Delayed Engagement as a Contributor to Sudden Unintended Acceleration

by

Ronald A. Belt
Plymouth, MN 55447
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Abstract: Delayed engagement of transmission gears is shown to be a contributor to sudden unintended acceleration (SUA) by allowing the engine speed to increase rapidly after a shift from PARK to DRIVE or PARK to REVERSE. Delayed engagement is the result of an extended clutch fill time in transmissions having planetary gears and hydraulic shift valves. The torque converters used with these transmissions also maintain torque to the wheels during a sudden acceleration incident, making it harder to stop. Vehicles with clutches between the engine and the transmission are less susceptible to delayed engagement and also are easier to stop during a sudden acceleration incident because applying the brakes removes all engine torque from the wheels. Other implications of these two types of transmissions regarding SUA are discussed.

I. Introduction

Many drivers involved in sudden acceleration incidents have claimed that their vehicle's engine RPM's increased <u>immediately</u> to several thousand RPM's when they shifted from PARK into DRIVE. This should not happen, since the vehicle's engine is loaded by the entire drive train while in DRIVE, limiting the percent rate of increase in engine RPM's to the percent rate of increase in wheel speed minus the percent rate of increase in torque converter speed ratio.[A] In DRIVE, after the torque converter speed ratio is maximized following a shift from PARK into DRIVE, the percent rate of increase in engine RPM's is limited to the percent rate of increase in wheel speed, which takes several seconds for even the highest powered engine to move a car from zero to 60 MPH.

This rapid increase in engine speed during sudden acceleration has puzzled the author, whose own explanation of sudden acceleration maintains that sudden acceleration occurs during a shift from PARK into DRIVE [B] because the shift into DRIVE activates a different throttle controller than the curb idle controller that is active in PARK. The difference between the two controllers is that the throttle controller active in DRIVE is an open-loop controller that treats all disturbances the same as throttle opening commands without being able to reduce the throttle opening if the disturbance causes the throttle opening to increase. The idle controller active in PARK, on the other hand, is a closed-loop throttle controller that is able to reduce the throttle opening if the disturbance causes the throttle opening to increase, allowing the engine to maintain a constant idle speed. Therefore, when the driver shifts from PARK into DRIVE, the change of throttle controller can explain how the throttle opening can increase after it behaved normally while idling in PARK.[C] But it cannot explain how the engine RPM's can increase <u>immediately</u>,

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A. This is because the engine speed N_E and the wheel speed N_W are related by $N_W = R \bullet S \bullet N_E$, where R is the transmission gear ratio and S is the speed ratio of the torque converter. As a result, one can show that $\frac{1}{N_E}\frac{dN_E}{dt} = \frac{1}{N_W}\frac{dN_W}{dt} - \frac{1}{S}\frac{dS}{dt}$, where each term is the percent rate of increase of the variable shown.

B. More generally, from either PARK or NEUTRAL into either DRIVE or REVERSE. These are known as "garage shifts", as opposed to "range shifts" which involve upshifts or downshifts from one gear ratio to another.

C. The sudden increase in engine RPM's <u>after</u> shifting into DRIVE is what takes most drivers by surprise, because if the engine is idling normally in PARK the driver feels safe to shift out of PARK and into DRIVE. Most drivers would not shift out of PARK or NEUTRAL if the engine was revving at four to five thousand RPMs because of the obvious danger involved.

because in DRIVE a higher load is placed on the engine that limits the rate of increase of engine RPM's to a slower rise with vehicle speed.

The answer to the question of how a car's engine RPM's can increase immediately to several thousand RPM's when the transmission is shifted from PARK into DRIVE is "delayed engagement". Delayed engagement means that the transmission gears do not engage immediately when the driver changes the transmission shift lever into DRIVE. Instead, a delay in the gear engagement occurs as a result of what is known as the clutch fill time. This delay time varies from a half a second to several seconds in vehicles with healthy transmissions, with some manufacturers saying that a value of three seconds or less is normal. But the delay time can be as much as ten seconds or more in vehicles with defective transmissions. It can vary with transmission component tolerances and transmission temperature, and can increase with transmission fluid quality, transmission age, and a history of transmission abuse. Delayed engagement has been a consumer complaint in all makes and models of vehicles from the 1990's to the present day, as the reader can verify by searching the Internet using the words "delayed transmission engagement" or "delay shifting into drive or reverse".

What this delay time means is that for the short time between changing the shift lever from PARK into DRIVE and the gears actually engaging into DRIVE, the transmission gears actually remain in NEUTRAL. However, the throttle controller is still changed immediately when the driver shifts the control lever from PARK into DRIVE. So, during this short delay time the throttle controller that is active only in DRIVE can cause the engine RPM's to increase as rapidly as they do in PARK or NEUTRAL. And we know from experience that one can rev up the engine rapidly in either PARK or NEUTRAL because there is no load on the engine while in PARK or NEUTRAL.

So, we now have an explanation for how a car's engine RPM's can increase immediately to several thousand RPM's when the transmission is shifted from PARK into DRIVE. The answer is delayed engagement. This non-ideal operation of the transmission is found in all makes and models of vehicles to a greater or lesser extent, and in all types of transmissions that depend upon planetary gears. Its presence makes the vehicle more susceptible to sudden acceleration when the throttle opening is increased by any abnormal operation of the throttle controller. The author's theory of sudden acceleration explains how such an abnormal increase in throttle opening can occur without leaving any diagnostic test codes, or DTC's. And the non-ideal transmission operation which causes vehicles to be more susceptible to sudden acceleration does not cause any DTC's either. Delayed engagement is the missing piece in the author's previous explanation of sudden acceleration.

We will now look at how delayed engagement is a result of the clutch fill time in automatic transmissions. This requires a brief understanding of how automatic transmissions operate.

II. Automatic Transmission Operation and Clutch Fill Time

We will now give a short course in automatic transmissions with the goal of learning what clutch fill time is and how it causes delayed engagement of the transmission gears. We will start by describing an electronically controlled planetary gear transmission, which is the type used by most vehicles over the past twenty years. We will then describe earlier automatic transmissions like hydraulically controlled planetary gear transmissions and later transmissions, like continuously variable transmissions (CVT) and dual clutch transmissions (DCT), to determine whether they can be affected by delayed engagement. Our main goal will be to understand how gear shifts are performed, and specifically garage shifts that are involved in most sudden acceleration incidents. If the reader wishes to skip these details of transmission design and just read a summary of them followed by the consequences of delayed engagement on sudden acceleration, he can proceed directly to Section III entitled "Summary of Review of Automatic Transmissions".

A. Electronically Controlled Planetary Gear Transmissions

Planetary gear transmissions have dominated automatic transmissions in automobiles since the original hydraulically-controlled transmissions in the 1950's and 1960's up to the electronically-controlled automatic transmissions introduced around the year 2000 and used mostly today. Both hydraulically-controlled transmissions and electronically-controlled transmissions use the same basic planetary gear set shown in Figure 1. It consists of an inner sun gear, multiple planetary gears joined by a planetary carrier, and an outer ring gear. By holding one of the three components stationary while using the other two components as either the input or the output, one can obtain both forward and reverse operation with either a higher or lower gear ratio. Neutral can be obtained by holding none of the components stationary. This provides all the modes of operation required in an automatic transmission, allowing two fixed gear ratios for either torque increase or speed increase in each mode, as shown in Table 1.

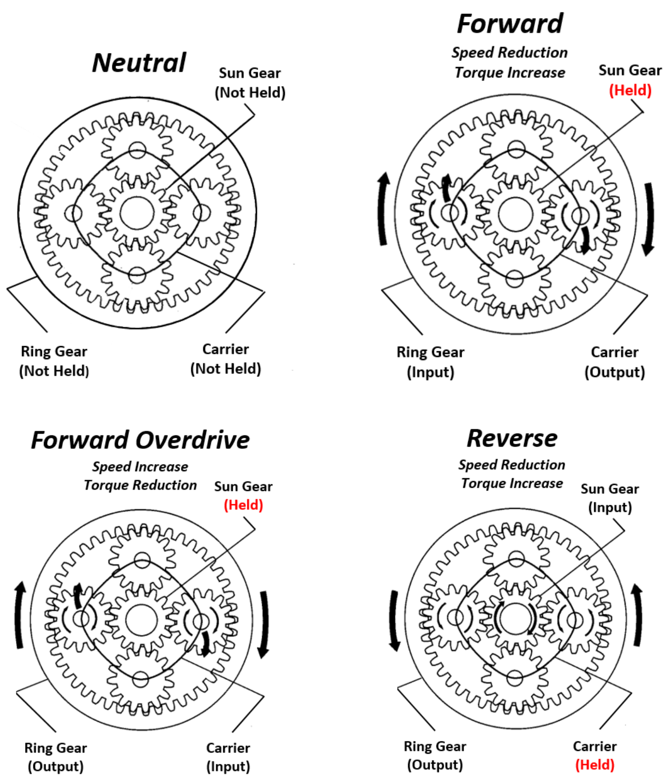


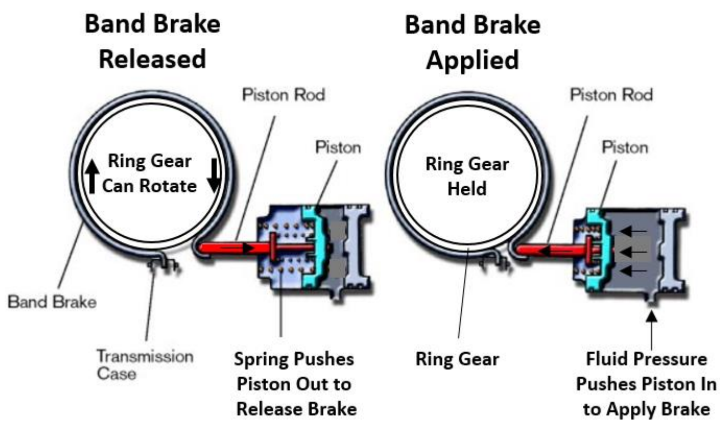
Fig 1. A simple planetary gear set can provide forward, reverse, and neutral by holding one of the three components stationary and using the other two for input and output.

Table 1. Summary of simple planetary gear operation.

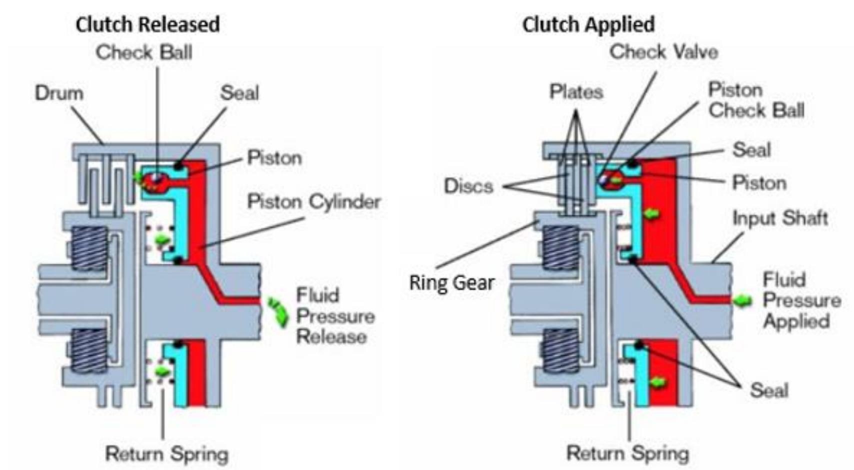
HELD	POWER INPUT	POWER OUTPUT	ROTATIONAL		ROTATIONAL DIRECTION
			SPEED	TORQUE	
None	Any	Any	Zero	Zero	Neutral
Ring Gear	Sun Gear	Carrier	Reduced	Increased	Forward
	Carrier	Sun Gear	Increased	Reduced	
Sun Gear	Ring Gear	Carrier	Reduced	Increased	Forward
	Carrier	Ring Gear	Increased	Reduced	
Carrier	Sun Gear	Ring Gear	Reduced	Increased	Reverse
	Ring Gear	Sun Gear	Increased	Reduced	

Note: Shaded areas represent combinations used in most transmissions.

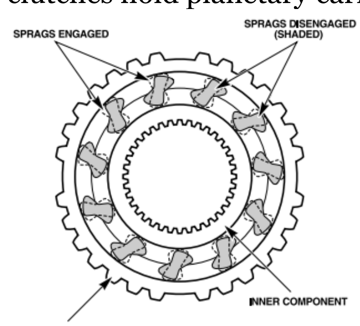
The actuators used to hold the components of the gear set stationary are shown in Figure 2. They consist of band brakes for holding ring gears, multi-plate clutches for holding planetary carriers and ring gears, and one-way Sprag clutches for holding sun gears. All clutches and band brakes other than Sprag clutches are actuated by forcing pressurized transmission fluid into the piston chambers to cause the the pistons to extend and increase the holding force of the clutches. The clutches are relaxed by springs that cause motion in the opposite direction.



(a) Band brakes hold ring gears



(b) Multi-plate clutches hold planetary carriers and ring gears



(c) One-way Sprag clutches hold sun gears to ring gears

Fig. 2. All clutches and band brakes other than Sprag clutches are actuated by pressurized transmission fluid acting on the clutch piston chambers.

In electronically-controlled transmissions, the pressure of the transmission fluid entering the clutch piston chambers is controlled by a fluid valve actuated by an electronic solenoid as shown in Figure 3. The valve receives transmission fluid at a pressure known as line pressure, and can deliver fluid to a clutch at any pressure between zero and line pressure by opening and closing the valve at a fixed rate with a variable opening time or duty cycle. The higher the duty cycle, the higher the clutch pressure and the more force the clutch can apply without slipping. The opening and closing of the valve is done by supplying the electronic solenoid with a 12V amplitude pulse width modulated (PWM) input waveform from the transmission control module (TCM) as shown in Figure 3.

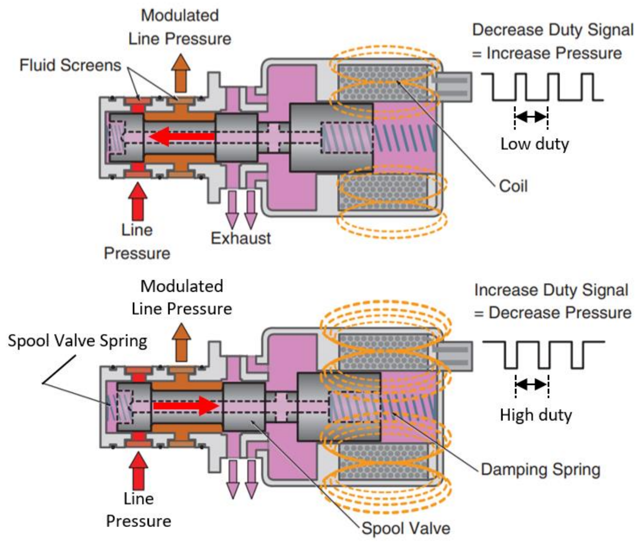


Fig 3. All clutches are actuated by varying the transmission fluid pressure to the clutches by using solenoid-controlled valves that modulate the line pressure by switching it ON and OFF using pulse width modulation (PWM) supplied from the transmission control module (TCM). A higher PWM duty cycle implies a higher clutch pressure.

