THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Transmissions

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Introduction

In 2012, the U.S. Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) finalized a joint rule establishing new greenhouse gas and fuel economy standards for vehicles.[1] The standards apply to new passenger cars and light-duty trucks, model years 2012 through 2025. A mid-term review of the standards will be conducted in 2017.

Assuming the fleet mix remains unchanged, the standards require these vehicles to meet an estimated combined average fuel economy of 34.1 miles per gallon (mpg) in model year 2016, and 49.1 mpg in model year 2025. The standards require an average improvement in fuel economy of about 4.1 percent per year.

The technology assessments conducted by the agencies to inform the 2017–2025 rule were conducted four to five years ago.[2] The ICCT is collaborating with automotive suppliers on a series of working papers evaluating technology progress and new developments in engines, transmissions, vehicle body design and lightweighting, and other measures that have occurred since then. Each paper will evaluate:

- How the current rate of progress (costs, benefits, and market penetration) compares to projections in the rule;
- Recent technology developments that were not considered in the rule and how they impact cost and benefits;
- Customer-acceptance issues, such as real-world fuel economy, performance, drivability, reliability, and safety.

This paper provides an analysis of transmission technology development and trends. It is a joint collaboration between ICCT, BorgWarner, Dana, the ITB Group, and FEV. The paper relies on data from publicly available sources and data and information from the participating automotive suppliers.

Table 1. Transmission technology compared to EPA/NHTSA 2017-2025 rulemaking. Rapid improvements in continuously variable transmissions and conventional automatics have compensated for slower than projected growth in the use of dual-clutch automated manual transmissions.

Behind RM / On schedule / Ahead of RM	Manufacturing cost	Efficiency benefits	Market penetration
Dual-clutch transmissions	Behind RM	Behind RM	Behind RM
Conventional Automatics	On schedule	Ahead of RM	On schedule
Continuously variable transmissions	Ahead of RM	On schedule	Ahead of RM

BACKGROUND

As recently as 2007, 4- and 5-speed automatic transmissions (ATs) dominated the vehicle market (>75% share). Lock-up torque converters had been widely used for over 20 years, but otherwise transmission efficiency had not improved significantly for decades.

1 US. EPA & NHTSA. *EPA/NHTSA Final Rulemaking to Establish 2017 and Later Model Years Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards*. Oct. 2012. Web. Jun. 2016. https://www3.epa.gov/otaq/climate/regs-light-duty.htm#2017-2025

2 U.S. EPA & NHTSA. *Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards*. Aug. 2012. Web. June 2016. https://www3.epa.gov/otaq/climate/regs-light-duty.htm#2017-2025 U.S. NHTSA. *Corporate Average Fuel Economy for MY 2017-MY 2025 Passenger Cars and Light Trucks: Final Regulatory Impact Analysis.* Aug 2012. Accessed June 2016. http://www.nhtsa.gov/fuel-economy

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These pre-2007 4- and 5-speed ATs were significantly less efficient than manual transmissions, due to losses in the torque converter and in the hydraulic systems inside the transmission. Since 2007, advances in torque converter lockup and hydraulics have improved so much that modern automatics have significantly reduced the gap in efficiency—in some areas eliminating it entirely.

A major breakthrough in transmission design was the development of the Lepelletier gear set system. This system enables additional gear combinations without increasing the number of clutches and gearsets. Six-speed Lepelletier automatics are usually slightly cheaper to manufacturer than 4-speed ATs,[3] and much cheaper than previously-designed 6-speed ATs. The additional number of gear ratios and increased ratio spans improves efficiency and performance by:

- enabling the engine to operate in more efficient regions of the speed/load curve;
- allowing more torque multiplication for vehicle launch, for better performance and engine downsizing;
- allowing lower engine rpm in top gear, for better efficiency and less engine noise.

Another important development in the last ten years is the dual-clutch transmission (DCT). Introduced in the European Union in 2003 on the Volkswagen DQ250, a DCT is essentially a manual (layshaft) transmission with the odd-numbered gears on one shaft and the even-numbered gears on a second shaft. Each shaft has its own clutch, and the gear on one shaft is disengaged at the same time the gear on the other shaft is engaged (see Figure 4). This design approaches the efficiency of a manual transmission, and offers the potential for smooth/quick shifts without torque interruption. One issue with the DCT is launch performance, as the vehicle must start moving while engaging a single clutch. Some manufacturers use a wet hydraulic clutch to solve this problem, although the need for continuous lubrication from the hydraulic system reduces efficiency somewhat. By contrast, dry DCTs use an accumulator and high-pressure hydraulics, which are used to shut off the hydraulic system.

The other major transmission type is the continuously variable transmission (CVT). Conventionally, this design uses a belt or chain to connect two pairs of concentric cones, with infinitely variable ratios between the maximum and minimum points. The efficiency of the transmission is reduced by friction losses related to clamping forces on the belt/chain (as well as high-pressure hydraulics), but the system allows the engine to always run at optimal speed/load points and thus maximizes engine efficiency. The efficient engine operation can more than offset the inefficiencies of the continuously variable transmission, especially during low-speed urban operation, and so produce overall fuel consumption reductions. CVTs were introduced in small volumes in the United States in 1989. However, the early designs suffered from belt limitations, which, in addition to high friction losses, restricted torque to such an extent that the transmission could only be used on smaller cars. Recent improvements in CVT controls and system design have reduced losses and expanded the torque capacity and ratio coverage, making the CVT another strong transmission competitor even for larger vehicles.

Technology history

According to the EPA fuel economy trends report,[4] manufacturers have been rapidly increasing the number of transmission gear ratios. Automatic transmissions (AT) considered by EPA in this report were divided into

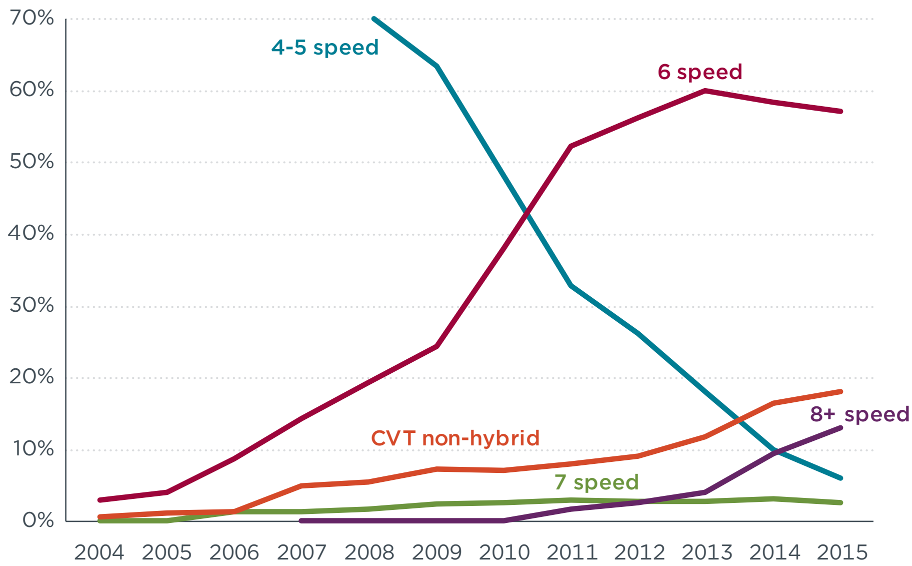

Figure 1. Historic market share of transmissions by number of ratios. (Source: U.S. EPA. *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015.* Dec 2015.)

