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Fuel Economy Effects and Incremental Cost, Weight, and Leadtime Impacts of Employing a Continuously Variable Transmission (CVT) in Mid-Size Passenger Cars or Compact Light Trucks

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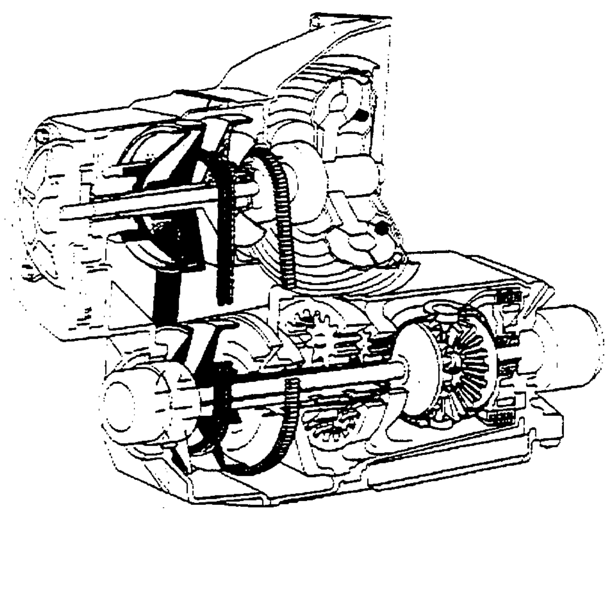

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This report is a paper study of the fuel economy benefits on the EPA City and Highway Cycles of using a CVT in a 3625 lb. car and compact light truck. The baseline vehicles are viewed as being equipped with contemporary four-speed automatic transmissions with lock-up torque converters (4SAT). The engines are each three liters in displacement, four valves per cylinder for the car and two valves for the truck, each with sequential port fuel injection and electronic throttle control. The continuously variable transmission selected for the study was a modified Van Doorne push belt type, termed the Dual Mode. Calculations were made for a range of CVT efficiencies: same, +3% AND +6% relative to the 4SAT. This range was thought to cover practical designs for larger vehicles. For the car only, the camshaft was modified to provide increased torque at low speeds, the HITORC engine. For the car, Combined Cycle economy gains ranged from 6.6% with equal to 11.0% with an assumed 6% transmission efficiency gain. Gains for the light truck were very similar; 6.0% to 10.8%.

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PREFACE

This report is a paper study of the fuel economy benefits on the EPA City and Highway Cycles of using a Continuously Variable Transmission (CVT) in a 3625 lb. car and compact light truck. This report was prepared for the Volpe National Transportation Systems Center under Contract Number DTRS57-98-P-80176 by Dr. Donald J. Patterson, Mr. Thomas R. Stockton, and Mr. Ronald L. Harris. This contract was in support of The National Highway Traffic Safety Administration's effort in exploring technologies that could improve the fuel economy of light duty vehicles without compromising their size, load capacity, emissions, or performance.

The authors wish to acknowledge the support of Thomas Leone, Walter Muench, and the Ford Motor Company for providing transmission wisdom and specifically speed and load times for the vehicles on the EPA Cycles. We also thank University of Michigan Ph.D. student Phil Prezbylo for his invaluable help in running the export version of the GM Engine Simulation Program. Likewise, we thank Aladar Simko for his assistance in selecting engine parameters. The excellent report graphics were produced by Mr. Rod Hill of the University of Michigan Mechanical Engineering Department. Last, but not least, we thank the NHTSA team of John Guglielmi, Orron Kee, and Sanjay Patel for their excellent support both in technical and contract areas.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches: 0 1 2 3 4 5

Centimeters: 0 1 2 3 4 5 6 7 8 9 10 11 12 13

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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I. INTRODUCTION

The search for increased automobile and light truck fuel economy has identified the Continuously Variable Transmission (CVT) as a potential means for achieving greater drivetrain efficiency. The contemporary four-speed automatic transmission with lock-up torque converter (4SAT) averages about 84% efficiency on the EPA City Cycle and perhaps somewhat higher on the EPA Highway Cycle, cycles which were designed to emulate fuel economy of vehicles in real world driving. A transmission whose efficiency is closer to 100% would theoretically increase fuel economy by about 20%, if all other factors contributing to fuel consumption were constant.

In the past a number of smaller cars with engines of 2 liters or less have been built with CVT's, mainly for markets outside the U.S. The vehicle market in the U.S. is dominated by larger vehicles and engines. The National Highway Traffic Safety Administration (NHTSA) is the agency within the Department of Transportation charged with setting and enforcing the Corporate Average Fuel Economy (CAFE) standards. The question arises: "To what extent can fuel economy of larger cars and light trucks be increased by use of the CVT?" The present study was designed to explore that question.

This report is a paper study of the fuel economy benefits on the EPA City and Highway Cycles of using a CVT in a 3625 lb. car and compact light truck. The baseline vehicles are viewed as being equipped with contemporary four-speed automatic transmissions with lock-up torque converters. The engines are each 3 liters in displacement, four valves per cylinder for the car and 2 valves for the truck, each with sequential port fuel injection and electronic throttle control. The continuously variable transmission selected for the study was a modified VanDoorne push belt type, termed the Dual Mode. Calculations were made for a range of CVT efficiencies: same, +3% and +6% relative to the 4SAT. This range was thought to cover practical designs for larger vehicles. For the car only, the camshaft was modified to provide increased torque at low speeds, the HITORC engine.

Part load fuel economy results were calculated by using a single cylinder engine computer program, published data and extrapolated experimental data. Fuel economy results are presented for both EPA City and Highway Cycles as the Combined Cycle. For the car, Combined Cycle economy gains ranged from 6.6% with equal to 11.0% with an assumed 6% transmission efficiency gain. Gains for the light truck were very similar; 6.0% to 10.8%. The Highway Cycle gains were larger than the City Cycle gains. These are very large gains, if they can be achieved without limits imposed by engine knock, emissions and driveability. The calculations yielded a significant increase in engine-out NOx emission. However, it is thought that this increase can be resolved with conventional catalyst technology together with engine and transmission software modifications. Thus no cost or weight penalties were assumed for emission control purposes. An analysis of the incremental cost, weight, and lead-time of the selected CVT relative to a conventional production 4SAT showed no significant differences.

II. SUMMARY OF FINDINGS

A. INTRODUCTION

The search for increased automobile and light truck fuel economy has identified the Continuously Variable Transmission (CVT) as a potential means for achieving greater drive train efficiency. The contemporary four-speed automatic transmission with lock-up torque converter (4SAT) averages about 84% efficiency on the EPA City Cycle and perhaps somewhat higher on the EPA Highway Cycle, cycles which were designed to emulate fuel economy of vehicles in real world driving. A transmission whose efficiency is closer to 100% would theoretically increase fuel economy by about 20%, if all other factors contributing to fuel consumption were constant.

Following are conclusions and observations regarding the fuel economy benefits on the EPA City and Highway Cycles of using a CVT in a 3625 lb. car and compact light truck. The baseline vehicles are viewed as being equipped with contemporary four-speed automatic transmissions with lock-up torque converters. The engines are each three liters in displacement, with four valves per cylinder for the car and two valves per cylinder for the truck. The continuously variable transmission selected was a modified Van Doorne push belt type, termed the Dual Mode. Calculations were made for a range of CVT transmission efficiencies from equal to that of the 4SAT up to 6% greater to cover practical designs for the CVT equipped vehicles.

The fuel economy benefits indicated below result from the generally lower speed and higher load engine operation with the CVT system. Lower speed reduces engine friction, accessory and transmission oil pump losses. Higher loads also reduce pumping losses, but increase NOx emissions.