With only one planetary gear set there are only a limited number of gear ratios possible. In order to obtain a higher number of gear ratios as desired to obtain lower engine speeds and meet higher gas mileage goals, one can use multiple planetary gear sets to make a complete transmission, as shown in Figure 4. The multiple gear sets are controlled by additional holding devices of the same types as already shown in Figure 2. Shifts from one gear ratio to another gear ratio are made by changing the holding devices as shown in Table 2. For example, the red arrows in Table 2 show which holding devices in Figure 4 are changed in order to shift from DRIVE1 to DRIVE2 and then from DRIVE2 to DRIVE3. All the shifts from one gear position to another are made in this manner.

Table 2 shows how the shifts in gear ratio are made, but not when they are made. The decision of when to make a shift is made in the transmission control module (TCM) according to a shift table as shown in Figure 5. This table plots the desired gear ratio versus engine torque and vehicle speed. In this table the accelerator pedal position is used to represent the engine torque while a vehicle speed sensor on the output shaft of the transmission is used to represent the vehicle speed.[D] As the engine torque and vehicle speed change in the table, upshifts and downshifts occur each time the engine torque and vehicle speed cross a line from a current

D. This is a table preferred by one vehicle manufacturer. Other vehicle manufacturers prefer to use the throttle position sensor as an indicator for the engine torque. In either case, the main goal is to use a measured torque as desired by the driver when he presses down on the accelerator pedal.

region of gear operation to a new region of gear operation. The regions of operation for each gear ratio are selected to obtain the best possible performance of the vehicle as a function of vehicle acceleration, speed, and fuel economy. More regions allow finer tuning of the engine performance at the expense of a more complicated transmission. In the year 2000 a three-speed or four-speed transmission was typical. In 2019, 8-speed to 10-speed transmissions are being considered to meet more aggressive gas mileage goals.

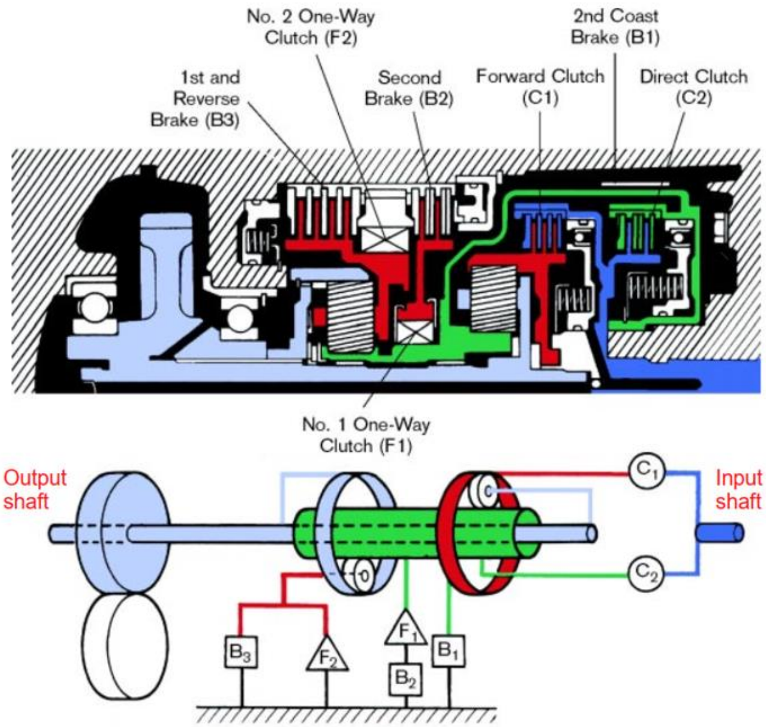


Fig. 4. An automatic transmission is composed of multiple planetary gear sets controlled by several types of holding devices

Table 2. Shifts from one gear position to another are made by changing the holding devices, i.e., clutches (C), bands (B), and Sprag clutches (F), as shown by the red arrows.

Shift Lever Position	Gear Position	C1	C2	B1	B2	B3	F1	F2
P	Parking							
R	Reverse		■			■		
N	Neutral							
D	1st	■						■
	2nd	■			■		■	
	3rd	■	■		⊠			
2	1st	■						■
	2nd	■		■	■		■	
L	1st	■				■		■
	2nd*	■		■	■		■	

*Down-shift in L range, 2nd gear only–no up-shift.

⊠ Indicates that holding device is applied but not a funtion of the current gear position.

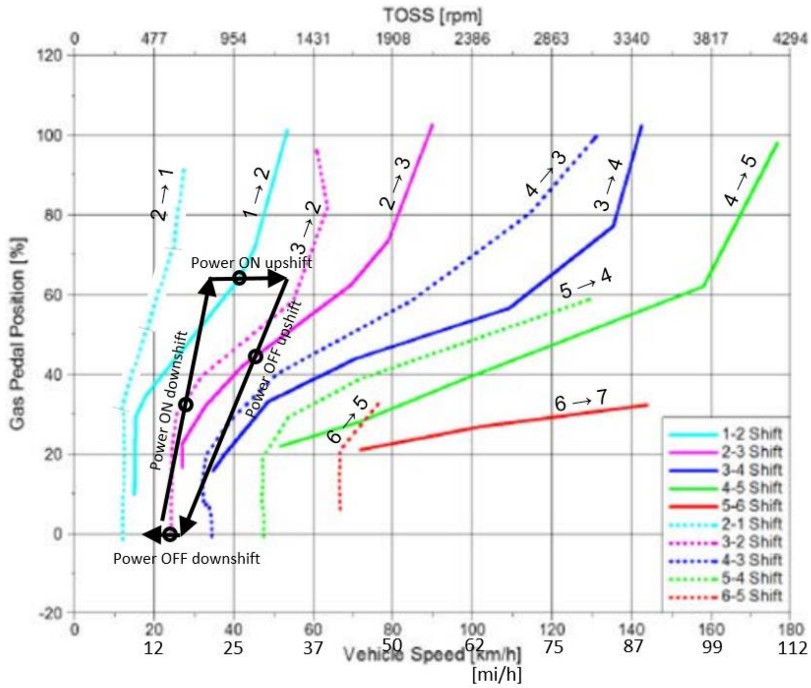


Fig. 5. Gears in an electronically controlled transmission are shifted based upon a shift map in the transmission control module (TCM) that depends on the engine torque and the vehicle speed.[1] The engine torque can be represented by either the accelerator pedal position sensor or the throttle position sensor. The dark lines in the figure show the four types of clutch-to-clutch shifts that can occur.

We have now seen how transmissions are designed and how gear shifts occur. But we still don't know how fast shifts occur. To understand this, it helps to know how the transmission fluid gets from the solenoid shift valves to the gear clutches. Figure 6 shows a valve assembly for a typical electronically controlled transmission. One can see that the solenoid valves at the top of the figure are connected to other valves and components by narrow passages for the fluid flow. These passages are then connected to the corresponding gear clutches by additional tubing or by passages inside the rotating gearshafts. When the pressurized fluid finally reaches the clutch piston chamber, it must fill the chamber before the clutch can generate enough pressure to cause the clutch to hold. Clearly, it takes time for the pressurized fluid to move through these passages and fill the clutch piston chamber. This means there is always a delay between actuation of the solenoid shift valves and clutch engagement. This delay is called the clutch fill time. It is normally on the order of 250 milliseconds. But this delay time can lengthen as a result of many things, such as low voltage in the solenoid valves, frictional variations in the fluid valves due to component tolerances and thermal variations, frictional changes in the same valves due to aging, impurities in the transmission fluid which increase valve friction, and changes in fluid viscosity due to aging or temperature (e.g., gummy transmission fluid).[E] These changes can produce intermittent delays as well as permanent delays in the clutch fill time.

E. Of all these changes, changes in the transmission fluid due to high temperature are the most common cause of transmission problems. Since the same transmission fluid is used by both the transmission gears and the torque converter, the high temperatures causing these changes can be generated either by high transmission speeds, high transmission loads, or high acceleration, abuse of the torque converter by long idle times or by idling at high engine speeds, or by faulty transmission fluid cooling due to plugged cooling filters. Transmission fluid abused in this manner is usually darker than normal with a noticeable burnt odor. For this reason, changing the transmission fluid and/or the cooling filter may be a solution to many transmission problems.

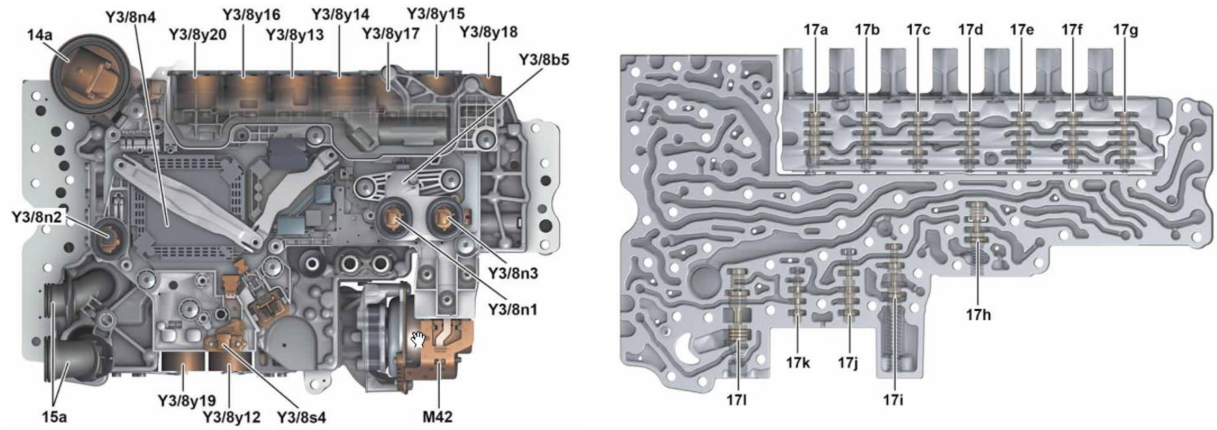


Fig. 6. The clutch pressure control system is a complex assembly of solenoid valves, shift valves, and fluid passages that transfer modulated line pressure from the PWM control valves to the gear clutches. There is always a delay for the pressurized fluid to pass from the PWM control valves through the narrow passages to the clutch actuators where it must fill the clutch piston chambers before it can apply holding pressure to the clutches. This delay is called the clutch fill time.

To understand how a longer clutch fill time can impact transmission operation, we will now look at some timing diagrams for how clutches operate during a transmission shift. The first timing diagram is for a PARK-to-DRIVE garage shift, as shown in Figure 7. This shift, and all other garage shifts, involves only one on-coming clutch. The shift starts when the driver puts the shift lever into DRIVE, which changes the throttle controller from a closed-loop idle controller to an open-loop throttle controller. The shift ends when the clutch reaches its maximum pressure. Smooth engagements require a gradual rise of pressure at the time of activation, which leads to a normal shift time of about 250 milliseconds. During delayed engagements, while the clutch pressure remains below the activation pressure as a result of a longer clutch fill time, the gears can remain in NEUTRAL for a period of one to ten seconds or more. If the engine throttle controller is operating normally during this time and if the driver is not pressing on the accelerator pedal, then the engine speed will remain at idle during this time in NEUTRAL. Then, when the on-coming clutch finally engages, there will be a modest “bump” or “clunk” in the transmission as the gears finally engage, and the driver can proceed as usual without any problems.

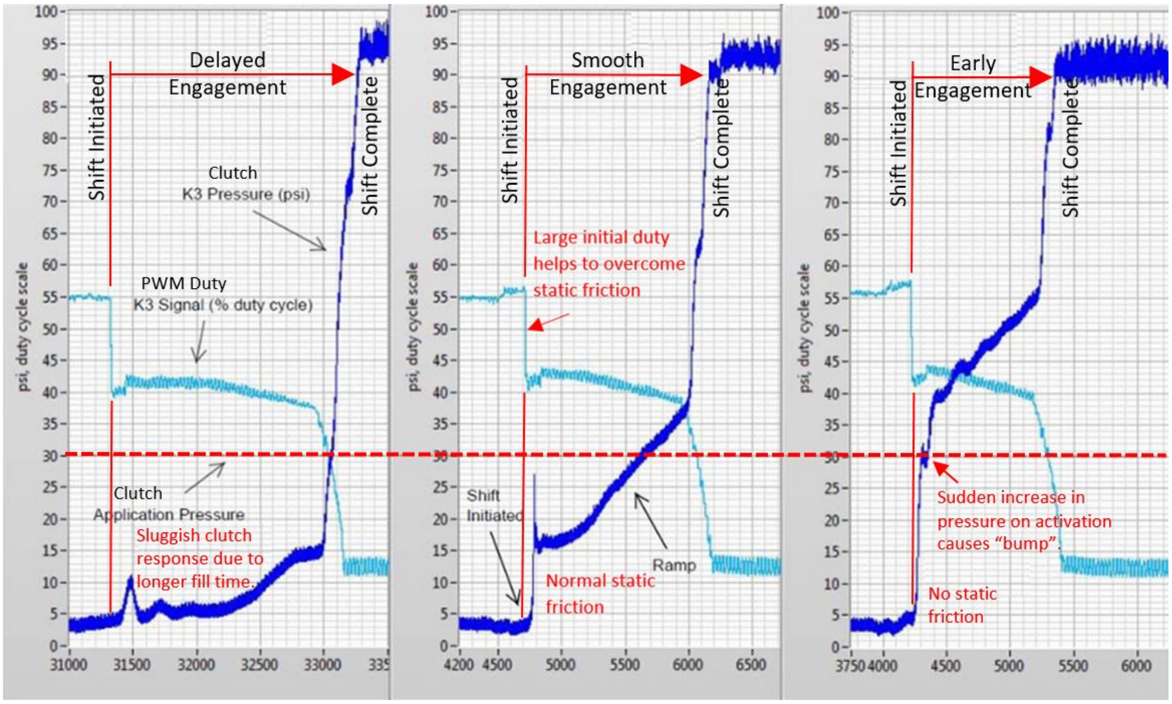


Fig 7. Shift solenoid PWM waveform and clutch pressure waveform for a PARK-to-DRIVE garage shift.[2] The shift starts when the driver puts the shift lever into DRIVE, which changes the throttle controller from a closed-loop idle controller to an open-loop throttle controller. The shift ends when the clutch reaches its maximum pressure. Smooth engagements require a gradual rise of pressure upon activation, which leads to a normal shift time of about 250 milliseconds. During delayed engagements, while the clutch pressure remains below the activation pressure as a result of a longer clutch fill time as shown in the left-hand figure, the gears can remain in neutral for a period of 1 to 10 seconds or more. Engine RPM's can rise quickly while the gears remain in neutral. If the pressure rise is too sudden, as shown for both delayed and early engagements, the engagement will be harsh and produce a noticeable shift "bump" or "clunk".