3 FEV. *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis*. Report commissioned by ICCT. Forthcoming.

4 US. EPA. *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015.* Dec 2015. https://www3.epa.gov/otaq/fetrends-complete.htm

Table 2. U.S. market penetration trends (cars and light trucks).
(Source: U.S. EPA. *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015.*)

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015*
4–5 speed	95.7%	93.3%	86.9%	76.6%	70.7%	63.4%	48.1%	32.9%	26.3%	18.2%	10.0%	6.1%
6 speed	3%	4.1%	8.8%	14.4%	19.4%	24.5%	38.1%	52.3%	56.3%	60.1%	58.4%	57.2%
7 speed	0.2%	0.2%	1.4%	1.5%	1.8%	2.5%	2.7%	3.1%	2.8%	2.8%	3.3%	2.7%
8+ speed	—	—	—	0.2%	0.2%	0.1%	0.2%	1.7%	2.6%	4.1%	9.5%	13.2%
CVT non-hybrid	0.7%	1.3%	1.4%	5.1%	5.5%	7.3%	7.2%	8.0%	9.2%	11.8%	16.6%	18.2%
CVT hybrid	0.4%	1.0%	1.5%	2.1%	2.4%	2.1%	3.8%	2.0%	2.7%	2.9%	2.3%	2.5%
Manual	6.8%	6.2%	6.5%	5.6%	5.2%	4.8%	3.8%	3.2%	3.6%	3.5%	2.8%	3.6%
AT w/ lockup	91.8%	91.5%	90.6%	87.1%	86.8%	85.6%	84.1%	86.5%	83.4%	80.4%	76.7%	74.0%
AT w/o lockup	0.3%	0.1%	0.0%	0.0%	0.2%	0.2%	1.2%	0.3%	1.1%	1.4%	1.6%	1.7%

* 2015 values are preliminary estimates.

two groups: ATs with lockup torque converter (lockup bypasses the torque converter under certain conditions to improve fuel economy) and ATs without lockup. Chrysler introduced the first lockup torque converter in the 1980s. By 2000, all automatics had lockup capabilities. Thus, dual clutch transmissions (DCT) are likely the main example of automatic transmission technology without lockup reported in the trends report. Unfortunately, EPA does not (yet) track DCT production, so the data gathered for the trends report did not separate DCT into a distinct category. (EPA acknowledges that data inconsistencies for DCTs represent an area of future improvement in the trends report.) Assuming it is correct that all 6+ speed ATs without lockup referenced in the trends report are DCTs, then DCTs are about ~2% of the transmission market in 2015.

CVTs have seen a huge increase in market share in the last three years: an estimated 22.6% of new, non-hybrid cars and 11.8% of non-hybrid trucks were equipped with a CVT in 2015, about twice the market share in 2012. The share of planetary gear systems used in Toyota and Ford hybrid vehicles, commonly referred to as electric CVTs (e-CVTs), has remained relatively constant between 2% and 3% since 2007. Thus, all of the growth in CVTs is attributable to increased adoption of CVTs in conventional powertrains (i.e., non-hybrids).

Manual transmissions (5+ gears) have remained between 3% and 4% of the market since 2010. Although the number of gear ratios has increased in both manuals and automatics, the rate of increase is higher for automatics.

Historical estimates of costs and benefits

The National Academy of Sciences (NAS) 2002 report[5] estimated that a 5-speed AT would see a 2%–3% fuel consumption reduction over a 4-speed AT at a cost of $70–$154.

Table 3. Historical estimates of transmission technology costs and benefits as compared to the 2017-2025 rulemaking.

	NAS 2002		NHTSA 2008–2011		EPA/NHTSA 2017–2025		
	BENEFIT	COST	BENEFIT	COST	BENEFIT	COST	Relative to
5-speed AT	2%–3%	$70–$154	2%–3%	$73–$160	1.1%–$1.6%	$70	4-speed AT
6-speed AT	1%–$2%	$140–280	1%–$2%,	$146–291	0.7%–$0.8%	($81)	5-speed AT
8-speed AT	—	—	1%–$2%	—	4.8%–$5.7%	$47	6-speed AT
Aggressive Shift Logic	1%–3%	$0–$70	1%–3%	$0–$70	5.1%–7.0%	$22	No ASL
DCT	3%–5%	$70–$280	3%–5%	$73–$291	5.7%–12.6%	($176)–$28	4-speed AT
CVT	4%–8%	$140–$350	4%–8%	$146–$364	6.0%–8.7%	—	4-speed AT
Adv CVT	0%–2%	$350–$840	0%–2%	$364–874	—	—	CVT

NB: The agencies assumed that an 8-speed AT would only be applied to a 6-speed AT vehicle with towing requirement, all other vehicles transition from 6-speed DCT to 8-speed DCT. DCT effectiveness and cost estimates include both wet- and dry-clutch.

5 Transportation Research Board and National Research Council. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE)* Standards. Washington, DC: The National Academies Press, 2002. doi:10.17226/10172.

More speeds continue the trend of greater efficiency: a 6-speed AT will give 1%–2% fuel consumption benefit over a 5-speed AT. Since this transmission was estimated to cost an additional $140–$280 and would require complex controls, NAS 2002 predicted 6-speed ATs in 2015 to be limited to luxury/performance vehicles. As shown in Figure 1, today 6-speed ATs occupy more than 50% of the market, and 7-speed+ automatics and non-hybrid CVTs take up the next two largest shares.

CVTs were estimated to have 4%–8% fuel consumption reduction (relative to a 4-speed AT) at a cost of $140–$350 in NAS 2002, but would be limited by consumer acceptance issues and production cost. Advanced CVTs, with toroidal friction elements or cone-and-ring, were estimated to have 0%–2% benefit over a conventional (belt) CVT, at a cost of $350–$480; these are able to handle higher torques, essentially opening up heavier vehicle classes to CVT implementation.

For its 2008–2011 rulemaking,[6] NHTSA largely accepted the NAS 2002 report estimates without change, although NHTSA found there would be additional benefits from switching to a 7-speed or 8-speed AT.

The rapid increase in computational power in onboard computers and the development of the Lepelletier gear set has led to levels of transmission technology adoption well beyond what was expected in 2002 and in the 2008–2011 NHTSA rulemaking. For the 2017–2025 rulemaking, the agencies estimated that dual-clutch automated manual transmissions (DCTs/AMTs) and conventional ATs with more gears and aggressive shift logic (ASL) would both be relatively inexpensive: an 8-speed AT with ASL would cost only $58 more than a conventional 4-speed AT for a 11% or more reduction in fuel consumption. DCTs would be even cheaper and more efficient than comparable ATs. EPA/NHTSA also considered consumer acceptance issues for DCTs and CVTs. CVT driveability issues were expected to continue to plague consumers, while the agencies assumed that better control algorithms would mostly eliminate DCT consumer acceptance issues and DCTs would replace CVTs and most ATs by 2025.

EPA/NHTSA 2017–2025 PROJECTIONS: MARKET PENETRATION, COSTS, AND BENEFITS

In the agencies' analyses, aggressive shift logic (ASL) and early torque converter lockup (ETCL) were combined in the models with automatic transmissions ("improved automatic transmission control"—IATC). The logic behind that decision was that their addition requires only minor physical modifications and calibration software. DCTs use clutches instead of torque converters, and are thus considered automated *manual* transmissions. As such, only ASL is applied to DCTs in the agencies' models.