B. FUEL ECONOMY FINDINGS AND EMISSION CONCERNS

1. Under the assumption of equal transmission efficiencies for the conventional 4SAT and CVT, the fuel economy gains on the Combined EPA Cycle were calculated to be 6.6% for the car and 6.0% for the light truck.

2. The Combined Cycle efficiency gains increased to 11.0% and 10.8% for the car and light truck respectively under the assumption of a CVT efficiency increase of 6% relative to the 4SAT.

3. Larger improvements in fuel economy were found on the Highway Cycle. This result arose from the large fuel consumption values at the higher speeds on that cycle, fuel consumption values that were most reduced by the generally lower engine speeds employed with the CVT. From another point of view, it might be said that under conditions of low or moderate engine speed with the conventional transmission, little benefit is realized with a CVT, since the speed of the engine is already low. This is the situation for a good portion of the EPA City Cycle.

4. Calculations of engine-out NOx emission yielded an increase of 43.7% on the EPA City Cycle for the CVT-equipped car with equal transmission efficiency. With +6% CVT transmission efficiency, this increase dropped to 34.1%. The increases for the light truck were lower, 17.6% and 9.6%. While the precision of these calculated results is in question, there is no doubt that some significant engine-out NOx increase will result. The increase can probably be resolved with current catalyst technology and engine and transmission control software changes. Hydrocarbon and carbon monoxide emissions were viewed as being about the same with the CVT. Thus, no cost weight penalties were assumed for emission control purposes.

C. COST, WEIGHT, AND LEADTIME FINDINGS

Analysis of the Dual Mode CVT design relative to a conventional, production 4SAT showed virtually no cost or weight differences. It was also concluded that there were no capital equipment or production leadtime differences relative to production of a new, conventional 4SAT.

D. OTHER CONCLUSIONS, OBSERVATIONS AND CONSIDERATIONS

1. The engine designed for a CVT application should have a camshaft designed for higher torque at low engine speeds, torque levels subject to knock, NOx and driveability constraints. This will enhance the CVT fuel economy benefits while allowing the same acceleration time.

2. Use of variable valve timing (VVT) is expected to further enhance CVT fuel economy benefits by allowing optimization of valve events at both high and low engine speeds. This should allow lower idle speeds and some engine downsizing. VVT may also improve NOx control problems with CVT use.

3. An engine designed for CVT application should have particular attention paid to the friction and accessory losses at the minimum sustained design speed, 1100 rpm in this study. This means particular attention must be given to valve train friction, especially if a VVT system were used.

4. Realization of maximum CVT economy gains may be limited by NOx emission, engine knock, intake noise, and roughness considerations. These are potentially serious constraints to widespread application of CVT's to larger vehicles in order to realize optimum fuel economy benefits therewith.

5. The application of a CVT to a rear wheel drive vehicle is somewhat constrained by packaging considerations due to the offset inherent in this transmission design. On the other hand, the CVT is well configured for a front drive car or van. Poor weight distribution is a problem for a front wheel drive pickup truck.

III. BACKGROUND INFORMATION

A. BACKGROUND

The National Highway Traffic Safety Administration (NHTSA) is the agency within the Department of Transportation charged with setting and enforcing Corporate Average Fuel Economy (CAFE) standards under the Energy Policy and Conservation Act of 1975. The rulemaking process requires extensive technical research and analysis before promulgating new standards or amending existing ones. Both technological feasibility and economic practicability must be established before new technologies can be included in projections of industry fuel economy capabilities.

This study was designed to provide two end products: a computer-assisted estimate of the vehicle fuel economy benefits of combining a continuously variable transmission (CVT) with a state-of-the-art V-6 engine of 3.0 liters displacement, and a cost, weight, and lead-time assessment relative to a conventional four speed automatic transmission with lock-up torque converter. Applications to both a 3625 lb. car and compact light truck are made.

B. STUDY PARAMETERS

EPA City, Highway and Combined Cycle fuel economy projections for both base and CVT transmission-equipped vehicles are made. Projections are based around a state-of-the-art engine and base transmission as follows:

a. The car engine is a fuel-injected, V-6 of 3.0 liters displacement with four valves per cylinder. The truck engine is the same except two valves per cylinder.

b. The base transmission is a four-speed automatic with lock-up, a state-of-the-art transmission for passenger car and light truck applications. Each vehicle is assumed to weigh 3625 lb. ETW. This includes driver and passenger (300 lb.).

c. The CVT-equipped vehicles are projected to have similar performance and driveability as the base vehicles.

d. The engine-CVT transmission and vehicle combination are estimated to comply with EPA Tier I Vehicle Emission Standards with respect to hydrocarbon, oxygenate and carbon monoxide emissions. High levels of engine-out NOx emission may be a problem.

The engine, vehicle and CVT system chosen for this study are further described in Chapter IV including the many assumptions needed for the calculations. The fuel economy and emission projections are presented in Chapter V. Cost, weight, and leadtime projections are presented in Chapter VI.

C. HISTORICAL PROSPECTIVE

Since the beginning of the automotive industry there have been many attempts to develop a shiftless, or continuously variable transmission. The objectives were to improve smoothness and ease of operation. The introduction of the Hydra-Matic transmission in the early 1940s provided the ease of operation, but the gear ratio changes were incremental, as are most automatic transmissions today. In the 1950s, the addition of a hydraulic torque converter added smoothness, but with some loss of fuel economy. The modern four speed automatic transmission (4SAT) with torque converter lock-up clutch has evolved as the industry standard. Although complex, it is cost effective, efficient, durable and provides good driveability. The 4SAT is not torque limited and is readily adaptable to both front and rear wheel drive. While torque converter lock-up has significantly improved its fuel economy, especially on the highway, the city fuel economy suffers due to frequent gear changes and the location of the operating point away from the best fuel economy region of the engine.

Meanwhile, in the 1960s the Van Doorne variable sheave transmission was introduced for the small DAF car and truck made in Holland. It was the first CVT to provide all the desired CVT transmission features and exhibit reasonable durability, fuel economy, and cost. Previously, some cars in the early 1900s, such as the Sears Roebuck, Carter and Reeves-employed CVT drives. They used leather facings and "V" belts of wooden blocks. They were impractical and did not survive.

What is a CVT? The conventional manual or automatic transmission provides a number or discreet speed ratios through positive gearing. In contrast, the continuously variable transmission provides a smooth transition between the maximum and minimum ratio extremes, typically equally spread between maximum underdrive through 1:1 to maximum overdrive. In principle, the CVT can then cause the engine to operate at its most fuel efficient speed under all driving conditions. This is generally the lowest speed to meet the power demand on the engine consistent with minimal combustion knock, and vehicle driveability impairment, vibration and noise. It is useful to point out that CVT transmissions always operate with some slip, whereas geared transmissions do not.

Experience indicates that knock is an especially serious problem with CVTs due to the sustained high loads and low speeds used consistent with their operation for optimum fuel economy. In this study we have assumed that the maximum torque permitted for sustained CVT operation is 80% of the maximum full load value, mainly because of knock considerations. Driveability problems arise when the engine speed is too low and the individual cylinder torque pulses too high for smooth operation of the vehicle. We might term that chugging, or a form of enhanced surge. The assumption of a six cylinder engine in this study helps that problem as does limiting maximum sustained torque to 80%. Another assumption of the present study is to limit sustained increased engine load operation with the CVT to 1100 rpm and above. Below 1100 rpm and including idle speed, normal engine/transmission operation is assumed. Engine noise and vibration become a problem with the CVT because of the high loads (high cylinder pressures) and relatively low engine speeds (better transmissibility of noise and vibration). In a paper study such as this, noise and vibration cannot be addressed quantitatively. However, it is likely that some greater acoustical and vibration isolation treatment may be required to make the vehicle commercial.