However, if there is a delayed engagement with the gears remaining in NEUTRAL for some period of time like three seconds or more, then a small increase in the throttle opening, caused perhaps by a slight change in the throttle motor gain, can cause the engine speed to increase rapidly because there is no load on the engine. This increase in engine speed will be small because the increase in throttle opening is small. But if the increase in engine speed lasts for longer than the throttle opening set-point period of 8 to 12 milliseconds, then the increase in engine speed can cause the set-point map to issue a new throttle opening set-point that is slightly higher than the previous set-point. And with each new set-point issued a slightly higher throttle opening set-point results. During a three-second period in NEUTRAL caused by a delayed engagement, the throttle opening set-point can increase 3 sec / 12 ms = 250 times, which results in a very large increase in the throttle opening set-point. This causes no DTC's because it is consistent with the normal operation of the system. But it can produce a large increase in the throttle opening without the driver pressing on the accelerator pedal. This large increase in throttle opening produces a large rapid increase in engine RPM's during the short time in NEUTRAL. The engine RPM's may even reach the maximum engine speed of 4000 to 5000 RPM's in the throttle set-point table. Then, when the on-coming clutch finally engages, there will be a large "bump" or "clunk" in the transmission as the gears engage, causing the driver's head to snap back and the vehicle will continue to accelerate without the driver pressing on the accelerator pedal. The result is sudden unintended acceleration.

Unfortunately, another possibility can occur. During the three-second period in NEUTRAL caused by a delayed engagement, the engine RPM's can also rise rapidly without a load on the engine because the driver is pressing on the accelerator pedal. Then, when the on-coming clutch finally engages, there will be a large "bump" or "clunk" in the transmission as the gears engage, causing the driver's head to snap back. If the driver continues to press on the accelerator pedal, then the vehicle will to continue to accelerate rapidly just as before. The effects are similar to a "neutral drop" maneuver used by some hot-rod enthusiasts to cause the tires to smoke before launching the vehicle at a high acceleration.[F]

A review of drivers' complaints on the Internet reveals that both types of incidents can occur. In the second type of incident, drivers are quite willing to state that they have pressed on the accelerator pedal to cause a high engine RPM during a delayed shift. This is because the delayed shift in itself can be dangerous when they are trying to accelerate to avoid a pending crash, like when leaving a parking lot with cross traffic bearing down on them. Another problem they mention is the unpleasant "bump" that occurs when the transmission finally engages with the engine RPM held high while they were pressing the accelerator pedal trying to accelerate. But in the first type of incident in which the engine RPM's increase without the driver pressing on the accelerator pedal, many drivers are just as adamant when they state that they are certain that their foot was not on the accelerator pedal, citing their driving record, their professional experience with driving cars, or the fact that their foot was on the brake pedal. It is interesting that the frequency of both these incident types correlates with vehicles that have had transmission problems, like the Jeep Cherokee and the Jaguar. And in all cases the manufacturers and NHTSA try to disavow vehicle defects by claiming that the driver caused the problem by putting his foot on the accelerator pedal instead of the brake pedal.

We will now continue our examination of how clutch fill time can affect transmission shifting by looking at the timing diagrams for a range shift. Range shifts involve clutch-to-clutch shifts from one gear ratio to another. There are four such types of clutch-to-clutch shifts, involving all combinations of up-shift or down-shift and power-on shift or power-off shift. We will look only at a power-on upshift.

Figure 8 shows the conceptual waveforms for a clutch-to clutch power-on upshift. We use conceptual waveforms to discuss this case because they illustrate more clearly the concepts involved.

In Figure 8 the goal is to shift from gear C1 to a higher gear C2. In this case, the off-going clutch torque T_{C1} decreases while the on-coming clutch torque T_{C2} increases. In Figure 8 we show two different ways of accomplishing this same operation. In the figure on the left, during the torque phase between times 1 and 2, torque is passed from the off-going gear to the on-coming gear. As the torque T_{C1} decreases, the engine speed and gear angular momentum rise because there is less of a load on the engine. As torque T_{C2} increases, the oncoming gear C2 receives both the torque and angular momentum from the off-going gear C1. But the angular momentum is too high for the on-coming gear C2. So during the inertia phase between times 2 and 3, torque T_{C2} is increased above torque T_{C1} temporarily to reduce the angular momentum of the on-coming gear. This reduces the engine speed and angular momentum, but also causes a "bump" in the drive train due to the more rapid increase in torque T_{C2}. The figure on the right shows that this "bump" can be eliminated by reducing the engine torque momentarily instead of increasing the on-coming clutch torque temporarily. This example shows not only how the two clutches

F. A "neutral drop" is performed by flooring the accelerator pedal while the transmission is in NEUTRAL to cause high RPM's and then suddenly dropping the shift lever into DRIVE. The sudden engagement of the gears produces a tremendous shock on the transmission, and makes the tires smoke if the accelerator pedal is kept floored.

operate in close synchronization, but also that engine torque control often is used to smooth out a "bumpy" transmission.

In either case of Figure 8, if the oncoming clutch has an excessively long fill time, then the delayed engagement of the on-coming clutch will cause the two clutches to no longer overlap. This results in the gears going into a temporary neutral state during which the load on the engine is significantly reduced. In this state the engine speed can increase rapidly to high RPM's, resulting in a transmission "shock" when the oncoming clutch finally activates. The result can be sudden acceleration. But this time the sudden acceleration can occur at a higher vehicle speed.

We have now finished our look at electronically controlled planetary gear transmissions. We now take a look at hydraulically controlled planetary gear transmissions.

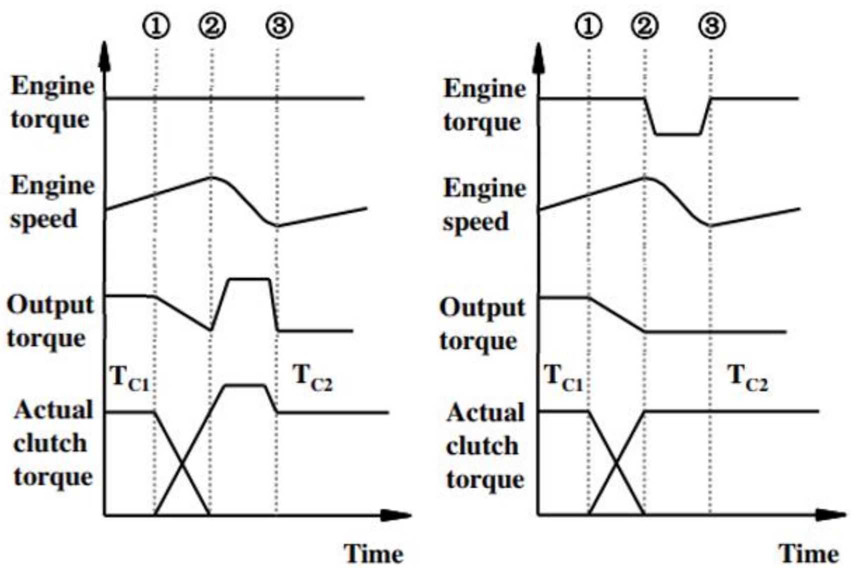


Fig 8. Conceptual clutch-to clutch waveforms for a power-on upshift.[3] The off-going clutch torque T_{C1} decreases while the on-coming clutch torque T_{C2} increases. In the figure on the left, during the torque phase between times 1 and 2, torque is passed from the off-going gear to the on-coming gear. As the torque T_{C1} decreases, the engine speed and gear angular momentum rise because there is less of a load on the engine. As torque T_{C2} increases, the oncoming gear receives both the torque and angular momentum from the off-going gear. But the angular momentum is too high for the on-coming gear. So during the inertia phase between times 2 and 3, torque T_{C2} is increased temporarily above torque T_{C1} to reduce the angular momentum of the on-coming gear. This reduces the engine speed and angular momentum, but also causes a "bump" in the drive train due to the more rapid increase in torque T_{C2}. The figure on the right shows that this "bump" can be eliminated by reducing the engine torque momentarily instead of increasing the on-coming clutch torque temporarily. If the oncoming clutch has an excessively long fill time, then the delayed engagement will cause the clutches to no longer overlap, resulting in the gears going into a temporary neutral state during which the load on the engine is significantly reduced. In this state the engine speed can increase rapidly to high RPM's, resulting in a "shock" when the oncoming clutch finally activates.

B. Hydraulically Controlled Planetary Gear Transmissions

Hydraulically controlled planetary gear transmissions are an older version of electronically controlled planetary gear transmissions that were used by every manufacturer up to about the year 2000. They both use the same planetary gear sets and holding devices, and differ only in how the holding devices are controlled. In hydraulically controlled transmissions the holding devices are controlled entirely by fluid valves responding to sensors that convert engine torque and vehicle speed into activation pressure signals. Therefore, there is no need for a transmission control module because the transmission is completely self-contained.

Figure 9 shows the manually controlled shift valve used in a hydraulically controlled transmission. Each position of the manual shift lever directs line pressure to a different set of shift valves that operate clutches for the various transmission ranges, such as P, R, N, D, L, and 2. In an electronically controlled transmission the shift lever provides only electrical inputs to the transmission control module, which then actuates specific solenoids to operate the shift valves.

Figure 10 shows the control section of each shift valve. It decreases the line pressure to one clutch while increasing line pressure to another clutch based on the value of the current vehicle speed and engine torque as represented by a governor pressure and a throttle pressure, respectively. The spring tension is adjusted to give each shift valve a unique threshold of vehicle speed/ engine torque, allowing different valves to actuate as the vehicle speed increases. This provides the same type of shift control matrix as the shift map in the transmission control module of an electronic transmission.

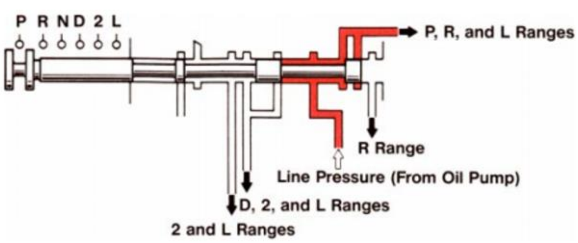


Fig 9. A manually operated shift valve is used to select transmission gear ranges based on the shift lever position set by the driver.

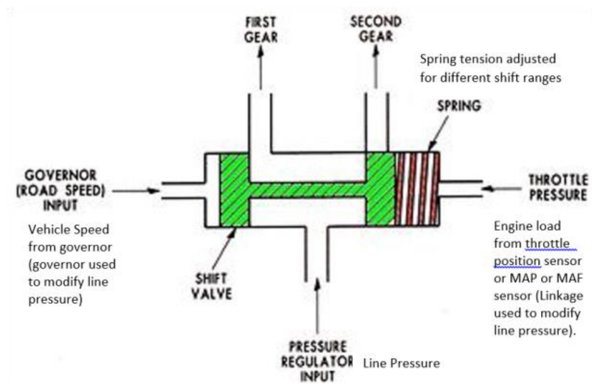


Fig 10. Each shift valve has a control section that switches the line pressure from the off-going clutch to the oncoming clutch based on the relationship of engine torque to vehicle speed. Different spring tensions determine the engine torque / vehicle speed relationship at which each shift valve operates.

Figure 11 shows how the throttle pressure (also known as detent pressure) to all shift valves originates. It can come from either a vacuum modulator valve, which senses the manifold vacuum, or from a detent pressure valve, which senses the mechanical throttle opening. Either one is a just a measure of the engine torque at any given time.

Figure 12 shows how the governor pressure to all shift valves originates. The governor is geared to the transmission output, and senses the vehicle speed. As the governor rotates faster, its outer weights are thrown outward, causing them to pivot upward while causing a valve piston to be pushed downward. This translates the vehicle speed into a fluid pressure value. Therefore, the governor in a hydraulic transmission is used only as a vehicle speed-to-pressure translation device or sensor and not as a device for limiting vehicle speed or engine speed.

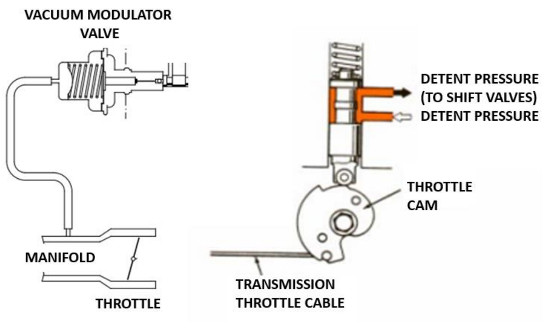


Fig 11. Either a vacuum modulator valve in the manifold or a throttle opening sensor valve is used to translate the engine torque into a throttle pressure used by all shift control valves.

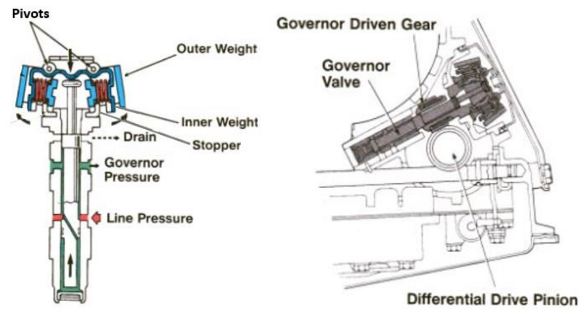


Fig 12. A rotating governor valve at the transmission output is used to translate the vehicle speed into a governor pressure used by all shift control valves.

Figure 13 shows a comparison of the shift valves in a hydraulically-controlled transmission with the shift valves in an electronically controlled transmission. The left-hand figure shows a hydraulically-controlled shift valve, with the control portion at the bottom and the shift portion in the center. All shift valves get the same throttle pressure and the same governor pressure and send the same activation pressure to a specific holding device. They differ only in the spring pressure. The right-hand figure shows an electronically-controlled shift valve with a solenoid valve portion on the left and a shift portion on the right. The transmission control module decides which solenoid gets activated and the shift portion sends pressurized fluid to a specific holding device or clutch.