The agencies used two levels of ASL. Level 1, essentially downspeeding, involves earlier upshift (i.e., at lower rpm during acceleration). Level 2 ("shift optimization") requires constant monitoring of all gear options and selecting the gear that puts the engine in the most efficient operating zone. Level 2 ASL is expected to come with driver acceptability dilemmas—including shift busyness—despite the progress that is being made in making shifting smoother and less noticeable (e.g.,

Table 4. Rulemaking projected market share, costs, and benefits of considered transmission technologies

	2021	2025	2025 Direct Manufacturing Cost	Fuel consumption reduction	Relative to
Aggressive shift logic	—	—	$22	5.1%–7.0%	no tech
Early torque converter lockup	—	—	$20	0.4%–0.5%	no tech
High efficiency gearbox	44%	95%	$163	4.3%–5.7%	no tech
6-speed AT	7%	0%	-$11	1.7%–2.3%	4-speed AT
8-speed AT	30%	35%	$47	4.8%–5.7%	6-speed AT
6-speed DCT	12%	0%	-$176 (dry), -$124 (wet)	5.7%–8.1%	4-speed AT
8-speed DCT	42%	56%	-$24 (dry), $28 (wet)	9.7%–12.6%*	4-speed AT
6-speed MT	5%	4%	$173	2.0%–2.5%	5-speed MT
CVT	—	—	—	6.0%–8.7%**	4-speed AT

** 8-speed DCT shows a 3.9%–4.7% improvement over 6-speed DCT, and costs $153 more.*
***CVT benefit was calculated in EPA's Lumped Parameter Model,[7] and is not in the rulemaking.*

6 U.S. NHTSA. *Light Truck Fuel Economy Standard Rulemaking, MY 2008–2011*. March 2006. Web. June 2016. http://www.nhtsa.gov/fuel-economy

7 "Lumped Parameter Model (LPM) for Light-Duty Vehicles." *EPA OTAQ: Transportation and Climate*. Feb 23, 2016. Accessed June 2016. https://www3.epa.gov/otaq/climate/lpm.htm

through more available gears). The agencies assumed that suppliers can minimize these issues by MY 2017, and they noted that if the problems persist, effectiveness may be lower and costs may be higher. The Level 2 ASL fuel consumption reduction is relative to a transmission without any previously implemented ASL. Level 2 ASL is expected to improve efficiency over Level 1 by 4%–5%, at virtually no additional cost.

Locking the torque converter in ATs (and CVTs) eliminates slip to improve fuel economy. However, at lower vehicle speeds, torsional energy is harder to dampen, and it can create shaking or shuddering as it passes through the vehicle. Thus, early torque converter lockup (ETCL) and partial lockup require upgraded materials to withstand higher loads. For the rulemaking, "early lockup" is considered to occur at lower speeds than conventional lockup strategies. As before, driver acceptability (driveability, noise, vibration and harshness) is key to successful implementation.

Reduction of mechanical friction drives the improvements in gearbox efficiency. A number of strategies are available for reducing gearbox friction, and all are generally applicable to any type of transmission. The fuel consumption reduction of a high efficiency gearbox (HEG) compared to a baseline AT is 4.3%–5.7% (lower bound due to 4WD trucks with an unimproved rear axle).

Increased numbers of gears also increase the transmission friction, costs, and weight. Thus, increasing the number of gears may see diminishing returns. Furthermore, as is common for many transmission technologies, increased shifting can lead to consumer acceptance issues (perceived shift busyness) as well as additional losses (due to shifting). The agencies expect 8-speed ATs to be readily available beginning in MY 2017 and widespread by MY 2025, so much so that they project 6-speed ATs will be virtually eliminated by 2025 (although 6-speed MTs are projected to maintain a 4% market share in 2025).

The effectiveness of a 6-speed AT is relative to a 4-speed AT, and incorporates a 7% improvement in gearbox efficiency that would accompany a switch to 6-speed AT. An 8-speed AT was applied after 6-speed AT only to vehicles with towing requirements (minivans, midsize and large trucks). The reported effectiveness of an 8-speed is relative to a 6-speed. Relative to a 4-speed AT, an 8-speed AT shows 6.5%–7.8% reduction in fuel consumption.

The incremental direct manufacturing cost (DMC) for 8-speed ATs from 6-speed is $47. Note that the agencies predict a net *savings* of $11 in switching from the older 4-speed design to a 6-speed Lepelletier AT. Thus, switching from a 4-speed to an 8-speed AT results in a DMC of $36.

Vehicles with no towing requirement were modeled as having an 8-speed DCT after a 6-speed DCT. The effectiveness of 8-speed DCTs over 4-speed ATs is 9.7%–12.6%, and 5.7%–8.1% for 6-speed DCTs over 4-speed ATs. Note that in the 2011 Ricardo study cited in the rulemaking, the effectiveness values include high efficiency gearbox. Independent of other improvements in transmission, DCTs were estimated to have 4%–6% improvement over ATs with same number of gear ratios. The agencies further split DCTs into wet-clutch and dry-clutch versions. Wet-clutch DCTs have higher torque capacity since the clutches are cooled and hydraulically actuated. Wet clutches are also useful in vehicles with low-torque engines, where cooling is required to allow the clutch to be slipped over a longer period of time. The agencies assumed that the hydraulic pump leads to reduced efficiency compared to dry-clutch DCTs (although today some wet-clutch DCTs have mostly overcome this problem with on-demand hydraulic systems). It was also assumed that, because there is no torque converter, DCTs would likely be paired with engines with high low-speed torque or with transmissions that have shorter gear ratios to match the torque multiplication of a torque converter.

Despite improvements in automatic transmission and dual-clutch transmission efficiency, the agencies consider manual transmissions to exhibit the most efficient energy transfer due to low internal gear losses, minimal hydraulics, and actuation energy input from the driver. Of course, the driver may not select the optimum gear for best fuel economy, so on the official test cycles advanced automatic transmissions usually provide better fuel economy.

More gear ratios (usually overdrive gears) permit the engine to operate in the optimum efficiency range more often. However, proper stepping of the ratios is important to driver satisfaction and acceptability. For the 2017–2025 rulemaking, the agencies assumed the number of gear ratios increases from 5 to 6 in manual transmissions. For reference, 6-speed and 5-speed manuals (MT) are estimated to occupy 2.78% and 0.76% of the market, respectively, in 2015.

Lastly, neither agency felt that CVTs would be competitive within the 2017–2025 timeframe. Nevertheless, the Lumped Parameter Model (LPM, EPA's model for effectiveness of various vehicle technologies) estimated CVT effectiveness as 6.0%–8.7%, relative to a 4-speed AT.

Figure 2 combines the historical market share from the FE Trends Report with projected market shares of various transmissions from the EPA/NHTSA 2017–2025 rulemaking for 2021 and 2025 (identified by the dotted lines). As indicated by the yellow region in the lower left of the figure, 4 speed transmissions (both manual and automatic) have been virtually phased out by 2015. Similarly, 5-speed transmissions (red) are losing market share and are estimated to taper off to zero by 2021. Future projections are for 8-speed+ATs and, especially, DCTs to dominate the market, with CVTs tapering off to zero by 2021.

CURRENT PRODUCTION COSTS AND BENEFITS ESTIMATES

Since the rulemaking was written in 2012, numerous developments have occurred in CVTs, DCTs, and conventional automatics. Several of these developments are described below.

CVT

The typical CVT utilizes a belt sandwiched between pairs of cones: essentially two variable-diameter pulleys (Figure 3). Historically, torque limitations hindered the adoption of CVTs in all but the smallest vehicles. But improvements in belt design have dramatically increased the torque capabilities of CVTs up to 450Nm.[8] CVTs captured an estimated 18% of the entire market in 2015 and sales include compact cars (1.0L to 1.8L) all the way through large passenger vehicles (>2.5L)[9] including the Nissan Murano—a midsize crossover SUV with a 3.5L engine.