In recent times, CVTs have been applied to a number of small vehicles in Europe and Japan. Honda sells a CVT in the Civic HX car in the U.S. Generally, application has been to engines of two liters or less. Because of fuel economy considerations, it is of interest to study the potential for a CVT in a larger domestic vehicle, such as the 3625 lb. vehicles assumed in this study. The fuel economy improvement of a CVT arises from at least three sources. In decreasing significance these are:

1. Reduction of engine friction and accessory losses (primarily oil and power steering pumps) resulting from lower speed operation of the engine.

2. Reduction of pumping losses resulting from higher load operation of the engine.

3. Reduction of transmission losses including oil pump compared to a conventional four-speed automatic with lock-up.

In addition to the above, it may be possible to downsize the engine somewhat while matching vehicle acceleration time. This is due to the ability of the CVT transmission to dwell close to the maximum power point of the engine, thereby delivering peak power more consistently than a geared transmission. Further, the CVT drivetrain may benefit from use of variable valve timing, VVT. This is because of the desirability to achieve high torque at low engine speeds with the CVT, while maintaining high load acceleration. In a fixed camshaft engine, a compromise would be required. VVT combined with CVT is expected to provide some additional economy gains, the combined total being less than the sum of the individual gains. This is because both lower pumping losses, and that benefit can only be realized once. VVT was not addressed in this study but was addressed by itself in a previous study, Reference 25. It should be pointed out that durability of CVT transmissions in large volume production for larger vehicles has not been demonstrated.

D. THE DIFFERENT TYPES OF CVT'S

The various types of CVT's can be classified as:

Friction drives (basis for this study)
Traction drives
Hydro-mechanical drives
Hydro-kinetic drives

1. Friction Drives

Recognized as the most practical of the friction drive concepts is the metal "V" belt system operating in an oil environment. It employs two pairs of moveable, conical steel pulleys and an all steel composite flexible "V" belt assembly. The pulleys are hydraulically clamped against the angled sides of the "V" belt to provide two parallel friction drive surfaces to resist belt slip under load. Unlike positive drive gearing, friction drives always encounter some tangential slip as well as contact surface "spin" losses, for a minor loss in efficiency. Belt clamping loads must be optimized to minimize these losses and to insure adequate life. Gearing also encounters minor friction losses at the tooth mesh surfaces as well as very minor spin losses. Figure III-1 shows the essential features of the Van Doorne design CVT transmission.

The "V" belt drive is ideally suited for the transverse mounted, front wheel drive engine, transmission system. This is because it provides a built-in offset from engine-to-wheel axis, an extra cost addition to the 4SAT. Conversely, the offset configuration makes this transmission less suitable for rear drive application. The three major contenders for this type of transmission are the Van Doorne "Pusher" belt concept, and the Borg Warner and Reimers tension link chains. At this time, the Van Doorne system is the unquestioned leader. However it is presently limited in torque capacity to smaller vehicles with about two-liter engine size. Of the three, it is the most viable design for the present study because of several years of production experience and demonstrated low noise level. The low noise is attributed to the elimination of the typical chordal action of chain links. The pusher belt utilizes a stack of relatively thin wedge-shaped steel, non-connecting blocks pressing against the pulley surfaces. The blocks are contained with a nest of thin steel bands which are forced in tension by hydraulic clamping of the pulleys. The stack of blocks is entirely in compression between the driving and driven side. The large area of pulley contact results in relatively low contact pressures as shown in Figures III-2a, b, and c. This design is reasonably resistant to failure and can experience occasional large slip without excessive noise which otherwise would constitute a failure mode.

The Borg Warner Morse Chain Division devoted extensive development to the chain link construction, including both low and high capacity chains. The latter was claimed capable of handling the output of a five-liter engine, even directly through a 2:1 torque converter. To do that, however, required extremely high hydraulic clamping pressures, leading to structural and friction issues. The high capacity application was focused on larger rear wheel drive cars and trucks, but would not have been economical unless manufacturing volumes were high. The lower capacity chains, however, could have been competitive with the Van Doorne belt; and these were explored by automotive industry research groups in the 1980s.

In addition to the steel "wet" belts, the Gates Rubber Company together with automotive industry groups, devoted considerable effort in developing an elastomeric, or "rubber" belt for automotive application. The belt operated dry, thus providing more than a five-fold advantage in driving friction over steel belts running in oil. This permitted lower cost construction of the pulleys and allowed much lower hydraulic clamping loads. The dry belt has found widespread application in snowmobiles, farm machinery and industrial use. For automotive application the durability, serviceability, and noise problems were judged to be too unacceptable.

2. Traction Drives

By evolved definition a traction drive differs from a friction drive in that it drives through rolling motion, and its heavily loaded contact "patches" are small in area. The heavy clamping load produces extremely high Hertz stresses at the contact. Under this condition the fluid film becomes a solid, and special synthetic oils were developed for the application. The drive is through viscous shear of the oil film. Excessive slip can destroy the surface, resulting in a "noise" failure.

As conventionally employed, traction drives are inherently reversing mechanisms with the output member rotation in the opposite direction from the input member. The two most common and best suited drives for automotive use are toroidal shaped input and output cavities clamped against spherical rollers, usually carried by a stationary cage. They are either the full torus, Figure III-3, known as the "Hayes" drive, or the half torus, Figure III-4, known as the "Arter" and "Deep Cone Roller" drives. Both types are and have long been under active development for CVT's. The rollers tilt about their axis to change the effective input and output rolling radius, thereby changing ratio.

Many years ago General Motors Research had an extensive program on the "Hayes" type. This was abandoned in favor of the Hydramatic automatic transmission. Later the design was explored for large truck gas turbine engines. Currently NSK in Japan has a large traction drive CVT program based on the "Arter" drive. As a means for canceling out the high axial clamping load and the counter rotation of either type, two toroidal cavities are usually mounted back-to-back. This doubles the capacity of the CVT, but introduces considerable complexity and cost. The "Arter" drive introduces an additional heavy radial thrust load on the rollers, which creates a formidable durability problem. Interestingly, the half torus has an efficiency advantage in that the rolling action approximates rolling cones, as in a tapered roller bearing. The full torus generates more elongated contact patches in the mid and outer rolling radii, resulting in increased "spin" losses compared with the half torus.

Another traction drive is the IVT. It has an infinite ratio range. Neutral is not a true Neutral but a "geared neutral" with a ratio of infinity. Either side of Neutral produces an extremely high Forward or Reverse ratio. This arrangement, known as the "Perbury" drive has been under development for decades in England, now by the British Technology Group, who renamed it "Torotrak." It employs a full torus, see Figure III-5. It is claimed that the transmission is production ready and yields a 20% fuel economy increase. Many automotive companies have licensing agreements on the Torotrak. The internal gearing of the double cavity design shown in Figure III-6 provides both a Low and High range. Assuming a scaled 2:1 gear reduction ratio from engine to the planetary gears and a planetary ring gear-to-sun ratio of 2:1, then the torus outer driving radius-to-inner driven radius would be 1.5 in geared neutral. Equal radii would yield an underdrive ratio of -2:1. When the torus driving radius-to-driven radius reaches 0.5 the Low clutch is released and the High clutch applied at a synchronous speed, where the belt and pulley system carries 100% power. Maximum overdrive ratio would be approximately -0.6. In the Low range the power path is split for improved efficiency. Past attempts at geared neutral have however revealed very serious control and driveability problems and susceptibility to traction failure.

Many variations of traction drives include the "split power path" and the "regenerative" power path, shown in Figures III-7 and III-8. The advantage of split path is to partially bypass the CVT unit, to improve efficiency and capability but at the sacrifice of ratio range. With the regenerative system, part of the output power is fed back to combine with input power. This increases ratio range but at the expense of efficiency and torque capacity. Both rely on complex gearing and are not being pursued.