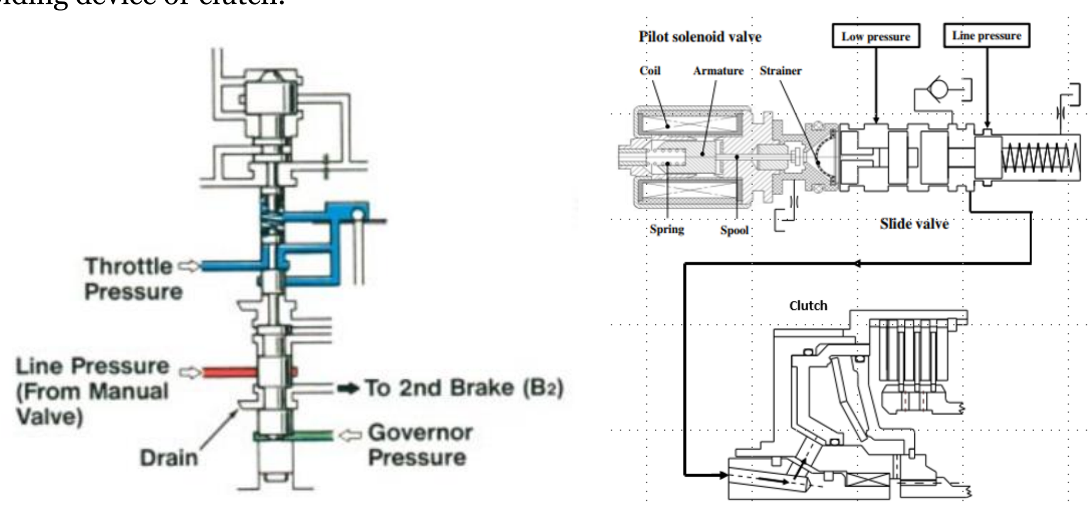


Fig. 13. Comparison of the shift valves in hydraulically-controlled transmissions and electronically-controlled transmissions. All shift valves in a transmission have the same control structure, using either hydraulic control or electronic control.

One can now see that, aside from the difference in the activation of shift valves, hydraulically-controlled planetary gear transmissions are similar in operation to electronically-controlled planetary gear transmissions. The same hydraulic shift valves and the same type of holding devices are used in both transmissions. Therefore, they should have the same type of defects, including the same susceptibility to delayed engagement. We should therefore expect that sudden acceleration incident rates would not change much as a result of the change from hydraulic control to electronic control. This appears to be the case.

So, why did manufacturers change from hydraulically-controlled planetary gear transmissions to electronically-controlled planetary gear transmissions? The answer is that hydraulically-controlled planetary gear transmissions kept getting more complex and larger as engineers had to add components like accumulators, flow limiting orifices, and ball check valves to smooth out the small "bumps" that occur during range shifts. This made hydraulically-controlled transmissions more expensive as time went on. Eventually, manufacturers saw an opportunity in the change to electronic throttles. By also changing the transmission to electronically controlled valves they could use the engine with its electronic throttle to help smooth out transmission shifts. This would allow them to eliminate the complicated hydraulic add-on components that made hydraulic transmissions more expensive, allowing them to make new electronic transmissions cheaper and smaller. It also made it cheaper to assemble vehicles with electronically controlled transmissions because they only required mating electrical connectors, instead of adjusting mechanical shift controls and making mechanical connections to a throttle sensor and governor.

C. Continuously Variable Transmissions (CVT)

Continuously variable transmissions are an old concept originally tried by GM in the 1930's. Because of their poor reliability, GM replaced them in 1937 with planetary gear transmissions, which have been used by all manufacturers to the present day. In 1985 Van Doorne made a breakthrough with a new steel belt design that encouraged Subaru to finally offer a production CVT in the USA in 1989. Now, every manufacturer is offering a CVT transmission with their newest vehicle offerings. Most CVT's are found in smaller vehicles because of limitations in transferring high engine torque without the belt slipping, which causes reliability problems. Heat from the constant movement of the belt on the pulleys is what kills a CVT.

A CVT with Van Doorne's steel belt design is shown in Figure 14. The belt transfers torque between two pulleys whose diameters vary to allow a continuous change of gear ratio. Most Japanese and American auto manufacturers like Nissan, Toyota, Honda, and Ford, use the Van Doorne belt design. Most German auto manufacturers like VW, Audi, and BMW use an alternative belt design invented by LuK with chain links. All manufacturers except Honda use the CVT with a torque converter as shown in Figure 14. Honda instead uses a clutch between the engine and the CVT, allowing the clutch to disengage the CVT while the vehicle is stopped.

Fig 14. CVT transmissions use a steel belt to transfer torque from one pulley to another. The figure inserts show the Van Doorne belt design used in most Japanese vehicles. A chain link belt designed by LuK is used in most German vehicles.

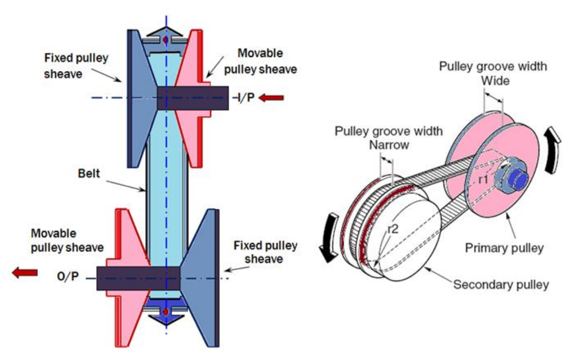


Fig 15. Gear ratios are varied by moving the red pulley sheaves in and out using electro-hydraulic actuators. As the space between the pulley sheaves increases (decreases), the steel belt rides lower (higher) in the V-shaped slot, changing the gear ratio.

Figure 15 shows how the CVT gear ratio is changed by varying the CVT pulley diameters. The diameters change as one of the sheaves in each pulley is moved in and out using a hydraulic actuator. As the space between the two sheaves changes, the belt rides higher or lower in the V-shaped slot because of the compressive forces on the sides of the belt. These compressive forces must be about 30% higher than the forces in the orthogonal direction, which are caused by the torques being transferred between the pulleys. This requires high hydraulic pressures in the control valves, on the order of 850 psi (5.9 MPa or 60 bar) at the present time. For comparison, brake pressure for drum brakes is about 1000 psi at the brake pads for a one ton load, or 1700 psi for a 1.8 ton load. As engine torque increases with vehicle size, these pressures must increase also.

Figure 16 shows another important fact. In order to obtain REVERSE and NEUTRAL, all CVT transmissions must have a planetary gear set between the torque converter and the CVT pulleys, complete with several holding devices. The only other way to get a change in gear rotation is to use a reverse idler shaft as used in manual transmissions, which is even more complicated. With a planetary gear set in series with the CVT, the behavior of the complete CVT transmission with respect to garage shifts like PARK to DRIVE becomes identical to the behavior of a planetary gear transmission, which we have discussed earlier. This means that all CVT transmissions should be susceptible to delayed engagement when shifting from PARK to DRIVE, a prediction that is borne out in actual practice. This, in turn, means that all CVT transmissions can enable high RPM sudden acceleration when following a garage shift from PARK to DRIVE. Once the CVT transmission is in DRIVE, then the change of gear ratios is continuous, so no further delayed engagements or sudden acceleration is possible.

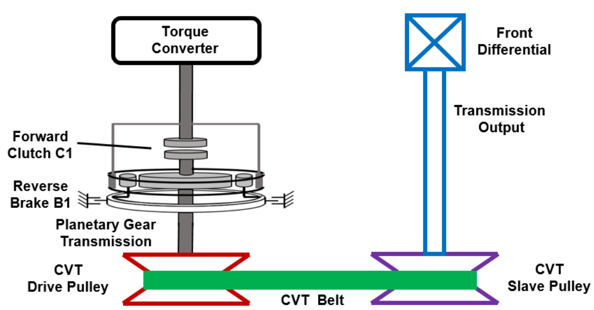


Fig 16. All CVT transmissions require a planetary gear transmission in series with the CVT to obtain REVERSE and NEUTRAL. The holding devices are controlled by solenoid-actuated shift valves.

Fig 17. Toyota has added a fixed first gear to provide higher torque when launching the vehicle from a stop. Shifting into and out of first gear is done using a gear selector as found in manual synchromesh transmissions.

The lone exception to the preceding paragraph is Honda CVT's. Since Honda CVT's do not use a torque converter, they rely solely on the forward clutch to engage during a garage shift from PARK to DRIVE. While this operation is susceptible to delayed engagement, and therefore to sudden acceleration, any resulting sudden acceleration can be cancelled promptly by applying the brake pedal, which opens the forward clutch and cancels all torque to the wheels. The result is similar to a manual transmission, which is known to support very few sudden acceleration incidents because one can always engage the clutch to stop any sudden acceleration that arises. (The few cases ever found of sudden acceleration in a vehicle with a manual transmission have all involved the driver not engaging the clutch or a slipping clutch that was partially engaged).

Having achieved our primary goal of assessing the susceptibility of CVT transmissions to delayed engagement, we now take a short excursion to look at a new development in CVT transmissions that should help their torque throughput and reliability.

In CVT transmissions, the highest torques are usually associated with launching the vehicle from a stop. Toyota has figured out a way to reduce the stress of this launching torque on the CVT belt by adding a fixed first gear to the CVT transmission as shown in Figure 17. Shifting into and out of first gear is done using a gear selector as found in manual synchromesh transmissions. The selector is controlled by a solenoid-actuated shift valve. With a fixed first gear to launch the vehicle, the CVT transmission is left only with the maintenance of the vehicle speed, which requires a much lower torque value. This means that the CVT portion can be optimized for a smaller range of speeds and torques, which usually means higher reliability.

Figure 18 shows a block diagram of Toyota's direct shift CVT. The CVT drive pulley is directly connected to the input shaft, causing the CVT pulleys to always be running. First gear is in parallel with the CVT portion. First gear is engaged by opening forward clutches C1 and C2 to isolate the CVT portion, followed by selecting 1st gear using a gear selector. (The gears are always meshed together, with only the first gear rotating freely on its shaft unless selected by the gear selector). After the vehicle is launched, the first gear remains engaged until about 15 to 25 mph. Then the forward clutches C1 and C2 are disengaged to allow the torque to pass through the CVT pulleys to the output shaft while the 1st gear is isolated. The 1st gear is re-engaged again and the CVT portion is bypassed only when the vehicle is at a complete stop. REVERSE gear is obtained by activating the holding device B1 while in 1st gear, and NEUTRAL is obtained by using REVERSE gear path, but with the 1st gear unselected. The addition of this first gear with its associated gears and second clutch does not change the susceptibility of the Toyota CVT transmission to delayed engagement during PARK to DRIVE shifts or other garage shifts.

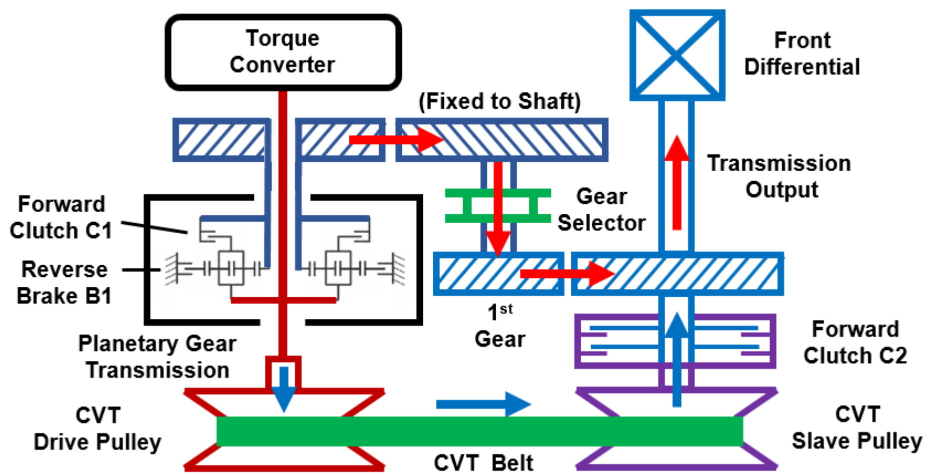


Fig 18. Toyota's direct shift CVT (DCVT) adds a selectable 1st gear in parallel with the CVT to get higher torque in 1st gear. When either the 1st gear (red arrows) or the CVT (blue arrows) is used, the other path is deactivated using clutches C1 and C2 controlled by solenoid-actuated shift valves.

All CVT transmissions use solenoid-actuated hydraulic shift valves to control the torque converter lock-up, planetary gear clutch and brake, and CVT pulleys. Figure 19 shows the block diagram of a typical CVT controller. The key take-away from this diagram is that control of the planetary gear transmission portion of the CVT is done exactly as in the case of a complete electronically controlled planetary gear transmission as discussed in section A. Therefore, the susceptibility to delayed engagement of CVT transmissions with torque converters is the same as for electronically controlled planetary gear transmissions. If a selectable 1st gear is added to a CVT transmission as Toyota has done, then more valves need to be added to this diagram to control the selectable 1st gear and the second forward clutch. But the susceptibility to delayed engagement of a CVT transmission with a torque converter will remain the same.

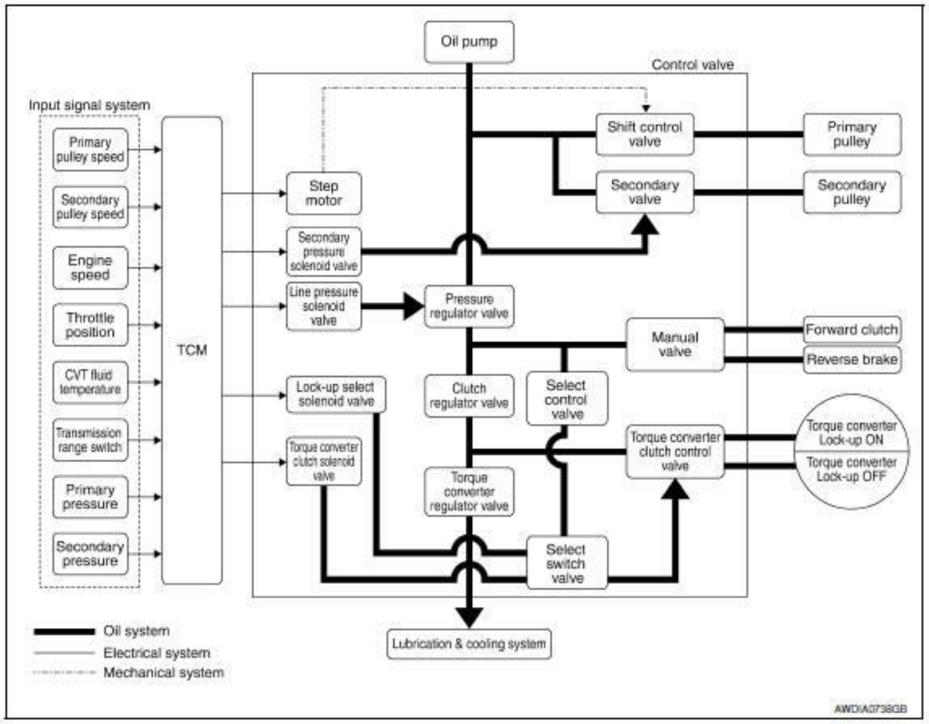


Fig 19. Transmission control units for all CVT transmissions use solenoid-actuated hydraulic control valves to control the DVT pulleys, planetary gear set for FORWARD and REVERSE gears, and lock-up of the torque converter. Additional valves are required to control a selectable first gear if present.