As an example of the improvements, Jatco produces a CVT for small cars that has an increased gear spread, which enhances launch and acceleration. It couples a small "sub-transmission" to the CVT. This "sub-transmission" is an auxiliary gearbox. Complexity is increased, but the overall size is reduced by 10% and weight by 13%. In addition to the efficiency benefits from reduced weight and the increased gear spread, internal friction is reduced by 30%.[10]

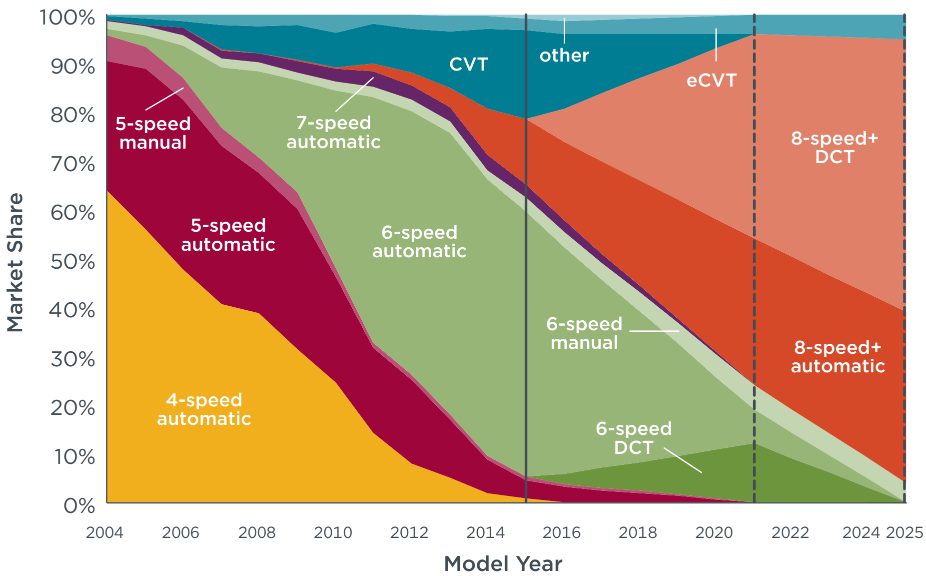

Figure 2. Market share of various transmissions by speed (color) and type (shade). CVT = continuously variable transmission for non-hybrid cars and trucks. eCVT = hybrid vehicle continuously variable transmission. DCT = dual clutch transmission. (Source: US. EPA. *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015.* Dec 2015.)

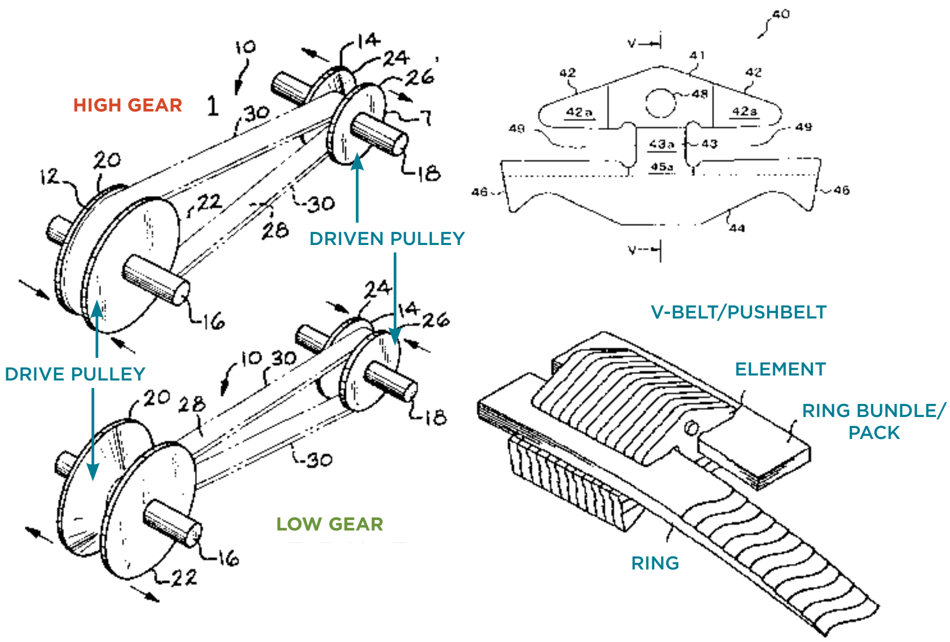

Figure 3. Typical belt-driven CVT configuration (left), and typical belt design (right).[11]

8 "Pushbelt (Working Principle)." *Bosch Transmission Technology B.V.* Accessed June 2016. http://www.bosch.nl/transmission_technology/en/html/5869.htm "Bosch Pushbelt – Efficiency on the Road." *Bosch Mobility* Solutions. Video accessed June 2016. https://www.youtube.com/watch?v=bwKKGdU0fjU

9 As but one example of several CVT suppliers, Jatco offers CVTs suitable for a range of vehicle sizes. "Product Information." *Jatco.* Accessed June 2016. http://www.jatco.co.jp/ENGLISH/products/

10 "Jatco CVT7." *Jatco Product Information.* http://www.jatco.co.jp/ENGLISH/products/cvt/cvt7.html. Accessed June 2016.

DCT

As shown in Figure 4, a DCT includes two clutches, one for each concentric input shaft (orange, purple). The two output shafts (countershafts, hidden) each have a number of gears (blue-gray) that can spin freely around their respective output shaft. Gear selectors (smooth gray) axially slide on the output shafts to select a specific gear and connect it to its output shaft, thereby driving the output shaft. Only one clutch is engaged at a time, so that only one of the countershafts drives the final output (largest gray gear). However, the gear selectors can preselect gears in order to shift faster without any torque interruption. That is, while one clutch and gear selector are engaged in a particular gear, a second gear selector on the non-driving countershaft (corresponding to the un-clutched input shaft) engages the next gear. The shift occurs when the first engaged clutch disengages and the previously disengaged clutch engages. Basic animations of DCT operation are widely available.[12]

Since DCTs represent a class of automated manual transmissions, they typically do not use a torque converter, as with conventional automatics. This elimination leads to launch issues. One option to solve this problem is to simply include a torque converter.[13] Honda uses one between the engine and an 8-speed DCT on the baseline 2015 2.4-L Acura TLX.[14] The DCT+torque converter combination is designed to improve the launch of the DCT, and achieves a 7.4% decrease in fuel consumption (compared to a conventional 5-speed AT). The torque converter improves launch behavior and acceleration through torque multiplication, but additional costs, complexity, length, and reduced efficiency come with it. However, the cost of the clutches for a DCT can be high, thus the torque converter does not make the transmission significantly more expensive.

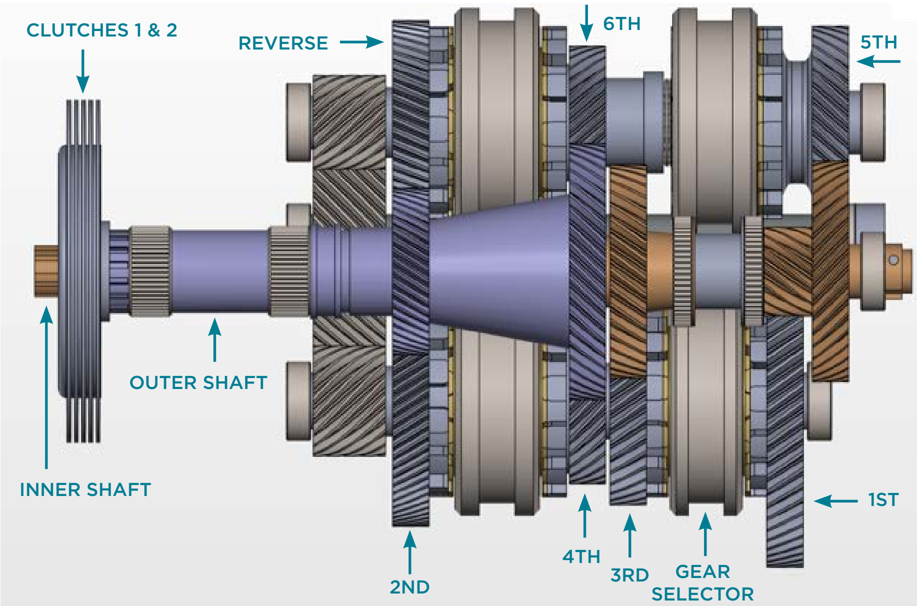

Figure 4. Typical DCT layout and operation.