Another CVT approach is the Two Pass system, Figure III-9. The concept described by Borg Warner employs the "V" belt and pulley system as the ratio changing device. In this arrangement either pulley can be driven by the engine at different gear ratios. The engine input shaft can be clutched to one pulley, with the opposite pulley becoming the output shaft. During vehicle start-up, the input pulley is in maximum underdrive. As the ratio reaches maximum overdrive, the input and output pulleys exchange function by switching clutches at a synchronous speed. The pulleys then proceed to destroke back to the original start-up position but now overdrive the output. The overall CVT ratio range thus becomes the square of the range of the pulley system. A modest 4:1 pulley range would thus extend the overall ratio to 16:1. It appears that this range is far in excess of the required optimum, and the added complexity and controls issues are difficult to justify. There is no known current activity on this approach.

3. Hydro-Mechanical Drives

Employing hydraulic pumps and motors in a wide variety of arrangements has been investigated for automotive CVT application. The pump motors can be either fixed or variable displacement and can be configured for either pure hydrostatic operation for 100% hydraulic power, or for a split mechanical-hydraulic power path for better efficiency. Pure hydrostatic drives have found widespread commercial use, primarily for providing a high force through limited travel with hydraulic cylinders. Pump-motor systems are also found as the primary drive for small equipment to large earth-moving machines, where low efficiency is not an important factor, but where simplicity and flexibility in the power transmission system is of great importance. Full oil filtration on the pump suction side is necessary for long life, ensuring that debris is continually removed.

The most extensive development on a hydraulic system was conducted by Orshansky Transmission in the 1970s. This was a split power path system, as is mandatory for good efficiency. The pure hydrostatic drive at vehicle start-up gradually shifted toward an all-mechanical path at the top end, for acceptable efficiency throughout the operating range. Vehicle testing indicated improved fuel economy over the then baseline three-speed automatic transmission with open torque converter, now obsoleted by the 4SAT. Obvious during start-up was the totally unacceptable hydraulic noise. All attempts to attenuate this noise were not fruitful. Noise is inherent in all high-pressure pumps and motors, due to the rapidly changing system pressures of up to 3000 psi. These pressure fluctuations and associated non-uniform flow exert cyclic forces and vibration throughout the entire transmission structure. These are difficult if not impossible to reduce to an acceptable level for a vehicle. Aside from the noise problem, automotive application dictates the use of a closed hydraulic system which must be pressurized with an external pump. This not only provides make-up oil from pump leakage but minimizes pump inlet cavitation, a firm requirement at medium and high speeds, and during cold weather operation. A major difficulty is the impracticability of full flow filtration. Any debris generated within the closed system remain and accumulate. This invariable shortens pump life. There are no known hydraulic CVT programs today directed at automotive application.

4. Hydro-Kinetic Drives

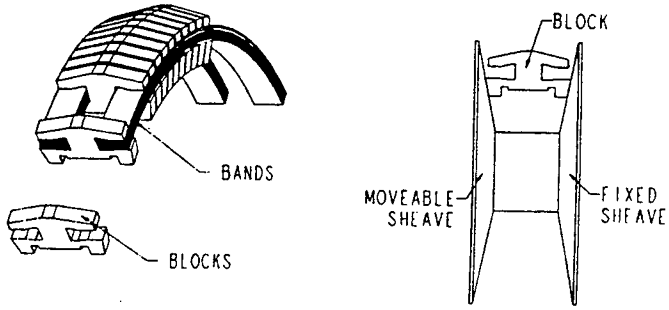
Prior to consideration of the CVT, the approach followed by the U.S. automotive manufacturers concentrated on developing high performance torque converters to achieve completely smooth ratio transition. In the late 1950s both Buick and Chevrolet introduced into production automatic transmissions utilizing five element torque converters. Figure III-10 shows the 1957 Buick Dynaflow design. The converter increased the stall torque ratio, extended the torque multiplication range and provided stepless shifting. However, the fuel economy was poor. Production continued for a very short period before these were replaced by more conventional automatic transmissions with better efficiency. Their ratio range and efficiency could never approach those of the friction or traction drive CVT mechanisms. However, the conventional three element torque converter with lock-up clutch is an ideal start-up device for a CVT. Not only is start-up inherently smooth, but the 2:1 stall torque ratio extends the overall ratio range of the CVT further improving vehicle fuel economy.

E. CVT TECHNOLOGY SELECTED FOR THIS STUDY - THE FORD DUAL MODE

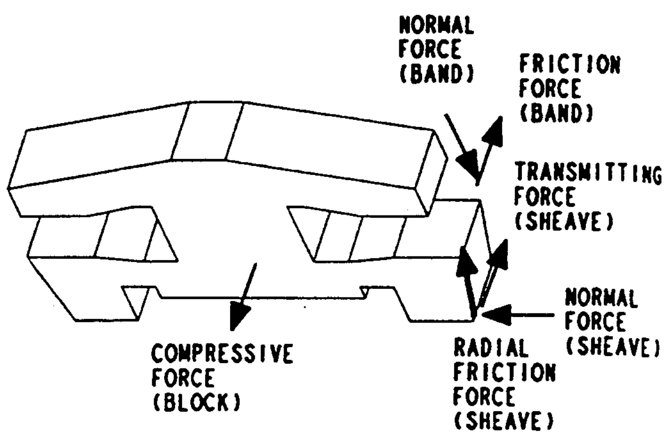
The only CVT's in production in modern times have utilized the Van Doorne belt and pulley system. Although no durability data are publicly available, the Van Doorne is generally viewed as being adequate in this regard. To date, application has been to smaller vehicles with engines of two liters or less. The start-up device has been some type of automatic clutch. This limits the overall ratio range to that obtained only with the belt and pulley system of about 5:1. This is comparable to a 4- or 5-speed manual transmission. If the CVT is to see widespread application in the U.S., the torque capacity must be increased significantly. Certainly that is the case for the three-liter engine and 3625- lb. vehicle combination of this study.

A specific CVT design is not needed to make the fuel economy predictions for this study. Only an estimate of its efficiency relative to a base transmission is needed, and this is discussed in Chapter V. Nevertheless, it is necessary to have in mind a specific design for the cost, weight and lead-time study. The concept technology selected for this purpose was the Ford Dual Mode CVT developed in the 1980s and described by Stockton.[32] Figure III-11a from that paper shows a front-wheel drive design and Figure III-11b a four-wheel drive derivative. The Dual Mode is a variation of the Van Doorne. It uses the same push type steel belt drive. While originally designed for a maximum of 138 NM torque capacity and fitted to a 1.6 liter engine, when upgraded, this CVT design is viewed as being a candidate for the larger engines and vehicles targeted in this study. Some details about the Dual Mode follow.

Upon start-up, the 2:1 stall torque ratio converter is active, thereby significantly reducing maximum input torque imposed on the steel belt. Near the converter coupling point a power transfer clutch is engaged during acceleration, transferring power flow from the converter to the variable speed belt drive. This effectively locks out the torque converter. It also improves driveability by providing an instant forced down-shift into the equivalent of low gear as in a 4SAT. Because of this design, durability and efficiency are improved during sustained heavy loading at lower vehicle speeds. A moderate ratio step, equivalent to a conventional AT 1-2 shift, can also be introduced to further increase over-all ratio coverage and reduce maximum belt loading. If added, this would permit better optimization of CVT operating ratio for improved fuel economy or performance during sustained cruise or moderate vehicle speed change. In the Dual Mode design, only two simple planetary gear sets are required to provide the desired axle reduction ratio and reverse operation.



PUSH TYPE CVT BELT AND SHEAVE ELEMENTS



FORCE COMPONENTS APPLIED TO THE BLOCK

Figure III-1. Essential features of the Van Doorne CVT belt and pulley system. Figure from Reference 15.