D. Torque Converters

All transmission types discussed to this point use a torque converter between the engine and the transmission to smooth out the change of gear ratios and to give the vehicle a small creep speed. Figure 20 shows a torque converter used with a planetary gear transmission, which is the standard automatic transmission used in the USA for the past 50 years or more. All CVT transmissions except Honda's use a similar torque converter. The torque converter merely changes the magnitude of the torque passed from the engine to the transmission. It cannot cause sudden acceleration because it lacks any controls that can change the acceleration. All torque converters, however, have a lock-up clutch as shown in Figure 21 that can be engaged at higher vehicle speeds to provide a 1-to-1 ratio of input speed to output speed. A lock-up clutch provides a fuel-saving mode to meet environmental regulations.

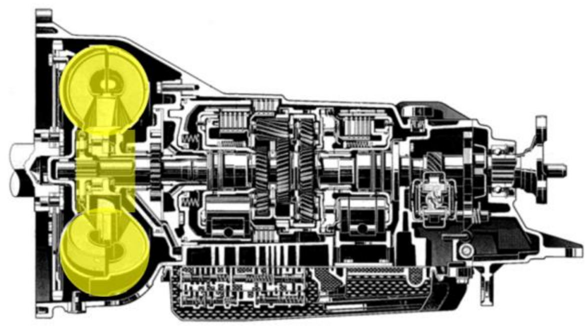


Fig 20. A torque converter is used with most planetary gear transmissions and CVT transmissions to smooth the change of gear ratios and to give the vehicle a small creep speed.

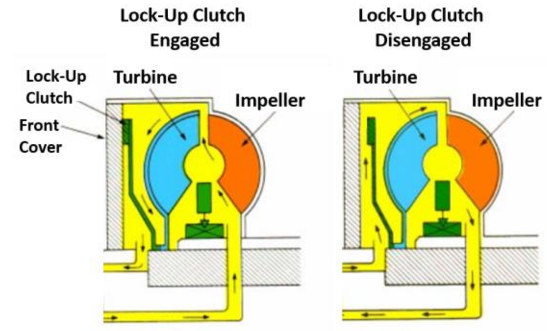


Fig 21. A torque converter passes torque from an impeller to a turbine by a pumping action on the transmission fluid. A stator helps to slow down the pumping action to provide a torque gain proportional to the ratio of the input speed to the output speed. A lock-up clutch can be engaged at higher vehicle speeds to give a 1-to-1 ratio of input speed to output speed.

E. Dual Clutch Transmissions (DCT)

Dual Clutch Transmissions (DCT), also known as Twin Clutch Transmissions or Direct Shift Gearboxes (DSG), are a subset of a more general class of transmissions called Automated Manual Transmissions (AMT) or Sequential Manual Transmissions (SMT), which may contain either one or two transmissions. All of these transmissions are versions of manual transmissions that use computer-controlled shifting in place of manually-controlled shifting. All DCTs consist of two manual transmissions connected to the engine using separate clutches without any intervening torque converter, shown in Figure 22. A differential is used to transfer the torque from either transmission to the wheels.

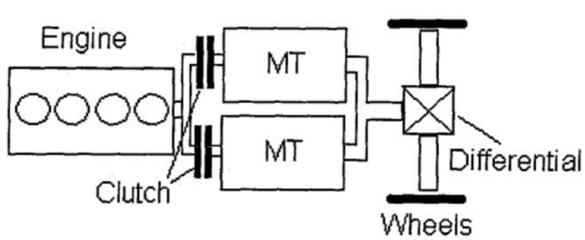


Fig 22. A dual clutch transmission (DCT) consists of two manual transmissions connected to the engine using separate clutches. The clutches eliminate the need for a torque converter.

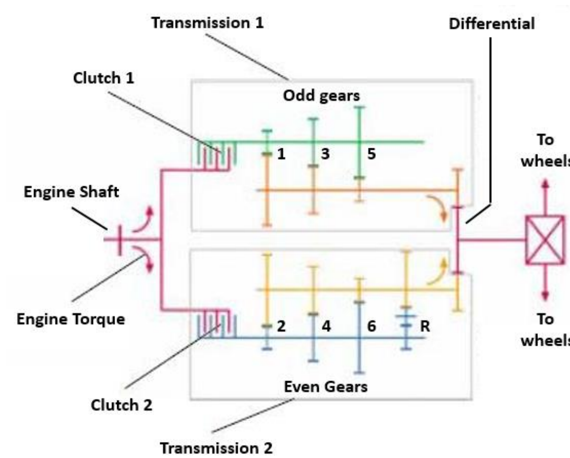


Fig 23. In a DCT, clutch 1 controls all the odd gears and clutch 2 controls all the even gears plus REVERSE. A differential is used to transfer the torque from the two transmissions to the wheels.

All dual clutch transmissions have one clutch that controls the odd gears and a second clutch controls the even gears plus REVERSE, as shown in Figure 23. This allows range shifts to occur from one gear shaft to another gear shaft with a clutch-to-clutch operation in between. REVERSE uses a gear on a special idler shaft in between the input and output shafts to obtain the required change of rotation.

Figure 24 shows a photo of the gears in a Hyundai/Kia DCT, which is similar to Ford's DCT. In this photo, transmission 1 with the odd gears is to the right and transmission 2 with the even gears and REVERSE is to the left. The input shafts of the two transmsissions are concentric, with each transmission having two output gear shafts, one on the top and one on the bottom. The two output shafts are connected to the input shafts by gears that are constantly in mesh but that spin freely on their output shafts. The gears are selectively engaged by moving selectors splined to the output gearshaft laterally to bind a desired gear to its output shaft by mating dog teeth on the gear to dog teeth on the splined selector. This is old technology introduced by GM in their synchromesh manual transmissions back in the 1950's. Finally, the torque from the two gear shafts is transferred to a single output shaft by means of a differential, which is shown to the left of gears R and 2 in Figure 24. Figure 24 also shows a cross section of the dual dry clutches used in the Hyundai/Kia and Ford DCT's.

Figure 25 shows a pictorial diagram of a DCT from Hyundai/Kia and Ford's competitor, VW/Audi, which they call a Direct Shift Gearbox, or DSG. This diagram shows more clearly that transmission 1 with odd gears (shown in red) is to the right and transmission 2 with even gears (shown in green) is to the left, with REVERSE (shown in blue) located in transmission 2. It also shows clearly that the two input shafts are concentric. VW/Audi uses the same type gear selectors as Hyundai/Kia and Ford. However, unlike Hyundai/Kia and Ford who use dual dry clutches, VW/Audi uses dual wet clutches in their DSG. Their first DSG, the DG200, used dry clutches, and had similar problems to Ford's dual clutch transmissions. But all their later direct shift gearboxes use wet clutches for improved reliability.

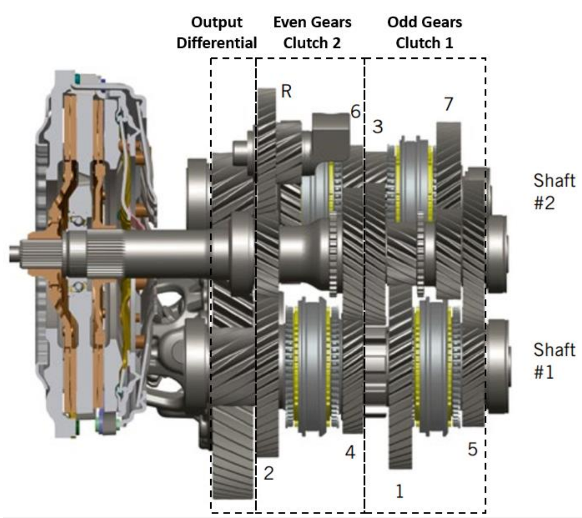


Fig 24. Ford andHyundai/Kia's DCT's use two dry clutches to pass torque to two concentric input shafts. Two outer shafts are connected to each input shaft by gears that are constantly meshed but spin freely on their shafts. The gears are selectively engaged by moving splined selectors laterally to bind a desired gear to its output shaft.

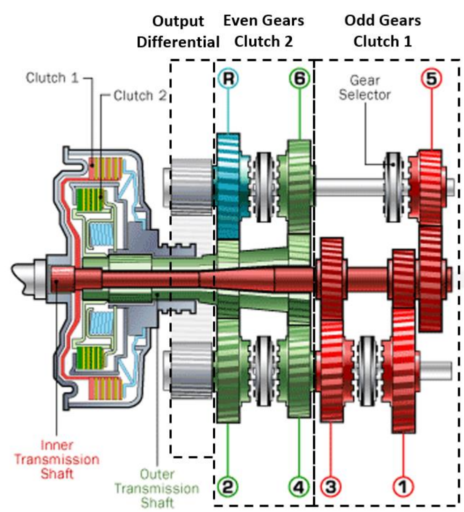


Fig 25. VW/Audi's DSG uses two wet clutches to pass torque to two concentric input shafts. Otherwise, VW/Audi's gear design and operation are similar to Ford's.

Figure 26 shows how the Hyundai/Kia and Ford dry clutches are operated. The clutches consist of clutch pads that rotate at engine speed, with each set of pads having a clutch disc in between. One disc is splined to the inner gear shaft (shaft 1) and the other disc is splined to the outer gear shaft (shaft 2). Activating a clutch transfers the torque from the rotating engine shaft, through the selected clutch pads and clutch disc, to the corresponding inner or outer gear shaft. The clutches are activated by internal linkages that press the clutch pads together to clamp the discs between them in much the same fashion as disk brakes. The internal linkages are connected via ball bearings to two sliding grooves on the outer gear shaft, which rotates at a different rate. By sliding either of the grooves back and forth along axis of the outer gear shaft, the corresponding clutch can be activated. To do this, Hyundai/Kia and Ford use two levers fixed to the gear housing that have pins that can slide in the rotating grooves. Hyundai/Kia and Ford's clutch housings contain no fluid. In fact, any trace of fluid or lubricants inside the housing can cause slippage of the dry clutches.

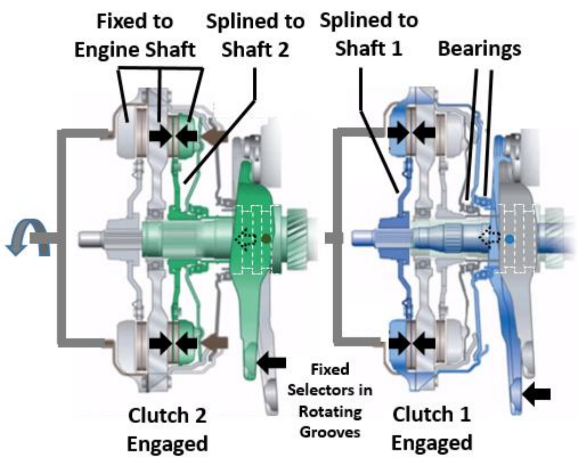


Fig 26. Ford and Hyundai/Kia's dry clutches are metal disks splined to the concentric gear shafts that spin between two clutch pads (much like disc brakes) moving at engine speed. The clutches are engaged by applying a force to the pads via linkages connected to sliding grooves on the outer gear shaft using bearings. Dry clutches have caused clutch engagement problems like slipping and randomly dropping out of gear at high speeds which have led to the recall of millions of Ford Fiesta and Focus models from 2011 to 2017.

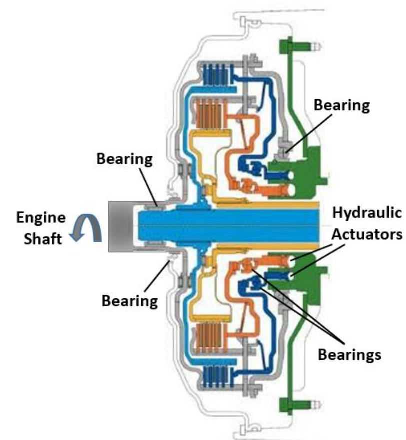


Fig 27. VW/Audi's wet clutches are multi-element clutch packs engaged by applying force to the clutches via linkages connected by ball bearings to the piston rods of hydraulic actuators. The clutch assembly's fluid and cooling system are completely separate from those of the transmission's gear assembly. Wet clutches provide more reliable clutch operation than dry clutches.

Figure 27 shows a cross section of VW/Audi's dual wet clutches. Instead of clutch pads, VW/Audi uses multi-element clutch packs as used routinely in planetary gear transmissions. The even elements of both clutch packs rotate at engine speed. The odd elements of clutch pack 1 are splined to the inner gear shaft and the odd elements of clutch pack 2 are splined to the outer gear shaft. Internal linkages apply force to the clutch packs generated from the piston rods of hydraulic actuators, with the linkages and piston rods connected via ball bearings. By activating one of the hydraulic actuators, the corresponding clutch pack can be activated. VW/Audi's clutch housing is filled with fluid just like a planetary gear transmission. A cooling system connected to a radiator is used to cool the clutches, which helps to improve clutch reliability. This cooling system is completely separate from the cooling system used to cool the transmission gears, which also helps to improve clutch reliability. By using wet clutches with active cooling, VW/Audi has been able to solve the problem with dry clutches experienced by both Ford and VW/Audi over many years. Ford's problems resulted in the 2019 recall of millions of Ford Fiesta and Focus models in the USA from 2011 to 2017, and VW/Audi's problems caused millions of defective DG200 transmissions in Europe over a similar time period. VW/Audi now uses only wet clutches in their DSG's. Ford has not yet changed.

Figure 28 shows that the clutches and gears in Hyundai/Kia and Ford's DCT's are actuated using electric motors. The motors rotate drums with spiral grooves that translate the drum's rotational motion into lateral motion of the clutch actuator rods and gear selector forks. Figure 29 shows that the clutches and gears in VW/Audi's transmissions are actuated by solenoid-actuated hydraulic shift valves. Both types of actuation involve a delay between the PWM output of the transmission controller and the initial movement of the actuator. However, this delay has no impact on DCT shifting speed because of how the shifts are performed in a DCT.