Today, wet-clutch DCTs approach the efficiency of dry clutches due to the expanded use of an on-demand hydraulic pump.[15] DCTs have also seen improvements in clutches and transmission fluids, mainly by optimized friction materials and clutch pressure control. These developments allow micro-slip of the clutches, which permits reduced system pressure and lower fuel consumption.

Wet-clutch DCTs are also useful for cooling the clutch in conditions where the clutch is slipped longer for low-drag torque. Under these conditions, dry-clutch DCTs would simply burn out.

DCT packaging is a concern, especially as the number of gears increases. Odd-number-geared DCTs may be easier to produce (due to the necessity of a reverse gear). Several 7-speed DCTs are already on the market, and their market share is expected to grow. For example, Hyundai now includes a 7-speed dry-clutch DCT option for all its Sonata, Elantra, and Tuscon models.[16]

In a report commissioned by the ICCT, currently in final draft form,[17] FEV estimated the incremental cost of a 10-speed wet-clutch DCT transmission over a 7-speed or 8-speed conventional automatic would be \$156. Based on the total costs listed in the report, the incremental cost of a 10-speed wet-clutch DCT over a 7-speed dry-clutch DCT is around \$110. Thus, FEV's estimated incremental cost of a dry-clutch DCT over a comparable automatic transmission is approximately \$46. This cost increase is higher than that estimated for the 2025 rulemaking, which was actually a cost *reduction* of \$8–\$165 for

11 U.S. Patent 5167587 & U.S. Patent 7846049

12 Thomas Schwenke. "Dual-Clutch Transmission / Double-Clutch Gearbox (Animation)." *YouTube*. May 7, 2014. https://www.youtube.com/watch?v=t-oULh0I3iA. Accessed June 2016.

13 Robinette, D., Skrzycke, T., "A Dual Clutch Torque Converter for Dual Input Shaft Transmissions," *SAE Int. J. Engines*, April 8, 2013. doi:10.4271/2013-01-0232

14 Dan Carney. "Honda's new 8-speed DCT uses a torque converter." *Automotive Engineering*. Aug. 6, 2014. http://articles.sae.org/13432/. Accessed June 2016.

15 Matthew Beecham. "Q&A with BorgWarner: Dual clutch transmissions." *Just Auto News & Analysis.* Jan. 22, 2013. http://www.just-auto.com/interview/dual-clutch-transmissions_id130903.aspx. Accessed June 2016.

16 Fuel Economy. U.S. EPA OTAQ. http://www.fueleconomy.gov. Accessed June 2016.

17 FEV. *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis*. Draft: Sept. 2015. Forthcoming report for ICCT.

wet-clutch and dry-clutch DCTs over their conventional AT counterparts.

FEV estimated the incremental cost of a dual wet-clutch alone over a dual dry-clutch would be $44, which is essentially on par with the estimated cost in the rulemaking of $52. Note that FEV estimated a 10-speed DCT would cost only $66 more than a 7-speed DCT. This is because FEV assumed 10 gear steps would be realized by applying an advanced connection scheme of gear wheels and synchronization units, a concept different from typical DCT layouts that tries to solve some of the packaging issues of 7-speed+ DCTs (albeit only for front-wheel drive vehicles).[18]

Upgrading a 6-speed manual to a 7-speed dry-clutch DCT decreased fuel consumption by 4.1%–7.9% on the smaller vehicle classes modeled by FEV. Unfortunately, the addition of advanced stop/start functions and weight reduction to all other DCT modeling prevents a separate assessment of the efficiency benefit of DCT over conventional automatics.

Conventional Automatics

Conventional automatic transmissions have also been undergoing incremental improvements. Unlike conventional DCTs, which must add gears for each expansion, the Lepelletier gear set design allows easier expansion of the number of gear ratios. For example, a 9-speed automatic made by ZF Friedrichshafen AG (and used by Chrysler, Jaguar Land Rover and Honda) uses 4 simple planetary gearsets and 6 shift elements.[19] The gearsets are also nested to save space, leading to smaller and lighter transmissions for the same number of gears compared to DCTs. Thus, the number of gear ratios in conventional automatics is increasing rapidly, up to 10 in the upcoming Lexus application and Ford/GM transmission, enabling both higher performance and lower fuel consumption than the 8-speed automatic transmissions modeled in the rulemaking.[20] And, due to some consumer dissatisfaction issues with some of the initial DCTs sold in the market (discussed more below), many OEMs are focusing on improved automatic transmissions.[21]

The 9-speed ZF automatic consumes 16% less fuel than a 6 speed automatic at the same driving speed. One innovation is that this 9-speed uses interlocking, splined dog clutches (rather than friction clutches) to achieve faster and more efficient torque transfer.[23] Splined dog clutches have lower spin losses on clutches that are not engaged.

Ongoing research on better friction materials has improved clutch performance and reduced friction losses,[24] leading to decreased fuel consumption.[25] The groove patterns and material in the clutch friction plates are engineered to reduce drag, which, in addition to improving fuel economy, provides seamless shifts for better performance and delivers durability that improves the life of the transmission.

Table 5. Comparison of estimated costs from rulemaking and suppliers. Source: EPA/NHTSA 2017-2025 rulemaking, FEV 2015, and FEV/EPA 2013[22]

TECHNOLOGY	BASELINE	Cost Estimates	
		RULEMAKING	FEV
6-speed dry-clutch DCT	6-speed AT	-$127 to $26 (NAS)	—
7-speed dry-clutch DCT	7-/8-speed AT	—	$46
10-speed wet DCT	8-speed AT	—	$156
8-speed wet-clutch DCT	6-speed wet-clutch DCT	$153	$161*
10-speed wet-clutch DCT	7-speed wet-clutch DCT	—	$66
Wet-clutch (DCT)	Dry-clutch (DCT)	$52	$44
8-speed AT	6-speed AT	$47	$54*
6-speed MT	5-speed MT	$173	$40

**Costs extracted from FEV/EPA 2013 report on advanced 8-speed transmissions and reduced by manufacturer learning trends as applied in the final rulemaking.*

18 Govindswamy, K., Hellenbroich, G. and Ruschhaupt, J., "7-XDCT: Compact and Cost-Efficient Dual Clutch Transmission for Small and Mid-Size Vehicles," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(2):2013, doi: 10.4271/2013-01-1271. "10-Speed Dual Clutch Transmission." *FEV North America, Inc.* https://www.youtube.com/watch?v=p_cBBRY7qhg. Video accessed June 2016.

19 Dan Carney. "Honda's new 8-speed DCT uses a torque converter." *Automotive Engineering*. Aug. 6, 2014. http://articles.sae.org/13432/. Accessed June 2016.

20 Sean Szymkowski. "General Motors will introduct 10-speed automatic on eight vehicles by 2018." *GM Authority.* Mar. 16, 2016. http://gmauthority.com/blog/2016/03/general-motors-will-introduce-10-speed-automatic-on-eight-vehicles-by-2018/. Accessed June 2016.