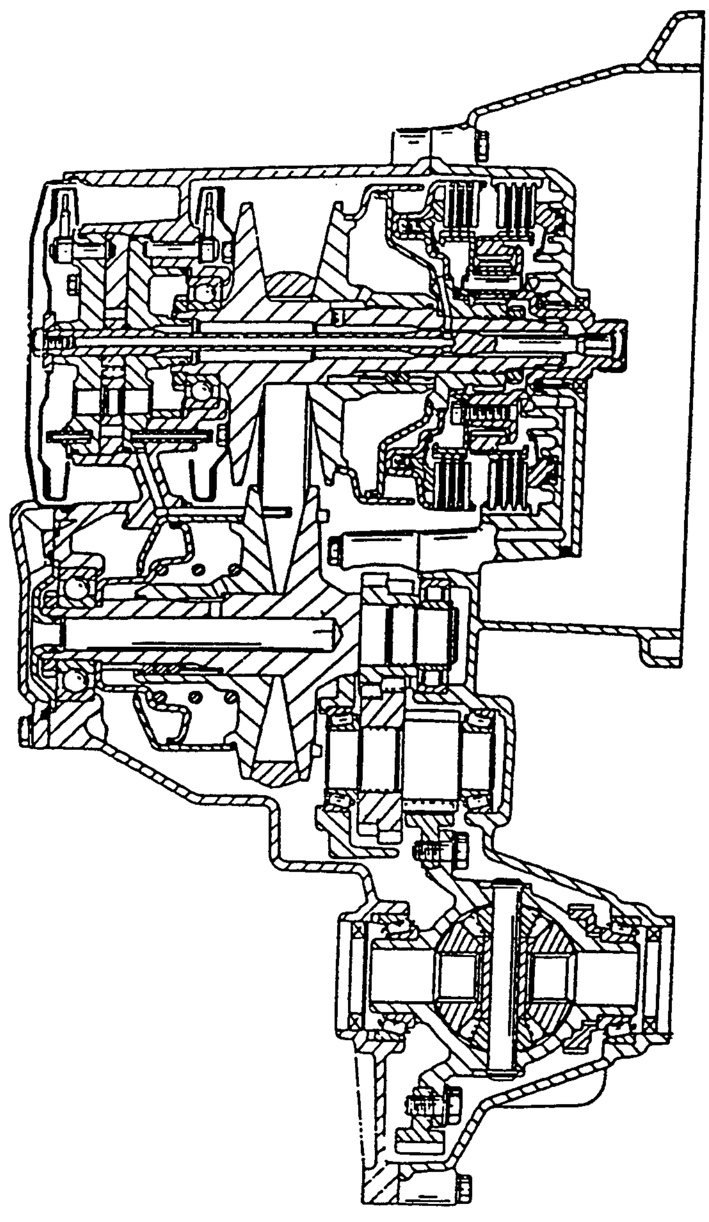


Figure III-2a. Plan view of Van Doorne push belt CVT.
Figure from Reference 12.

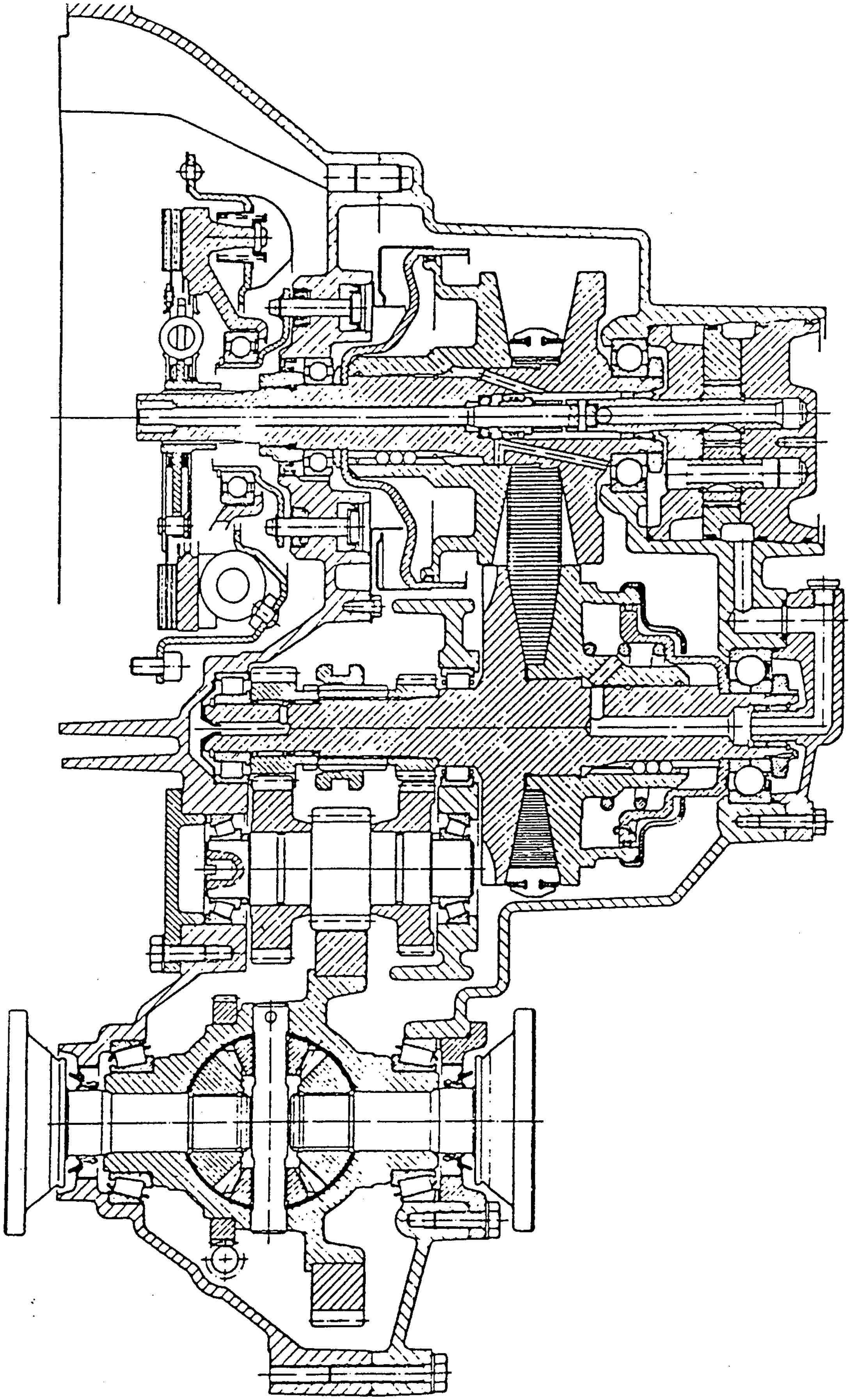
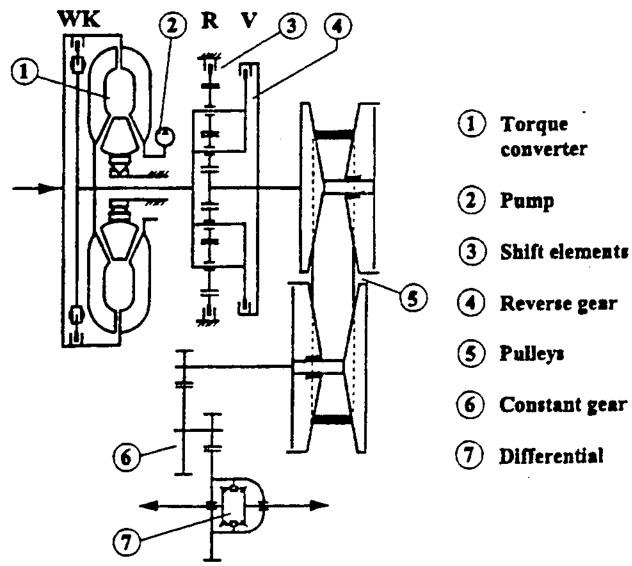
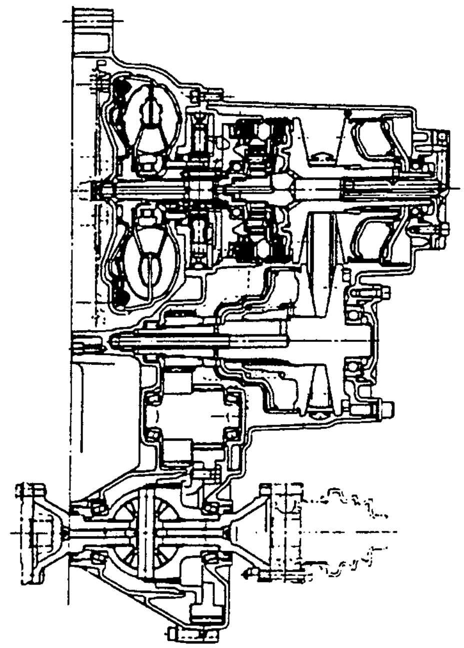