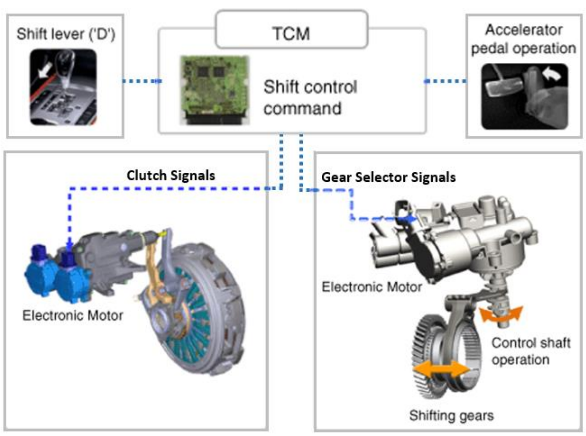


Fig 28. Ford and Hyundai/Kia's clutches and gear selectors are actuated using electric motors that rotate drums with spiral grooves that translate the drum's rotational motion into lateral motion of the clutch actuator rods and gear selector forks.

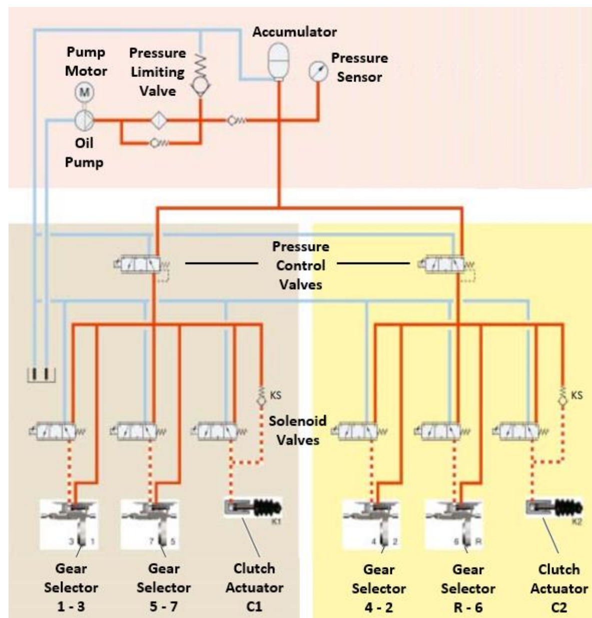


Fig 29. VW/Audi's clutches and gear selectors are actuated using solenoid-actuated hydraulic shift valves that operate at a pressure of about 70 bars.

In all DCT's, whenever a gear is selected on one output gear shaft, another gear is preselected on the other output gear shaft according to the situation at hand. Thus, if one is accelerating from a stop, when first gear is selected on one output gear shaft, second gear is preselected on the other output gear shaft. This preselection process includes the actual binding of both gears to their output shafts, which is possible because only one output shaft will be selected by one of the two clutches. This means that when shifting from first gear to second gear, only the clutch activation times are important, and not the gear actuation times. Since the shift involves the de-activation of the first gear's clutch followed by the activation of the second gear's clutch, the activation delays of the two clutches also become unimportant as long as they remain the same. The resulting shifting time from one clutch to another can then be made as small as 8 milliseconds. This is faster than any human can shift a manual transmission. Even with unequal clutch activations times, this shifting time can still be made less than 200 milliseconds, which is still faster than any human can shift. And during this shifting time the engine speed can be adjusted to smooth out any bumps produced by the shift. Finally, once the vehicle has completed the shift to second gear, the first gear is immediately de-selected, and third gear is pre-selected automatically so it can be ready to shift when its clutch is selected.

The above operation applies to all range shifts, whether they occur while accelerating (upshifting) or decelerating (downshifting). The transmission controller can easily decide what the situation is with respect to vehicle acceleration and make the proper choice of the next gear to be selected. However, the situation is slightly different when garage shifts are performed.

During a garage shift from PARK to DRIVE the driver must first put his foot on the brake pedal. This de-activates both clutches and decouples both gear shafts from the engine shaft. Only while the driver's foot is on the brake pedal can the shift lever be moved from PARK to DRIVE, which causes the 1st gear on output shaft 1 to be selected and the 2nd gear on output shaft 2 to be preselected. Then, when the driver releases the brake pedal, clutch 1 is selected to put the transmission into 1st gear. As the driver steps on the accelerator pedal, he can then accelerate the vehicle away from its current position.

With only one clutch involved in a garage shift, this means that the clutch activation times do not cancel. This produces the situation shown in Figure 30, which shows that delayed activation of the on-coming clutch can produce a short overlap with the throttle controller being in open-loop mode, because the throttle controller changed from closed-loop mode to open-loop mode when the accelerator pedal was pressed. This time overlap is much smaller than the case of shifting from PARK to DRIVE in a planetary gear transmission, because in a planetary gear transmission the open-loop throttle controller is selected at the same time the gear shift lever is changed from PARK to DRIVE. In a planetary gear transmission this results in almost the full delayed engagement time overlapping with the open loop throttle controller, which can lead to sudden acceleration. In a DCT transmission this overlap time is much smaller, which significantly reduces the likelihood of the engine RPM's going to a high value. This reduces the chances of sudden acceleration.

But DCT's also have another advantage over planetary gear transmissions that further reduces the likelihood of a sudden acceleration. The additional advantage is that whenever the driver presses on the brake pedal, both clutches are de-activated, causing both gear shafts to be decoupled from the engine shaft, as shown in Figure 30. This means that if something in the engine controller does cause high engine RPM's to produce a sudden acceleration, then stepping on the brake pedal will immediately stop all engine torque to the drive wheels. This is unlike the situation with planetary gear transmissions, which maintain the connection between the engine torque and the drive wheels when the brake pedal is pressed. The only penalty paid by the DCT transmission for this additional safety feature is that the vehicle no longer has a creep speed while in idle. With DCT's there is no creep at a stop light or while pulling into a parking place. Either the transmission is completely separated from the engine by the clutches being inactivated while the brake pedal is being pressed, or the vehicle is ready to accelerate because the driver has engaged the engine by releasing the brake pedal and has begun to apply the accelerator pedal. The situation is very similar to a manual transmission, which is known to have essentially no susceptibility to sudden acceleration incidents.

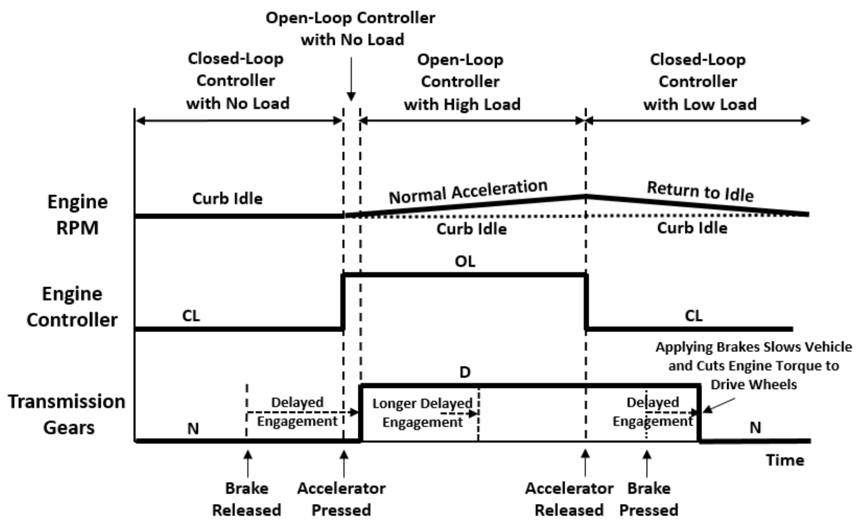


Fig 30. A timeline for DCT operation shows that a small overlap of delayed engagement time with the engine controller being in open loop mode can still occur, but it is smaller than for planetary gear transmissions. DCT transmissions have an added safety feature that applying the brake pedal at any time separates the engine shaft from the transmission gears, removing all torque to the drive wheels. This helps to stop sudden acceleration if it occurs.

DCT transmissions still have many problems that have been reported. These problems include:

- sudden loss of forward propulsion (unanticipated/abrupt shifting to NEUTRAL while driving)
- harsh/unanticipated vehicle jerking during downshifting at low speeds (often referred to as lunging or lurching)
- occasional harsh/unanticipated vehicle jerking during upshifts
- violent or intermittent shuddering during shifts
- intermittent or continuous abnormal sound/noise during shifting
- intermittent sudden/unanticipated acceleration during a gear shift (sometimes referred to as lunging or lurching, but not for long durations as in SUA)
- gears staying stuck (mostly odd gears 1, 3, 5)

The change to wet clutches has reduced these problems, but has not completely eliminated them. This has caused an automobile CEO previously employed by Nissan to remark,

> *"Ten years ago, it [the DCT] still looked like the transmission of the future. Now it is starting to look like the transmission of the past. A good conventional [planetary] automatic gearbox like the ZF is cheaper, which is absurd when you think that the manual gearbox [DCT] has survived because it is meant to be the less expensive option, but there's so much technology loaded onto a DCT to make it work. It's heavier as well, which is another disadvantage, but the real issue is the gear change itself. It's actually now faster in a [planetary] automatic, because you can control the torque. That means ultimately your 0-100 km/h times are quicker with an auto [planetary automatic], which takes away all of the marketing puff for the dual-clutch."* [4]

F. Neutral Idle Control

Neutral Idle Control, otherwise known as Neutral Idle Logic, Idle Neutral Control, Idle Neutral Logic, Automatic Neutral, or just Neutral Idle, is the automatic return of the engine to a closed loop idle mode (curb idle) when the vehicle is stopped for any reason, such as at a traffic light. Manufacturers are incorporating this feature into their newer automobiles because it can save up to 10% of the fuel used during normal city driving, as determined by standard EPA tests. It does this by taking the load off the engine so the engine can idle at the lower curb idle rate of about 800 RPM instead of the creep idle rate of about 1200 rpm when the full load of the drive train is present.

This feature applies only to vehicles having a torque converter, such as planetary gear transmissions, because it is already present in vehicles having clutches that can disconnect the drive train load from the engine, such as DCT transmissions. With this feature the vehicle no longer has a creep mode while idling at a stop. Therefore, the driver must move his foot from the brake pedal to the accelerator pedal when he wants to inch the vehicle forward at a traffic stop or in a parking lot, just as with DCT transmissions.

One interesting side effect of neutral idle control is that it may also reduce the rate of sudden acceleration incidents. This expectation comes from the observation that transmissions having clutches between the engine and the drive train, like DCT transmissions and manual transmissions, have a lower rate for sudden unintended acceleration incidents than transmissions having torque converters, like planetary gear transmissions. It has also been observed that the incident rate for sudden unintended acceleration in Mitsubishi Montero Sport vehicles in the Philippines dropped to zero when neutral idle control was added to Mitsubishi's new Gen V vehicle in 2015. In this case, very few other changes were made that could have affected the SUA incident rate, including changes to the Diesel engine, which has a completely different mechanism for SUA origination. Whether this lowering of the SUA incident rate is caused by the reduction of delayed engagement in the planetary gear transmission which keeps SUA from happening, or whether it is caused by the ability of the driver to disconnect the engine torque from the drive wheels after SUA has occurred, is still to be determined. Nevertheless, it appears that SUA can be reduced in vehicles by having a clutch between the engine and the transmission, as occurs with automatic DCT transmissions, manual transmissions, and now neutral idle control.

Adding neutral idle control to electronically controlled planetary gear transmissions is conceptually very easy. In this case, the transmission controller already has electronic control over all shifting operations, so it can easily shift the transmission into NEUTRAL whenever the vehicle is stationary instead of leaving it in DRIVE as currently done. The result is just like manually shifting the transmission into NEUTRAL at every stop, which reduces the load on the engine to allow a lower idle RPM. In practice, however, adding neutral idle control with the intent of reducing the SUA rate requires more careful control over the garage shifting operation to prevent the possibility of a delayed shift into DRIVE from overlapping with the change of engine controller to open-loop idle mode. If this is not done, then the automatic shift from NEUTRAL back into DRIVE when the light changes may still allow delayed engagement and sudden unintended acceleration. It is believed that this more careful control is possible, as evidenced by experience with Mitsubishi's 2015 Montero Sport. Whether SUA reduction was intended or not by Mitsubishi when adding neutral idle control is still unknown.

G. Manual Transmissions

Manual transmissions are considered in this review only to note that they are the cheapest and lightest of all the transmissions. Their incident rate for sudden unintended acceleration is also essentially zero over the past forty years if stuck accelerator pedals and stuck throttles are excluded. This low SUA incident rate may be due to the driver being able to quickly disconnect the torque from the wheels by disengaging the clutch whenever the engine RPM's get too high. The few SUA incidents with manual transmissions that the author was able to find over the past ten years were all short-duration lurching type incidents that were controlled in this manner.

III. Summary of Review of Automatic Transmissions

A summary of the findings from our review of automatic transmissions is shown in Table 3. To the left of the white division line we see that all transmissions neatly fall into two categories; i.e., those with torque converters between the engine and the transmission, and those with clutches in between. All transmissions with torque converters use planetary gears that can have delayed engagement, which is a defect that can allow the engine speed to rapidly increase during garage shifts when the open-loop throttle controller active in DRIVE overlaps with the transmission still being in NEUTRAL. And if the engine speed increases to cause a higher vehicle speed, there is no way for the driver to disconnect the drive wheels from the engine to reduce the vehicle speed. On the other hand, transmissions with clutches in between the engine and the transmission have practically no delayed engagement that can cause the engine speed to rapidly increase. And if the engine speed does increase to cause a higher vehicle speed, they are able to disconnect the drive wheels from the engine to reduce the vehicle speed to help bring the vehicle under control by braking. These findings are verified by a knowledge of how the transmissions operate.

To the right of the white division line in Table 3 we find the results of an Internet search for the susceptibility of various transmission types to sudden unintended acceleration. We see that the transmissions most susceptible to both high RPM sudden unintended acceleration and lunging type of sudden acceleration are those with torque converters between the engine and the transmission. Transmissions with clutches between the engine and the transmission have practically no susceptibility to sudden unintended acceleration. It is understood that the results to the right of the white division line are more subjective than those to the left because no statistical evidence is given for these results. This is why they are separated with a white division line. Still, it is believed that these results are accurate, and will be supported by statistical evidence when it is obtained.