21 David Sedgwick. "Once-promising dual-clutch transmissions lose favor in U.S." *Automotive News.* Dec 7, 2015. http://www.autonews.com/article/20151207/OEM06/312079988/once-promising-dual-clutch-transmissions-lose-favor-in-u.s. Accessed June 2016.

22 U.S. NHTSA. *Corporate Average Fuel Economy for MY 2017-MY 2025 Passenger Cars and Light Trucks: Final Regulatory Impact Analysis.*. Aug 2012. Accessed June 2016. http://www.nhtsa.gov/fuel-economy. FEV. *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis*. Draft: Sept. 2015. Forthcoming report for ICCT. U.S. EPA. *Light-Duty Vehicle Technology Cost Analysis, Advanced 8-Speed Transmissions: Revised Final Report*. FEV. April 2013. EPA-420-R-13-007.

23 "9-speed Automatic Transmission." *ZF Technology for Cars: Automatic Transmission.* http://www.zf.com/corporate/en_de/products/product_range/cars/cars_9_speed_automatic_transmission.shtml. Accessed June 2016.

24 Merkel, H. "Development Trends of Friction Products". BorgWarner Transmission Systems. CTI Symposium. December 2013.

25 "BorgWarner Delivers Advanced Technologies For New GM 8-Speed Transmission." *PR Newswire*. Sep 21, 2015. http://www.prnewswire.com/news-releases/borgwarner-delivers-advanced-technologies-for-new-gm-8-speed-transmission-300145826.html. Accessed June 2016.

Leakage from hydraulic pumps and valves is also a major source of transmission energy loss. Consequently, there is a concerted effort among suppliers and OEMs to improve hydraulics (especially in combination with start-stop).[26]

IMPROVEMENTS IN DEVELOPMENT

DCT

DCTs may be ideally suited for hybrid and electric vehicle applications (as in the VW Jetta Hybrid and the 2017 Hyundai Ioniq). The electric motor can provide assist during launch, eliminating the starting clutch and allowing simpler clutches and lower cooling requirements.[27] Several companies continue to make incremental improvements in DCTs.[28]

VariGlide planetary variator[29]

VariGlide planetary variator technology is a compact traction drive that employs rotating planets that can be tilted on their axes to smoothly and continuously vary the drive ratio. As shown in figure 5, by changing the angle of tilt of each planet's axis of rotation, the contact radii ratio changes, and therefore the speed ratio may be continuously varied as the transmission is shifted through the ratio range.

Figure 5: Cross section diagram showing planetary ball tilt angle determining drive ratio.

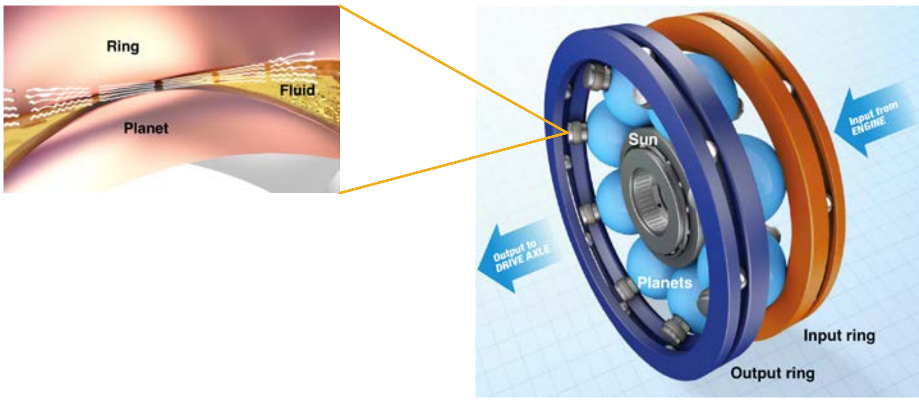

Figure 6: *The VariGlide planetary variator employs elasto-hydrodynamic lubrication (EHL) to transfer torque. The components and ball cam clamping features in the ring are shown on the right.*

It is similar to a dual-ring planetary gear set, but the planets in the VariGlide planetary variator are spherical rollers (standard bearing technology), which transfer load through traction rather than gear teeth. The carrier allows the planets to rotate about their tilting axes and find their equilibrium. The input and output power are delivered on the same centerline (as opposed to spur gears), and like a planetary gear, the drive can be used to power-split or power-sum.

As a traction drive, it transmits forces between the rolling surfaces (between ring and planet ball contacts) through resistance to shearing of a thin film of traction fluid. This mechanism of torque transfer is also known as elasto-hydrodyamic lubrication (EHL).[30] At the traction contact there are losses that include slip, side-slip and spin. Variable clamping force is provided by simple mechanical ball cams, which enable the correct amount of clamping force for the given load without the need for active control.

While the production capability has yet to be proven, the design has a number of potential benefits over belt CVTs. It uses roller bearings instead of a belt to transmit loads, which should be more durable. These bearings also eliminate the need for a high-pressure pump, which contributes to some of the benefits over

26 Reduced system pressure, electrohydraulic pumps (Getrag), variable mechanical pumps (ZF), bi-pressure pumps (GM, Aisin/Toyota), and low leak solenoid valves are some of the many approaches to reducing transmission leakage.

27 Matthew Beecham. "Q&A with BorgWarner: Dual clutch transmissions." *Just Auto News & Analysis.* Jan. 22, 2013. http://www.just-auto.com/interview/dual-clutch-transmissions_id130903.aspx. Accessed June 2016.

28 Ernest DeVincent. "GETRAG DCT New Modular Platform: From 100Nm to 500Nm." *Getrag*. Presentation given at 7th International CTI Symposium May 2013, Detroit. http://www.getrag.com/media/products/powershift/7dct300/Presentation_7DCT300.pdf "Efficient Transmissions." *Getrag Transmission Technology*. 2016. http://www.getrag.com/en/technology/transmission_technology/pleasure_and_consumption/efficiency_and_dynamics_1.html

29 This is a relatively new concept that operates differently than current production CVTs.

30 Fern Thomassy. *An Engineering Approach to Simulating Traction EHL*. CVT-Hybrid International Conference Mecc/Maastricht/The Netherlands, Nov. 17–19, 2010.

belt CVTs.[31] The planetary CVT can handle higher torque than belt CVTs and the same design can be used in both FWD and RWD applications.

The VariGlide has some similarities to the (virtually extinct) toroidal/roller CVT, in that both use a traction fluid, rather than friction, to transmit torque.[32] Used by Nissan ("Extroid CVT") in the 1990s on several passenger cars and currently produced by Torotrak[33] for use on heavy duty vehicles, toroidal CVTs have largely stalled in development for light-duty vehicles. The VariGlide has some of the same potential issues tied to the need for traction fluid, such as spin losses and traction fluid durability. According to Dana, traction fluids have shown significant improvements in both durability (resistance to degradation) and overall traction coefficient. They continue to work with their OEM partners to jointly develop specifications that will ultimately meet the expected "fill for life" expectations.[34] The core technology has also been subjected to 70,000 hours of durability testing, which shows robustness against slip-induced damage.[35]

Electrification

As manufacturers roll out increasing numbers of vehicles equipped with start-stop (shutting of the engine instead of idling while stopped or coasting) and further levels of electrification, transmissions are also upgrading to handle these changes. Not only are hydraulic systems changing to adapt to more engine starting and stopping (discussed above), auxiliary pumps are also being developed. For example, FEV sees an integrated electric motor as an option on their 7-speed+ DCTs.[36]