Figure III-2b. Plan view of Borg Warner metal belt CVT.
Figure from Borg Warner Corporation.



CFT 20 configuration



Sectional view of CFT 20

Figure III-2c. Schematic and plan views of the ZF CVT.
Figure from Reference 5.

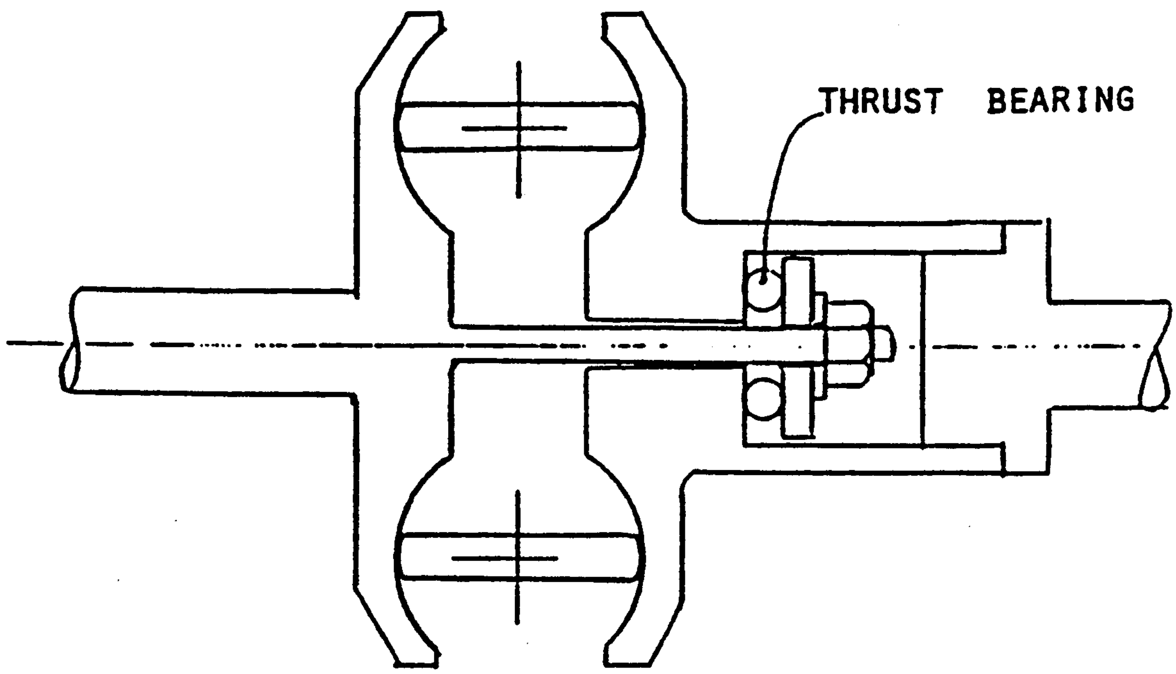
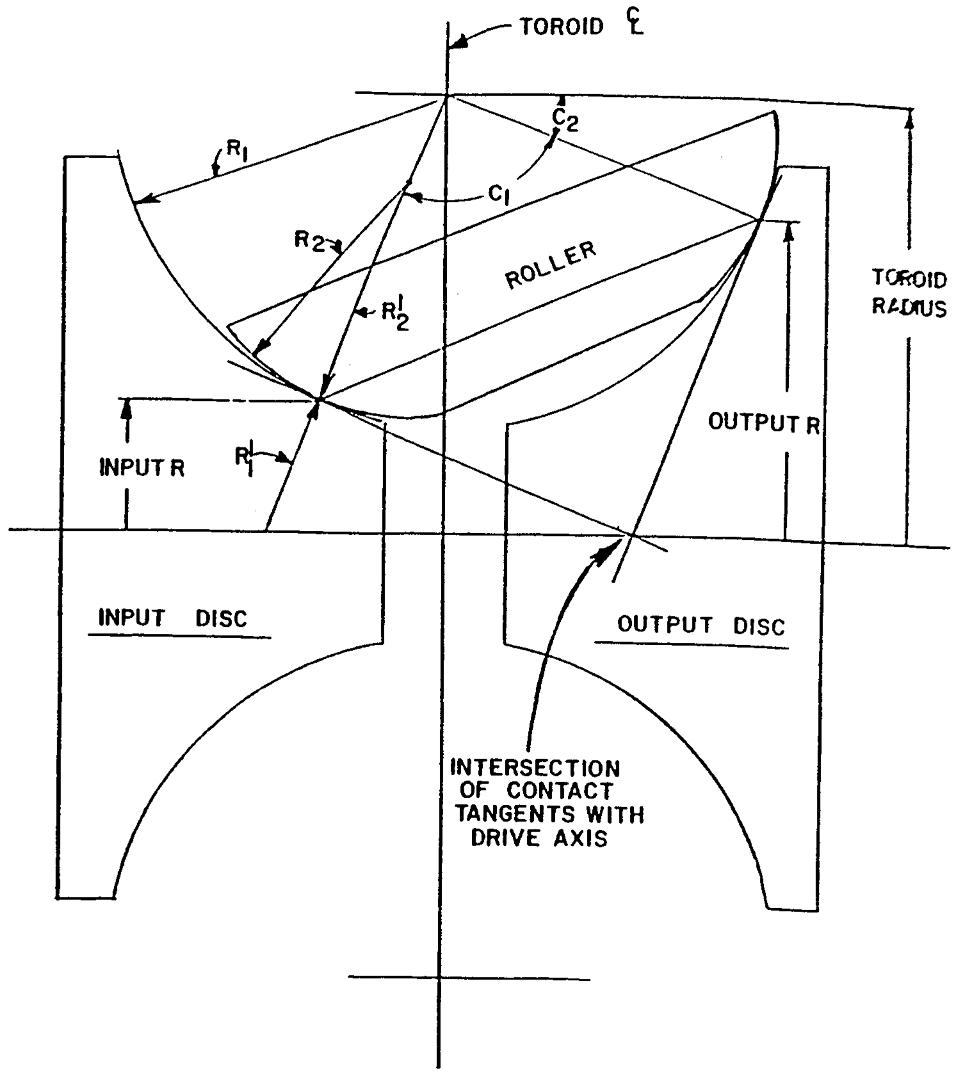


Figure III-3. Full torus or "Hayes" traction drive.
Figure courtesy of Excelermatic Inc.[17]



