. By 2025, the cost of these two technologies will have fallen to about 85% of their original costs. Similarly, on the brown curve, EPA estimates that stop-start costs will fall to about 75% of their original value by 2020 and drop to about 64% of their original value by 2025.

As the figure shows, manufacturers have significant experience with a majority of technologies, and these technologies fall on the blue line.

The dotted blue and brown lines illustrate how the learning curves shift assuming production volume in a bifurcated market is reduced to 40%

of full learning rates (solid lines). The dotted lines decrease at a rate 40% as fast as the solid lines, indicating the rate of production volume accumulation is slashed by 60%. For example, stop-start costs, which, under the full learning rate would reach about 64% of original cost by 2025, could fall to 70% under this slower learning rate. This corresponds to approximately a 9.2% increase in cost for stop-start in a split market. The percent increase in cost and estimated 2025 market penetration of certain critical efficiency technologies are summarized in Table 5.

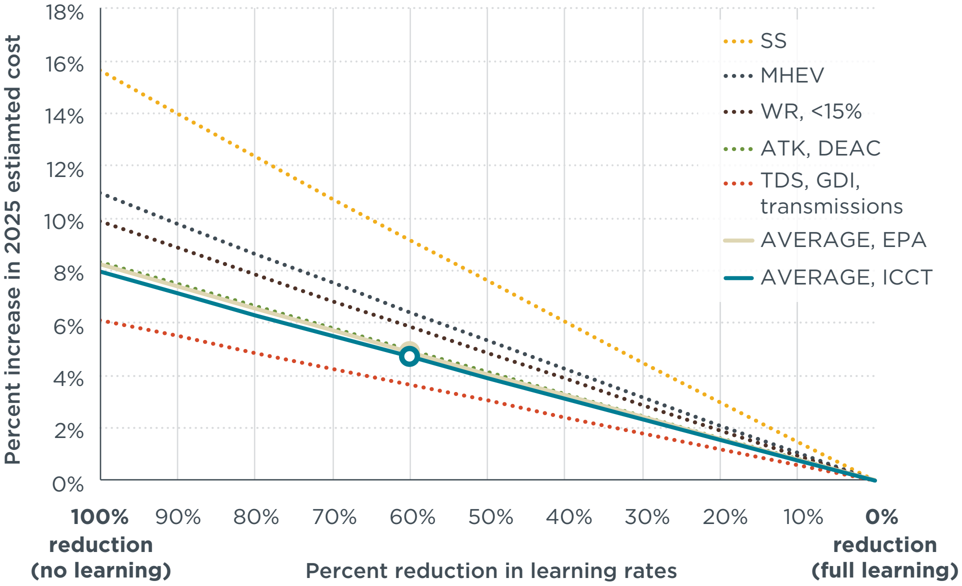

Figure 9. Percent increase in cost vs. percent reduction in learning rates

Thus, all technologies would experience less than a 10% increase in cost, and the majority experience only 3%–5% cost increase due to a market split. Averaging the percent increases shown in Table 5, weighted by market share in Figure 1, leads to an overall cost increase of 4.7%–4.9%. This percent increase corresponds to a dollar increase of $41–$67 CAD based on the costs in Table 3. The reason costs are affected marginally if the market splits is that the most important technologies to meet the 2025 targets are well-known, broadly applied improvements to conventional vehicles.

Furthermore, manufacturers apply technology for reasons other than fuel efficiency. Many technologies also provide performance, handling, and safety benefits, all of which consumers value. Even without GHG standards, consumer expectations of improved features and performance would influence manufacturers to apply these technologies to their vehicles. And manufacturers still must provide viable options for those consumers that do consider fuel economy in their purchase decisions. It is unlikely that a market bifurcation would lead to the level of reduction in learning, and increase in cost, hypothesized above. Though learning rates might indeed slow down, they likely would not drop by 60%.

Some individual technologies could show increased costs from a market split due to late market introduction and reduced cumulative production volumes. Examples of such technologies include dynamic cylinder deactivation, variable compression ratio, and spark-controlled compression ignition. To see how costs change as the market split changes, the learning curves were adjusted for varying levels of technology penetration across the combined Canada-U.S. market. The results of this analysis are plotted in Figure 9.

As the figure illustrates, at a 60% reduction in learning rates (corresponding to a market size of 40% of the combined Canada-U.S. market), costs increase by 4.7%–4.9%. If the market split is less drastic, cost increases are not as high, and eventually reach zero (no change in cost) as the reduction in learning rates go to zero. This outcome corresponds to no market split whatsoever, or a scenario in which all the technologies applied in Canada are also applied across the United States, regardless of a difference in GHG standards.

However, if the market were to split more dramatically, such that learning rates and cumulative production volumes decreased beyond 60%, costs would likely increase on average and for specific technologies. This outcome is representative of technologies with late market introductions and low market shares. Even in the worst case scenario of no learning after 2020, costs could be expected to increase by only 7.9%–8.2%. This would equate to approximately $68–$112 CAD in additional technology costs per vehicle. Costs at this level are 4 to 7 times lower than the annual fuel savings in the first few years of ownership. Thus, the added costs leave the payback period for both cash and loan purchase virtually unaffected (Posada et al. 2018c).

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