Table 3. Summary of Review of Automatic Transmissions

Transmission Type	Connection between engine & transmission	Delayed engagement during garage shifts	Torque to wheels cut when brakes applied		High speed SUA incidents reported	Lunging incidents reported
Electronically controlled planetary gear transmission	Torque converter	Yes	No		Yes	Yes
Hydraulically controlled planetary gear transmission	Torque converter	Yes	No		Yes	Yes
Continuously variable transmission with torque converter	Torque converter	Yes	No		Yes	Yes
Continuously variable transmission with clutch	Clutch	No[1]	Yes		No	No
Dual clutch transmission	Clutch	No[1]	Yes		No	Yes[2]
Neutral idle control	Clutch	No[1]	Yes		No	No
Manual transmission	Clutch	No	Yes		No	No

Note 1. Delayed engagement can still occur, but the time that the transmission can be in NEUTRAL with the open-loop engine controller active is severely reduced. Therefore, the engine speed cannot increase rapidly to high RPM's while the engine is operating without a load.

Note 2. Most DCT lunging occurs during downshifting while coming to a stop, not during upshifting as with planetary gear transmissions.

These findings are explained further with the help of Figures 31 to 33. Figure 31 shows what happens with transmissions having planetary gears, which also use torque converters in between the engine and the automatic transmission. When the transmission is shifted from NEUTRAL into DRIVE, the engine throttle controller changes immediately from a closed-loop fixed RPM throttle controller able to reduce the engine RPM's if they get too high, to an open-loop torque-based throttle controller able to provide any torque the driver wants, but unable to reduce the RPM's if they get too high. This normally would not cause a problem if the gears shifted immediately into DRIVE because this would place a load on the engine that would limit the rate of increase of the engine RPM's. But if the gears do not engage immediately into DRIVE, as can happen occasionally with all planetary gear transmissions, then the transmission remains in NEUTRAL for a time of one to three seconds or more. During this time the engine RPM's can increase rapidly as shown in region I of Figure 31, because there is no load on the engine while the engine remains temporarily in NEUTRAL.

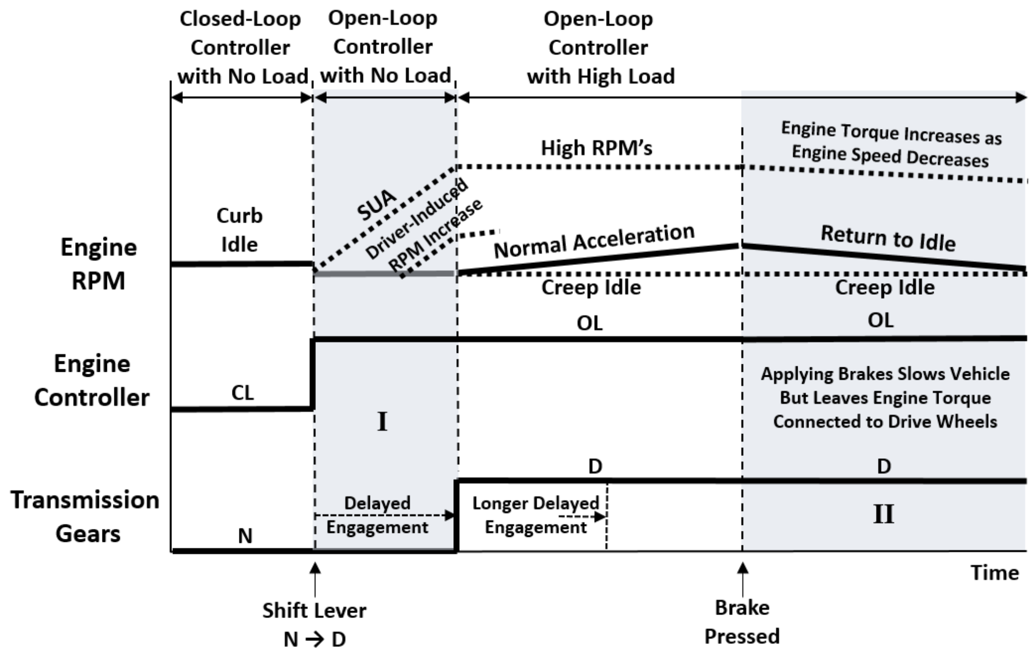


Fig 31. Transmissions with planetary gears allow delayed engagement in varying degrees. As the delayed engagement time increases, the engine spends more time in the open-loop throttle controller mode with the transmission remaining in neutral as shown in shaded region I. With no load on the engine, the engine RPM's can increase rapidly during this time. Engine RPM's can increase because the driver may press on the accelerator pedal before the gears engage, or because of sudden acceleration. In the former case, the engine RPM's achieved are lower and return to idle when the accelerator pedal is released while applying the brakes, making the brakes more effective. In the case of sudden acceleration, in shaded region I the engine RPM's rev up much faster and to a higher RPM while the accelerator pedal is released, which is usually the maximum engine RPM's possible in the throttle set-point table, as shown by the red line AB in Fig 32. When the driver applies the brakes in shaded region II, the engine RPM's decrease because of the additional load on the engine caused by the brakes, which increases the torque that the engine puts out as shown by the red line BC in Fig 32, making braking more difficult.

Engine RPM's can increase in region I either because the driver may press on the accelerator pedal while the transmission is in NEUTRAL, or because sudden acceleration may occur without the driver pressing on the accelerator pedal. Both cases have happened often. In the first type of incident, drivers are quite willing to state that they have pressed on the accelerator pedal to cause a high engine RPM during a delayed engagement. This is because the delayed engagement itself can be dangerous when they are trying to accelerate to avoid a pending crash, like when leaving a parking lot with cross traffic bearing down on them. Another problem they mention is the unpleasant "bump" that occurs when the transmission finally engages when the engine RPM's were held high while they were pressing the accelerator pedal trying to accelerate.

In the second type of incident in which the engine RPM's increase without the driver pressing on the accelerator pedal, many drivers are just as adamant when they state that they are certain that their foot was not on the accelerator pedal, citing their driving record, their professional experience with driving cars, or the fact that they verified their foot was on the brake pedal. But they are not believed when they maintain that their foot was not on the accelerator pedal, even when sudden acceleration incidents have occurred in which the engine continues to run at thousands of RPM's after the driver has exited the vehicle following a crash, and the engine can only be stopped by a first responder turning off the ignition switch.[G] It is also interesting that the frequency of both these incident types correlates with vehicles that have had planetary gear transmissions with delayed engagement problems, like Jeep Cherokees and Jaguars.

During sudden acceleration, as the engine RPM's increase while the driver's foot is off the accelerator pedal, the engine torque remains low as the engine speed increases, as shown by the red line AB in Figure 32. This RPM increase occurs rapidly in the shaded region I of Figure 31. The full RPM increase consists of many small RPM increases that occur during each iteration of an outer throttle control loop that issues new set-points. This happens every 8 to 12 milliseconds, allowing the RPM to increase 250 times or more during a 3 second duration of delayed engagement. The small RPM increases occur because the normal command to the throttle motor associated with each set-point is increased by about 20% without the ECU knowing it as a result of an improper battery voltage compensation process, as explained by the author's previous papers on sudden acceleration. This causes the engine speed to increase about 20% with each iteration of the set-point loop, producing a rapid increase in engine RPM without an increase in engine torque as shown by the red line AB in Figure 32. This all happens without a DTC being issued, either by the engine control unit (ECU) or the transmission control unit (TCU) because the changes in engine performance and transmission performance involve only changes in the magnitude of operating quantities, with no defects in hardware or software operation.

There is another feature of planetary gear transmissions that associates them with high RPM sudden acceleration incidents. This is because of their use of torque converters between the engine and the transmission. These torque converters allow the high engine RPM's to continue when the driver applies the brakes as shown in shaded region II of Figure 31. This diminishes the effectiveness of the brakes in stopping the vehicle. But the situation is even more problematic because when the driver presses on the brake pedal to stop the vehicle, the brakes place an additional load on the engine that causes the engine speed to slow down. And when the engine speed slows down, the engine torque increases as shown by the red line BC in Figure 32. This is the reason why many drivers involved in sudden acceleration incidents say that pressing on the brake pedal caused the vehicle to accelerate. And they are correct because the harder they pressed on the brakes, the faster the engine speed decreased and the faster the engine torque increased to cause vehicle acceleration.

G. There was even a case of high RPM sudden acceleration recently where a vehicle continued to run at high RPM's after the driver fell completely out of the vehicle, causing the vehicle to continue to run on its own for another one hundred yards until it crashed into a small structure. This incident serves as an existence proof that sudden acceleration can happen without the driver pressing on the accelerator pedal. And if it can happen only once, then it can happen again.

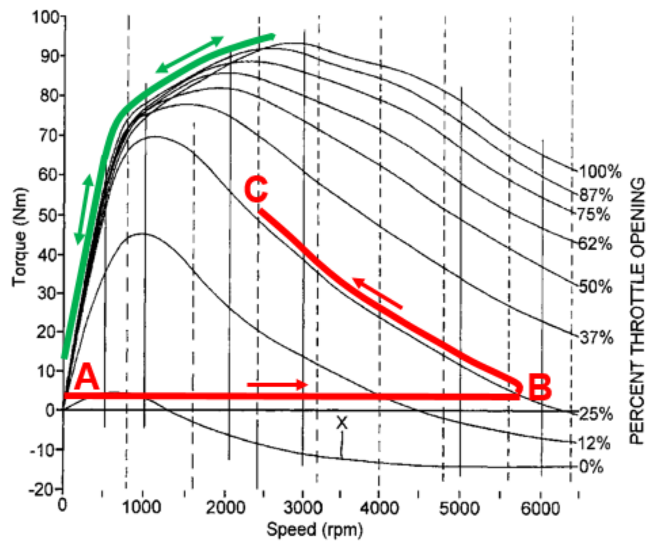


Fig 32. Engine torque versus engine speed showing normal operation (green) and operation during sudden acceleration (red).[H] During normal operation the engine follows a curve to the left of the maximum points in the throttle opening curves, causing the engine torque to decrease as engine speed decreases. But during sudden acceleration the engine speed increases rapidly from A to B on the red curve with no torque produced because there is no load on the engine due to delayed engagement, which leaves the gears temporarily in NEUTRAL. At point B the gears finally engage into DRIVE or REVERSE, putting a sudden load on the engine, causing the vehicle to begin moving forward or backward. When the driver applies the brakes, the load on the engine increases further, causing the engine speed to decrease. But as the engine speed decreases, the engine torque increases as a result of operating to the right of the curve maxima where the slopes go downward with engine speed. This causes the vehicle to accelerate as the driver applies the brakes. This is the reason many drivers involved in sudden acceleration incidents say that pressing on the brake pedal caused the vehicle to accelerate. This observation is correct because the engine torque increased as the engine speed decreased when they applied the brakes harder.

The above discussion has considered transmissions having torque converters and planetary gears that can have delayed engagement. Transmissions with clutches between the engine and the transmission, however, have a much different behavior with respect to sudden acceleration.

Figure 33 shows a timeline for DCT transmission operation. The operation of any transmission having a clutch between the engine and the transmission will be the same. In this case, region I with an open-loop throttle controller and no load on the engine is much smaller than region I for transmissions with planetary gears as shown in Figure 31. This happens because, even though there can be a delayed engagement of the clutch when the brake pedal is released while shifting from NEUTRAL into DRIVE, the throttle controller is not switched to an open-loop throttle controller at the same time. Instead, it is switched later when the accelerator pedal is depressed. Therefore, there is a smaller overlap of the open-loop throttle controller with the transmission

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H. Data in this figure, but appropriate to the engine under consideration, is used in a table that supplies throttle opening set-points to the PID throttle controller used for opening the throttle in all gasoline engines having electronic throttles. This table gets its torque inputs from a preceding table that translates the accelerator pedal position into a torque request value. The throttle opening set-points obtained from this table are issued every 8 to 12 milliseconds. Note that they depend upon the engine RPM. If the engine RPM resulting from an issued set-point is slightly higher than the RPM used to obtain the set-point from the table, then the new set-point issued in the next iteration will be higher than the previous one as a result of the higher engine RPM that was produced. This leads to sudden acceleration.

being in NEUTRAL. This means that the delay between releasing the brake pedal and stepping on the accelerator pedal is subtracted from the clutch delayed engagement time, leaving a much smaller time in region I for sudden acceleration to occur.

Not only is the likelihood for sudden acceleration reduced in transmissions having clutches between the engine and the transmission, but the clutch also helps to stop the vehicle in region II of Figure 33 by disconnecting all torque from the wheels when the brake pedal is applied. This is unlike the case for transmissions with torque converters, which remain connected to the engine during sudden acceleration as shown in region II of Figure 31, during which the engine torque can actually increase as the brake pedal is applied, making stopping much more difficult.

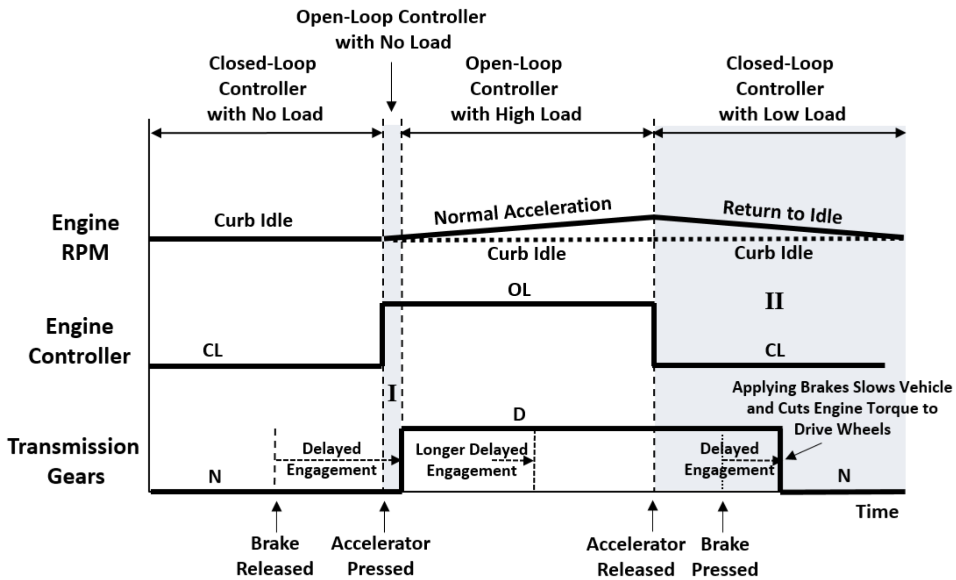

Fig 33. A timeline for DCT operation shows that a small overlap of delayed engagement time with the engine controller being in open loop mode can still occur, but it is smaller than for planetary gear transmissions. DCT transmissions have an added safety feature that applying the brake pedal at any time separates the engine shaft from the transmission gears, removing all torque to the drive wheels. This helps to stop sudden acceleration if it does occur.

IV. Consequences of Delayed Engagement

We will now point out some of the consequences of delayed engagement and transmission design on the susceptibility of a vehicle to sudden unintended acceleration.