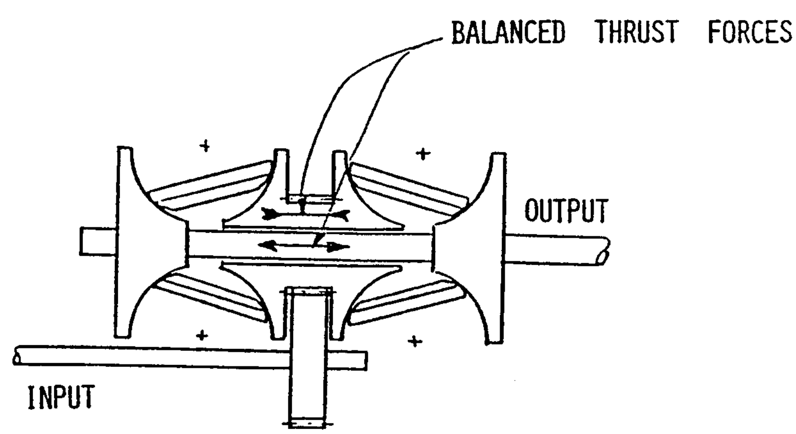


Figure III-4. Half torus or "Arter", "Deep Cone Roller" drives.
Figure courtesy of Excelermatic Inc.[17]

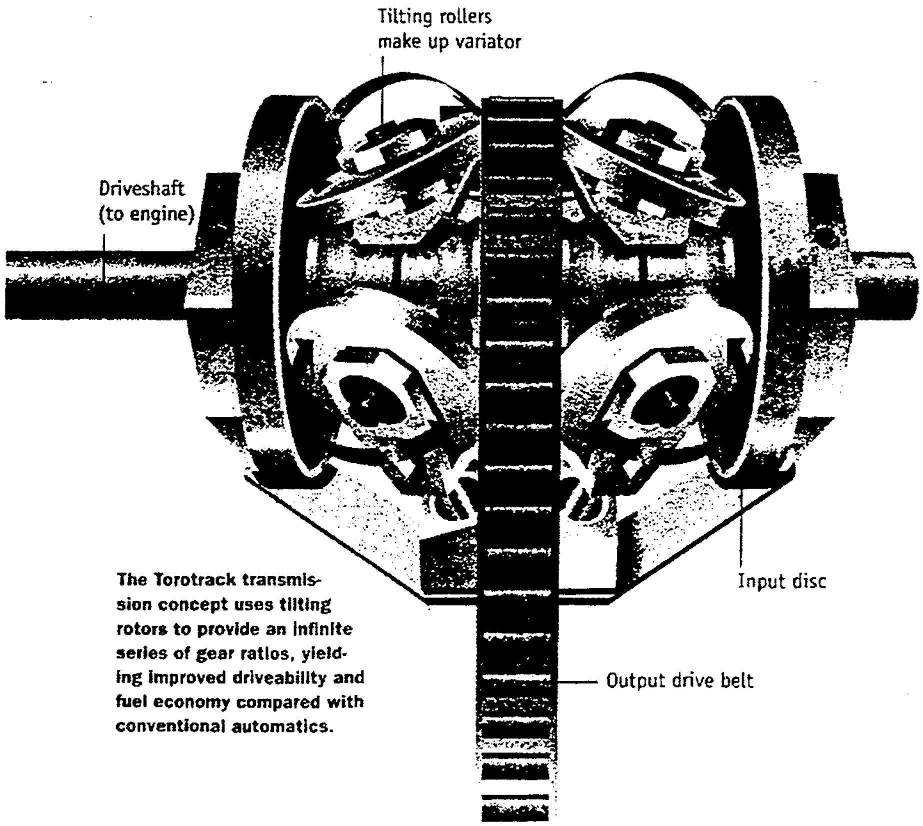


Figure III-5. The Torotrak CVT for front-wheel drive.
Figure from Torotrak.

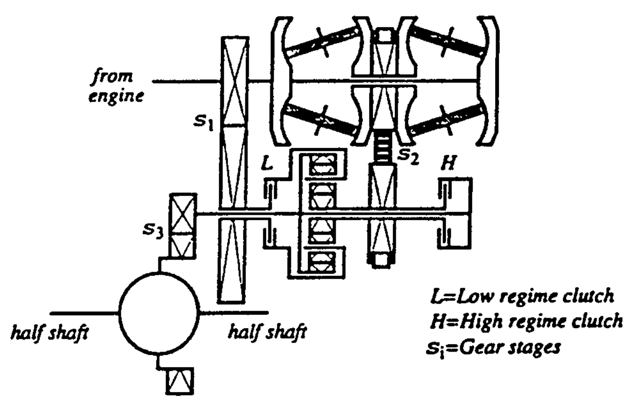


Figure III-6. Schematic of the Torotrack CVT.
Figure from Reference 21.

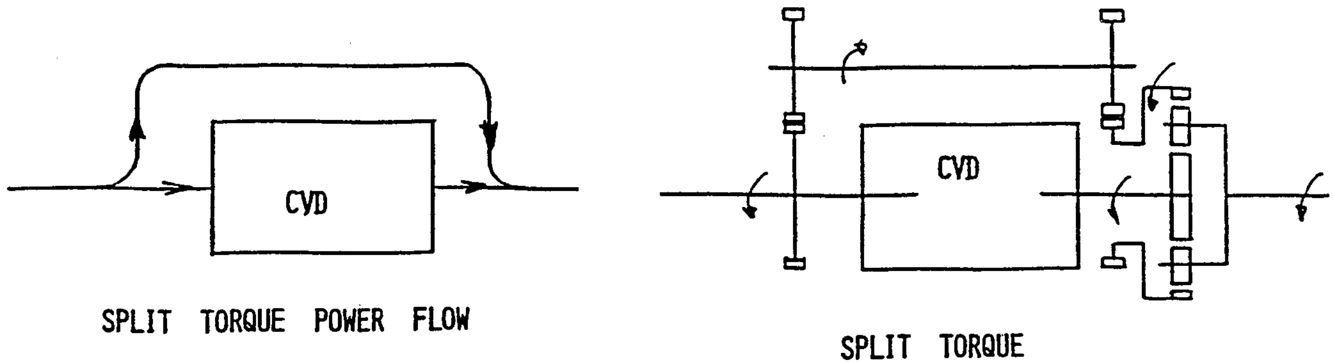


Figure III-7. Split torque power flow CVT.
Figure courtesy of Excelermatic Inc.[17]

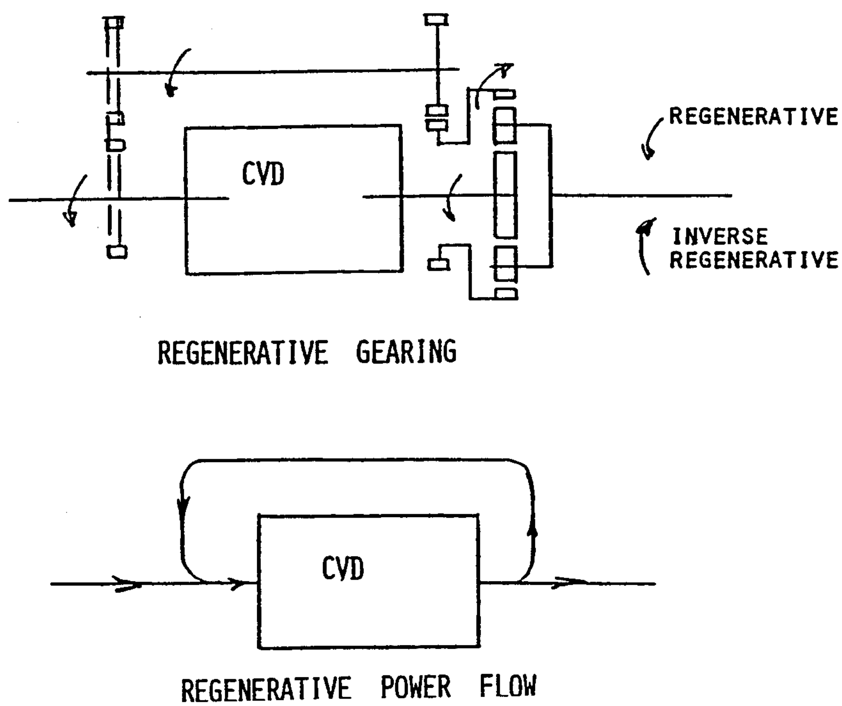


Figure III-8. Regenerative power flow CVT.
Figure courtesy of Excelermatic Inc.[17]