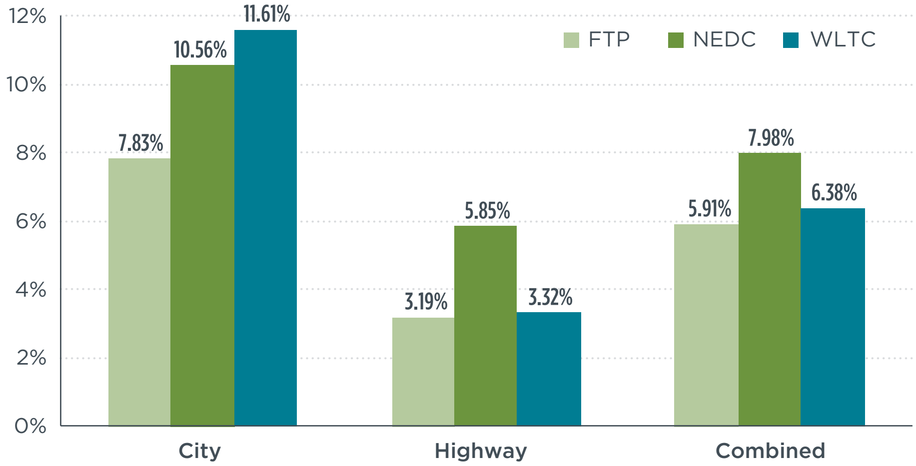

Figure 7. Fuel economy comparison with 6-speed AT

Manual transmissions

Manual transmissions, too, may use electric clutches for reducing fuel consumption and increased comfort. A system by Schaeffler can reduce fuel consumption by 3.1% (idling the engine when coasting in the highest gear) to 8.2% (stopping the engine when coasting) at a direct manufacturing cost of $112. This system enables coasting start-stop for manual transmisions; idling the engine or stopping it entirely depending on the degree of savings.[37]

CONSUMER ACCEPTANCE ISSUES

Consumer acceptance issues must be considered for any new or improving vehicle technology. Transmissions, in particular, suffer from these issues, since they directly affect how the engine sounds and how the vehicle feels. DCTs and CVTs generally have much more pronounced issues than improved automatics. But automatics also have some issues, primarily gear "hunting" when the number of gears increases.

The transmissions with more gear ratios and wider gear spread have major positives in addition to better fuel economy: lower gears improve vehicle launch, a lower ratio for the top gear provides quieter operation on the highway, and more gears can better maintain both lower rpm for better fuel economy and higher rpm for faster acceleration. These advantages have contributed to the rapid adoption of more gear ratios in recent years.

DCTs and CVTs have the potential for even better efficiency than ATs, but some early models of DCTs and CVTs have been criticized for poor shift quality and a different "feel," respectively, from what customers expect.

DCTs are losing favor with some manufacturers, largely due to abrupt shifting and lurching on many initial

31 "VariGlide ® CVT Efficiency." *Dana Holding Corporation*. June 21, 2016. https://www.youtube.com/watch?v=N34pxHDoGO4&feature=youtu.be. Video accessed June 2016.

32 "Extroid CVT." *Nissan's CVT Technologies*. http://www.nissan-global.com/PDF/tcvt_e.pdf. Accessed June 2016.

33 "Torotrak." *Torotrak Group Products*. http://www.torotrak.com/products-partners/products/torotraktransmissions/. Accessed June 2016.

34 Written comment received from Dana on June 29, 2016.

35 Dana claims over 70,000 hours of component durability testing for the VariGlide. "VariGlide ® CVT Testing." *Dana Holding Corporation*. June 21, 2016. https://www.youtube.com/watch?v=DZeJ1kUiEHg&feature=youtu.be. Video accessed June 2016.

36 "10-Speed Dual Clutch Transmission." *FEV North America, Inc.* https://www.youtube.com/watch?v=p_cBBRY7qhg. Video accessed June 2016.

37 Luca Ciferri. "Schaeffler touts fuel-savings e-clutch for manual gearboxes." *Automotive News*. June 6, 2016. http://www.autonews.com/article/20160606/OEM10/306069990/schaeffler-touts-fuel-saving--e-clutch-for-manual-gearboxes. Accessed June 2016.

DCT applications. For example, the first DCT used on the Ford Focus was criticized for abrupt shifts, shift "busyness," and poor launch.[38] Poor calibration and gear ratio selection likely explain much of these early challenges facing DCTs. Indeed, there are examples of DCTs that have been widely praised, e.g. the 2015 VW Golf,[39] which suggests that part of the problem is not the hardware but software controls that are not yet sophisticated enough**.** However, it may not be possible to remove all of the shift shock with dry-clutch DCTs, as the high temperature variations make it difficult to control clutch engagement. And even wet-clutch DCTs may never launch like a conventional hydraulic automatic transmission, as they are, fundamentally, manual transmissions shifted automatically. DCTs are popular in Europe, as manual transmissions have a high market share in Europe and customers are used to the launch quality of a manual transmission, but this familiarity is not the case in the United States. Manufacturers are testing different options based on their expertise: those with manual transmission experience (primarily European-based manufacturers) are implementing DCTs, with or without torque converters. Other improvements are also coming to DCTs, such as electro-mechanical clutch actuation (rather than hydraulic).[40]

Some manufacturers—primarily Nissan, Honda, Toyota, and Subaru—are avoiding the calibration challenges and perceived shift "busyness" associated with many DCTs by switching to CVTs. However, CVTs also come with their share of criticism. CVTs have been derided for the exact opposite behavior as DCTs. With no "shifting," CVTs can appear as constantly revving (or constantly not revving), with engine speed seemingly uncorrelated to accelerator pedal input, as consumers are accustomed to. Again, calibration is partly at fault for this issue, but this effect may simply take a bit of getting used to. For example, *Consumer Reports* recently praised the CVT used in the 2016 Honda Accord. This evaluation suggests, again, that the primary problem is not the hardware, but software controls. New shifting logic attempts to recreate some of the shifting experience of driving an automatic on a CVT.[41] Indeed, improved drivability acceptance of CVTs is reflected in the doubling of market share since 2012 to over 1 in 10 trucks and 1 in 5 cars (Figure 1 and Table 2).

DISCUSSION

CVT

After years of slow development, many of the solutions to problems associated with CVTs have reached a point where CVTs are now a real alternative to traditional automatics. Increased hydraulic pressure and improved belts vastly expanded the torque range of CVTs. The engine efficiency benefits possible with CVTs finally offsets the losses associated with high-pressure pumps and friction, offering net efficiency improvements. The CVT is an inherently lower cost design and suppliers have managed to keep costs low enough so that CVT sales are increasing rapidly. Continued incremental development will further reduce losses and cost.

There is no doubt that CVTs suffer greater losses than DCTs and conventional ATs. Their eventual cost and market share, especially compared to DCTs, depends on the degree to which these losses are minimized and the rate of improvement in DCTs (cost and consumer acceptance).

New "planetary" CVTs,[42] which use traction fluid, show promise, although they have yet to be introduced at a commercial scale. Their relatively simple design, compared to belt-driven CVTs, could also mean they are, overall, less expensive to manufacture. However, as with all traction-drive transmissions, at the traction contact there are losses that include slip, side-slip and spin. Improvements are being made to traction fluid durability and assuring "fill for life" is a prerequisite for market acceptance.