1. Sudden acceleration does not occur with all transmission types. Only transmissions having planetary gears, whose shifting depends on the operation of hydraulic valves, have delayed engagement that causes sudden acceleration. These include:
    a. Electronically controlled planetary gear transmissions,
    b. Hydraulically controlled planetary gear transmissions, and
    c. CVT transmissions with planetary gearsets.

   These same transmissions also have torque converters that maintain torque to the wheels when the brakes are applied after a sudden acceleration. Transmissions having clutches between the engine and the transmission do not have these features, and do not support sudden acceleration. These include:
    a. CVT transmissions with clutches instead of torque converters,
    b. DCT transmissions with dual clutches,
    c. Manual transmissions, and
    d. Transmissions with Neutral Idle Control.

2. Pedal confusion as a cause of sudden acceleration is inconsistent with the differences in SUA susceptibility between transmission types. If sudden acceleration is caused by the driver pressing on the accelerator pedal instead of the brake pedal, as NHTSA, automobile manufacturers, accident investigators, reporters, and nearly all internet commenters believe, there would be no differences in SUA susceptibility between transmission types. Yet, it can be verified that differences exist in the susceptibility of different transmission types to sudden acceleration.
3. The low rate of sudden unintended acceleration incidents in Europe compared to the USA is the result of using transmission types that are not susceptible to sudden acceleration. In Europe, not only are most transmissions of the manual type, which have essentially no susceptibility to sudden unintended acceleration, but most of the remaining automatic transmissions are of the DCT type, which are essentially dual manual transmissions having a dual clutch between the engine and the transmission. Transmissions having clutches between the engine and the transmission do not support sudden acceleration.
4. Sudden acceleration incident rates are higher in vehicles having transmissions that suffer from delayed engagement, such as Jeep Cherokees and Jaguars. Jeep Cherokees, in particular, are notorious for both sudden acceleration in car washes and for transmissions with delayed engagement.[5] A review of transmissions in this publication shows that the two problems are correlated.
5. After an SUA incident, a vehicle can be tested to verify whether the transmission has delayed engagement. If it has delayed engagement, or if a history of delayed engagement can be shown via repair records, then the case for vehicle-induced SUA becomes much stronger. It the event that the delayed engagement is intermittent, a test performed after a sudden acceleration incident might not show that delayed engagement was performed. But a history of intermittent delayed engagement would still provide strong evidence.
6. All vehicles with planetary gear transmissions have delayed engagement to a greater or lesser extent. Delays can vary from a minimum of 250 milliseconds to one to three seconds or more. Some cases have reported as long as ten seconds. The longer the delay, the greater is the likelihood that sudden unintended acceleration can occur.
7. Shifting delays can increase with vehicle age and transmission abuse, which cause sluggish valve operation and sticking of the hydraulic shift valves. Delays can be caused by low voltage in the solenoid valves as well as friction in the hydraulic shifting valves due to component tolerances and aging, impurities in fluid which increase friction, and changes in fluid viscosity due to aging or temperature. Changing the transmission fluid may help in some cases to reduce delayed engagement.
8. Manufacturers find it hard to eliminate delayed engagement because there is no way to provide feedback on the fill status of the clutch reservoir being activated. This is why manufacturer's upgrades and recalls often involve software changes that change the clutch filling times and/or the times between clutch-to-clutch hydraulic valve operations.
9. No diagnostic test codes (DTC's) are triggered during a delayed engagement. This is because the control the hydraulic valves is an open-loop process in which one cannot tell when the valve actuation has actually occurred.
10. The effects of a delayed engagement are similar to a "neutral drop", which is a deliberate maneuver that involves flooring the accelerator pedal while in NEUTRAL to cause high RPM's and then suddenly dropping the shift lever into DRIVE. The sudden engagement of the gears during a neutral drop maneuver produces a rapid acceleration that throws the driver's head back and makes the tires smoke, especially if the accelerator pedal is kept floored. Needless to say, this produces a tremendous shock on the transmission that results in transmission failure after only a few times.
11. All makes and models of vehicles having either gasoline engines or diesel engines can be affected by delayed engagement in transmissions with planetary gears.

12. While the transmission is in neutral during a delayed engagement, the engine speed can increase either due to the throttle increasing on its own or due to the driver stepping on the accelerator pedal. Manufacturers claim only the latter can happen. But drivers' accounts have noted a difference between the two behaviors. Many drivers have readily admitted when they increased the engine speed by stepping on the accelerator pedal during a delayed shift, remarking instead about the delayed acceleration response and how in some cases it was dangerous to them as a result of the inability to accelerate to avoid a threatening situation and in other cases because of the "bump" when the gears finally engaged. Yet, thousands of other drivers have staunchly affirmed that their foot was on the brake pedal when the sudden acceleration occurred, claiming instead that the engine accelerated on its own. But they are not believed when they maintain that their foot was not on the accelerator pedal, even when sudden acceleration incidents have occurred in which the engine continues to run at thousands of RPM's after the driver has exited the vehicle following a crash, and the engine can only be stopped by a first responder turning off the ignition switch. There was even a case of high RPM sudden acceleration in 2014 where a vehicle continued to run at high RPM's after the driver fell completely out of the vehicle, causing the vehicle to continue to run on its own for another one hundred yards until it crashed into a power box.[6] This incident serves as an existence proof that sudden acceleration can happen without the driver pressing on the accelerator pedal. And if it can happen only once, then it can happen again. It is also interesting that the frequency of both these incident types correlates with vehicles that have had planetary gear transmissions with delayed engagement problems, like Jeep Cherokees and Jaguars. Drivers who claim sudden acceleration cannot all be insurance scammers or careless drivers who are unaware that their foot was on the accelerator instead of the brake pedal because some of them have been professional drivers, like policemen[7], taxi drivers, chauffeurs, auto mechanics, and people with safe driving records spanning many decades. They know that they will be accused of causing the incidents as a result of putting their foot on the accelerator instead of the brake pedal. But they still insist that their foot was on the brake pedal because they believe that they are right.
13. Adding neutral idle control to a transmission with planetary gears should prevent sudden acceleration in that vehicle. This seems to follow from the observation that Gen V Mitsubishi Montero Sport vehicles with neutral idle control have not had any sudden acceleration incidents since their inception in 2015, while over 212 incidents occurred in the previous six years with essentially the same engine and transmission. Neutral idle control (NIC) was added to reduce fuel consumption under city driving conditions. But it may have unintentionally reduced the susceptibility to sudden acceleration also. This addition must be done carefully to ensure that delayed engagement cannot occur. Otherwise, it will be ineffective.
14. It should always be possible to shift the transmission into NEUTRAL during SUA. Shifting into NEUTRAL is always possible with hydraulically-controlled automatic transmissions that use a manually actuated shift valve. However, shifting into NEUTRAL with newer electronically controlled automatic transmissions (ECT's) depends upon whether the transmission is in a limp-home mode or not. In limp-home mode it is impossible for a driver to shift an ECT transmission into NEUTRAL because the power to control the electronic shift solenoids is shut off, leaving the transmission in a forward gear like 3rd or 2nd gear without the ability to shift to another gear. Therefore, if the sudden acceleration causes the transmission to go into limp home mode, then it will be impossible to shift into NEUTRAL. At this time it appears that sudden unintended acceleration does not cause the transmission to go into limp-home mode because this would cause a DTC to be set, which does not happen during SUA. Therefore, it should be possible to shift the transmission into NEUTRAL during SUA.

V. Summary and Conclusion

Delayed engagement of transmission gears is shown to be a contributor to sudden unintended acceleration (SUA) by allowing the engine speed to increase rapidly after a shift from PARK to DRIVE or PARK to REVERSE. Delayed engagement is the result of an extended clutch fill time in automatic transmissions having planetary gears and hydraulic shift valves. A review of automatic transmissions shows that automatic transmissions are of two basic types. Transmissions having planetary gears and torque converters not only have delayed engagement that can lead to sudden acceleration, but they also remain connected to the engine when the brakes are applied, allowing the engine torque at high RPM's to resist the action of the brakes during a sudden acceleration incident. Transmissions having clutches between the engine and the transmission, on the other hand, are not only less susceptible to delayed engagement, but also disconnect the transmission from the engine when the brakes are applied, making stopping easier during a sudden acceleration incident. The implications of having two types of automatic transmissions that behave differently with respect to sudden acceleration are discussed.

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http://www.wranglerforum.com/f202/jeep-wrangler-2014-serious-acceleration-problem-359385.html

12. 2012 Jeep Grand Cherokee while parking with the brakes engaged, the vehicle erroneously accelerated and crossed a four lane road and then crashed into a tree. The engine continued to rev after the driver exited the vehicle. 20 other incidents described. http://www.carproblemzoo.com/jeep/grandcherokee/car-accelerates-on-its-own-problems.php

[6] Police said no charges will be filed after a Ford Expedition SUV sped out of a car wash, through a parking lot, across a busy road, and traveled more than 100 yards before hitting a major power box at a courthouse on Wednesday July 10, 2014. After crossing Dupuy Avenue, the SUV hit the curb, knocking the driver out of the seat and onto the ground before traveling more than 100 yards. https://wtvr.com/2014/07/10/update-no-charges-in-runaway-suv-case/

[7] Watch a video of a policeman in a Crown Victoria police car crashing as he exits a police parking lot at 8:00 AM on Jul 17, 2019, in "Police Car Crashes During Unintended Acceleration - Gibsonville, NC", https://www.youtube.com/watch?v=SG1D0Q9MA9kH.

Appendix I
Summary of Belt's Theory of Sudden Unintended Acceleration

The throttle valve in a drive-by-wire vehicle uses an electric throttle motor that runs off of the 12V supply voltage. If the 12V supply voltage decreases, as it can when the engine RPM is low and the battery is not fully charged[7], then the throttle motor torque decreases in proportion to the supply voltage, even though the PWM duty cycle to the H-bridge controlling the throttle motor remains the same. This can cause the throttle to open less when the DC supply voltage is low, thereby lowering the amount of air into the engine, causing the engine to run at a lower RPM as the 12V supply voltage decreases. To prevent this from happening, the throttle motor controller samples the 12V supply DC voltage, and then compensates for any decrease in the supply voltage by multiplying the H-bridge PWM duty cycle by the inverse amount that the DC battery voltage decreases. This increases the current to the throttle motor, making the throttle motor current independent of the supply voltage. This voltage sampling operation is normally done when the engine is idling at low RPM, with the sampled supply voltage being stored in a memory for subsequent use at all engine speeds.

This voltage compensation function works well as long as the DC supply voltage is sampled correctly. But sometimes an error can occur during the voltage sampling operation. This can happen when the 12V supply DC voltage is sampled at the same time that a negative voltage spike occurs on the 12V supply line. Such negative voltage spikes are present in all vehicles. They can be caused by other electric motors or solenoid valves under the hood turning on, such as air conditioner motors, radiator fan motors, or brake solenoid valves. When these actuators turn on, the inrush current to them acts like a temporary short on the 12V supply line, pulling it down towards zero volts, or ground. The 12V supply line may then go down to 10 volts, or 8 volts, or even lower, for a very short time, like a few hundred microseconds or so. This short negative voltage spike does not affect the operation of the throttle motor because the throttle motor has a large inductance, making it sensitive only to the long-term DC value of the applied voltage, which remains at 12V. But if the 50 microsecond voltage sample is taken during a negative voltage spike, then the voltage sampling operation reads a lower supply voltage which it thinks is the DC voltage, but it really is not. When the inverse of this sampled supply voltage is used to compensate (i.e., multiply) the H-bridge duty cycle while the throttle motor is supplied with a normal 12V DC supply voltage, it <u>increases</u> the throttle motor current above its normal

12V supply value. This causes the throttle motor torque to increase above its normal value, thereby allowing more air into the engine and causing the engine to run at a higher RPM. This is the root cause of sudden acceleration.

But there is more. It turns out that the inputs to the throttle motor controller don't come directly from the driver pushing on the accelerator pedal. Instead, they come from a table that issues set-points to the throttle motor controller every 10 milliseconds or so, based on the accelerator pedal position on one table axis and the RPM of the engine on the other axis. Therefore, if the engine RPM increases slightly because of an incorrect voltage compensation factor, it causes the table issuing the set-points to the throttle motor controller to issue a new controller set-point that is slightly higher, which raises the engine RPM even higher. This happens even though the accelerator pedal input to the table remains unchanged. And with each new set-point issued, which happens every 10 milliseconds or so, the engine RPM increases a little bit more, causing the engine RPM to increase over 100 times in less than one second. This means that in less than one second a small increase in engine speed caused by a small increase in the compensation factor will eventually rise to the maximum value stored in the set-point table, which may be 5000 to 7000 RPM. And when it reaches this maximum value, the engine will continue to operate at this speed until the engine is turned off or until a crash occurs. This is what causes sustained runaway engine speed, or sudden acceleration.

One can see from this explanation that the root cause of sudden unintended acceleration is the random coincidence of a short 50 microsecond pulse with a slightly longer pulse of a few hundred microseconds in duration that occurs only once every few minutes or so under the hood in all motor vehicles. The randomness of this coincidence explains the randomness of sudden acceleration incidents, which amounts to about 10 incidents per 100,000 automobiles per year. One can also see from this explanation why no evidence is ever found afterward for the cause of sudden acceleration. This is because after the ignition is turned off, when it is turned back on again, a new voltage sample is taken from the 12V supply line for voltage compensation purposes. But this time, the chances are slim that a random negative voltage spike occurs during the voltage sampling operation. Therefore, the voltage compensation is usually done correctly this time, and the engine runs normally again, with no evidence remaining to show investigators that a defect occurred to cause the previous sudden acceleration incident. This is because everything has worked completely as designed -- hardware, software, and control algorithms, both before, during, and after the incident – except that a negative voltage spike interfered with the throttle motor voltage compensation operation in a way that was never conceived of by the automobile design engineers. [During the incident the improper voltage compensation data caused by a negative voltage spike caused the throttle motor, throttle, and engine to go into an undesired state.] After all, no circuit simulations, algorithm simulations, or software testing performed by any automobile manufacturer, NHTSA, or NASA has ever included the effects of negative voltage spikes on the 12V supply line during the voltage compensation process of the throttle motor, and no EMI testing by these organizations has never applied negative voltage spikes coincident with the voltage sampling process.

There are more implications to this explanation for sudden acceleration that one can find by reading the author's papers at https://www.autosafety.org/dr-ronald-a-belts-sudden-acceleration-papers/. It is recommended that one starts reading the papers by reading the most recent papers first, starting with the paper entitled "A Clear Explanation of Belt's Theory of Sudden Unintended Acceleration". This is because the author's understanding of automobile throttle control systems has continued to improve with each paper being written, possibly leaving some older papers with incorrect statements that were later changed in newer papers.

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