DCT

DCTs have not taken off in the United States as forecast due to consumer acceptance issues and difficulty in packaging.[43] Furthermore, due to temperature constraints, it may not be possible to solve the consumer acceptance issues with dry-clutch DCTs. Wet-clutch DCTs are becoming more efficient than predicted, approaching the efficiency of some dry-clutch DCTs, and they benefit from reduced temperature issues compared to dry-clutch DCTs. Better

38 David Sedgwick. "Once-promising dual-clutch transmissions lose favor in U.S." *Automotive News*. Dec 7, 2015. http://www.autonews.com/article/20151207/OEM06/312079988/once-promising-dual-clutch-transmissions-lose-favor-in-u-s. Accessed June 2016.

39 Mark Rechtin. "Volkswagen Golf, Ford F-150 win car, truck of the year awards." *Consumer Reports*. Jan 12, 2015. http://www.consumerreports.org/cro/news/2015/01/volkswagen-golf-ford-f-150-win-car-truck-of-the-year-awards-detroit-nactoy/index.htm. Accessed June 2016. VW Golf Consumer Reports' Road Test. *Consumer Reports*. http://www.consumerreports.org/cro/volkswagen-golf-road-test.htm

40 Liu, F., Chen, L., Yao, J., Zhang, J. et al., "A New Clutch Actuation System for Dry DCT," SAE Technical Paper 2015-01-1118, 2015, doi:10.4271/2015-01-1118.

41 Lindsay Chappell. "Nissan tweaks CVTs to be less CVT-like." *Automotive News*. July 13, 2014. http://www.autonews.com/article/20140713/OEM03/307149936/nissan-tweaks-cvts-to-be-less-cvt-like. Accessed June 2016. Keith Griffin. "Why do today's transmissions have so many gears?" *U.S. News & World Report*. July 16, 2015. http://usnews.rankingsandreviews.com/cars-trucks/best-cars-blog/2015/07/Why_do_Todays_Transmissions_Have_so_Many_Gears/. Accessed June 2016.

42 McIndoe, G., VanSelous, J., Liu, T., and David, J., "Efficiency Analysis of Multi-Mode Passenger Car Transmission Concepts Featuring a VariGlide® CVT," SAE Technical Paper 2016-01-1108, 2016, doi:10.4271/2016-01-1108.

43 According to BorgWarner, packaging issues are mainly due to the DCTs increased girth.

control logic will also improve the lurch and launch problems.[44]

The need to add a wet clutch adds $52 to the cost according to agency estimates ($56 according to a recent FEV analysis[45]), and degrades fuel economy. The efficiency improvements to the wet clutch reduce the efficiency penalty, but at some additional (un-quantified) cost. FEV's recent cost assessment suggests that DCTs may be more expensive than assumed by the agencies in the rulemaking, although still cheaper compared to conventional automatics.

Conventional AT

Some OEMs (particularly in North America) are sticking to designs they have experience with and relying on higher-speed ATs rather than DCTs and CVTs. Incremental improvements in these higher-speed automatics have led to efficiencies roughly on par with what the agencies predicted. However, 9- and 10-speed automatics have already been introduced in the market, which have incremental efficiency improvements over the 8-speed transmission modeled for the rulemaking. In addition, friction clutches can be replaced with mechanical clutches, as on the new ZF 9-speed transmission, although that requires faster on-board computers to better calibrate shifting.

The agencies projected in the rulemaking that 8-speed ATs would completely replace 6-speed ATs by 2025. However, BorgWarner believes it is likely that 6-speed ATs will continue to be used for at least the small car segments, due to their low cost.[46]

Changes since agency evaluations were conducted for 2017–2025 rulemaking

It appears that manufacturers may be sticking to the transmissions they know best. Most vehicles in Europe still use manual transmissions. DCTs, which are simply manual transmissions shifted automatically, are widely used by European manufacturers in the United States, and their customers seem to be accepting them. CVT transmissions are extremely popular in Japan, as they excel in the low-speed congested conditions that dominate driving in Japan. Japanese manufacturers used to use conventional automatics in the United States, due to the higher performance and torque requirements and the better fuel economy of conventional automatics on the highway. However, as CVTs have improved to handle higher torque and expand the ratio spread for better highway fuel economy, the Japanese manufacturers have largely replaced conventional automatics with CVTs in the United States. The U.S. manufacturers are experimenting with both CVTs and DCTs, but early customer acceptance issues appears to be pushing them back onto their traditional expertise with conventional automatics. Both manufacturing history and consumer history with the feel of a torque converter favor conventional automatics for the U.S. manufacturers.

DCTs will certainly have a significant share of the future transmission market. However they will cost more than estimated in the rulemaking, they may not be quite as efficient due to the need for a wet clutch or a torque converter, and they will never shift quite like a conventional hydraulic automatic. Combined with improvements to CVTs and ATs, DCTs are unlikely to largely replace CVTs and ATs in the 2025 time frame, as projected by EPA/NHTSA in the 2017-25 rulemaking. James Verrier, CEO of BorgWarner, thinks the DCT future in the United States "will be primarily the wet DCT for higher torque applications," such as diesels and gasoline turbocharged engines.[47]

Some, if not all, of the DCT shortfall will be replaced by improvements to CVTs and conventional automatics. Newer CVTs have reduced internal friction, wider ratio spread, and increased torque capacity. They will likely be strong competitors to DCTs and conventional ATs through at least 2025, especially for manufacturers with extensive CVT expertise. Conventional automatics can add additional gear ratios in a relatively inexpensive manner and maintain a compact size. Recent improvements are increasing efficiency, such as improved clutch designs and the use of splined dog clutches, and ATs largely avoid consumer acceptance issues. They are likely to maintain a larger share of the market in 2025 than projected in the rulemaking.

SUMMARY

In their technology analyses for the 2025 rulemaking, EPA and NHTSA projected that DCTs would overtake conventional automatics by 2021 and continue to increase market share through 2025. However, due to numerous consumer acceptance issues (which may be due primarily to calibration, rather than the actual hardware), their sales have not reached levels indicative of such a transition. While some of the technical challenges faced by DCTs are being solved, the solutions will likely make

44 Cho, D., Gupta, R., Dai, E., McCallum, J. et al., "Launch Performance Optimization of GTDI-DCT Powertrain," SAE Int. J.Engines 8(3):2015, doi:10.4271/2015-01-1111.

45 FEV. *2030 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis*. Draft: Sept. 2015. Forthcoming report for ICCT.

46 Personal communication from BorgWarner to ICCT, received on June 16, 2016, via email.

47 Richard Truett. "Ford gets the PowerShift dual clutch transmission right, but is it too late?" *Automotive News*. January 5, 2016. https://www.autonews.com/article/20160105/BLOG06/301059997/ford-gets-the-powershift-dual-clutch-transmission-right-but-is-it. Accessed June 2016.

them slightly more expensive and slightly less efficient than projected by the agencies. Although DCTs remain an attractive option in terms of comparative cost-effectiveness and efficiency, they are unlikely to match the penetration estimates in the rulemaking.

Conventional automatics, in general, are matching the predicted cost and likely exceeding the projected benefit, due to the introduction of 9- and 10-speed transmissions and the increased efficiency of mechanical/dog clutches. The growth in market share for higher speed automatics is strong, putting ATs on track to meet projections, and possibly to help fill in the gap left by lagging DCTs.

When the rulemaking analyses were conducted four to five years ago, CVTs were not projected to be a competitive option by 2025. However, years of incremental improvements have shown that CVTs can, and are, a good alternative transmission. Market share has grown rapidly since 2012 and consumer acceptance issues no longer seem to be plaguing CVTs. Although the agencies did not explicitly predict the costs or benefits of CVTs in the rulemaking, CVTs today appear to be on track to match the benefit estimates available in EPA's lumped parameter model and they cost less than conventional automatics.

While the VariGlide® Planetary Variator was not considered in the overall assessments in this paper, if it proves successful it may offer another bump in efficiency, reduced cost, and improved durability.