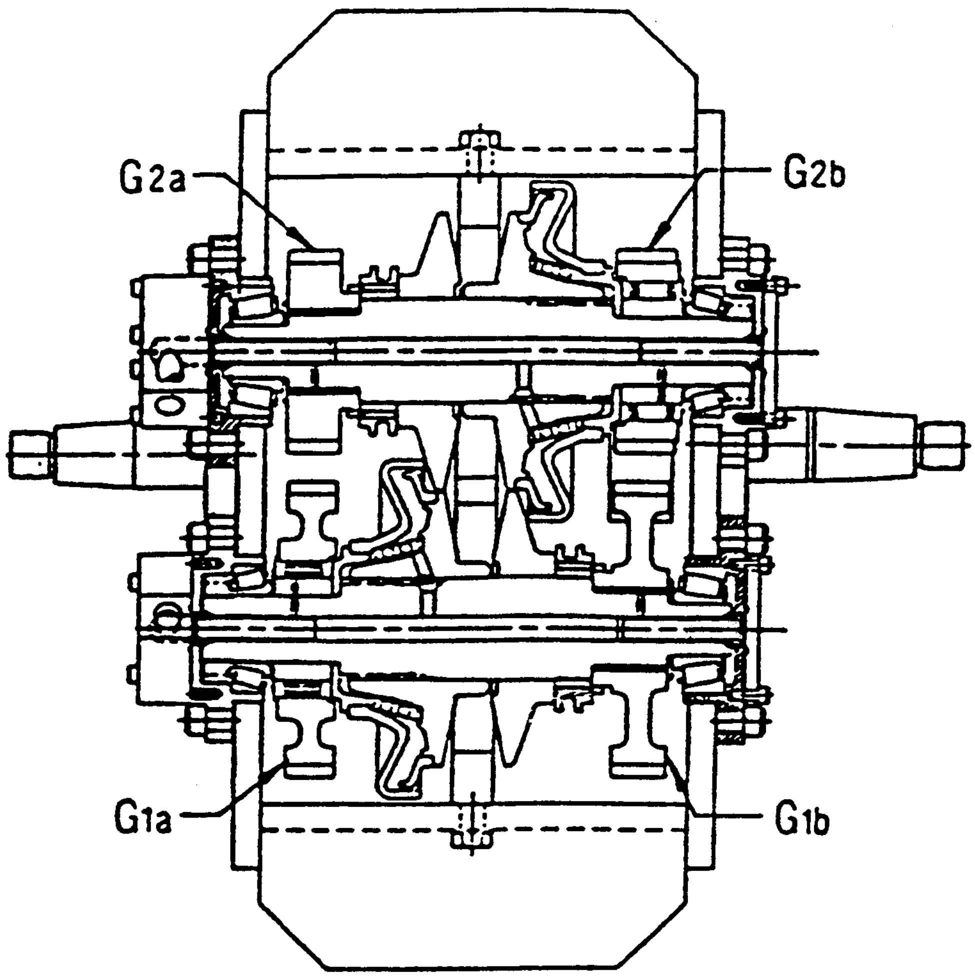


Figure III-9. Borg Warner Two Pass metal belt CVT.
Figure from Reference 27.

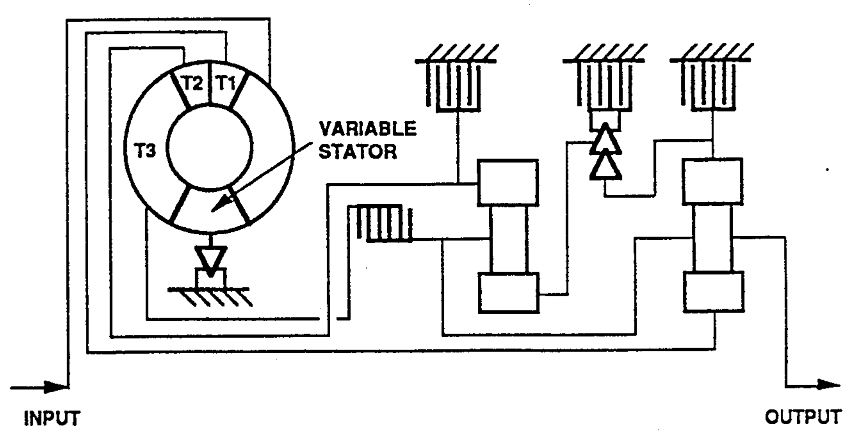
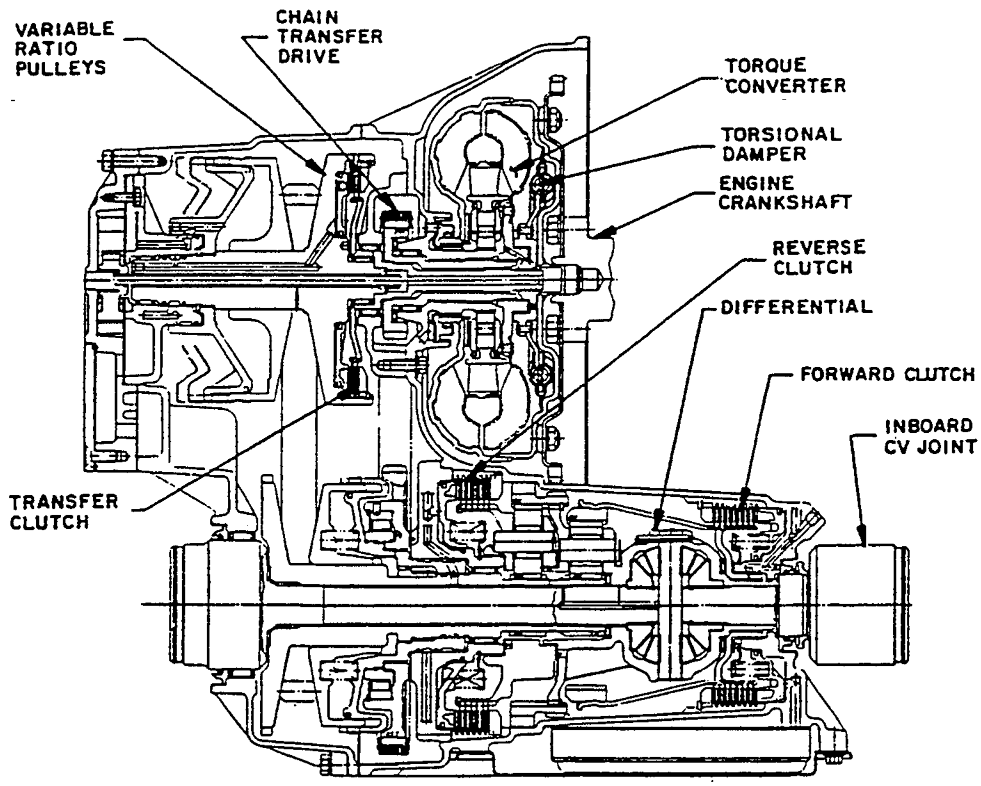
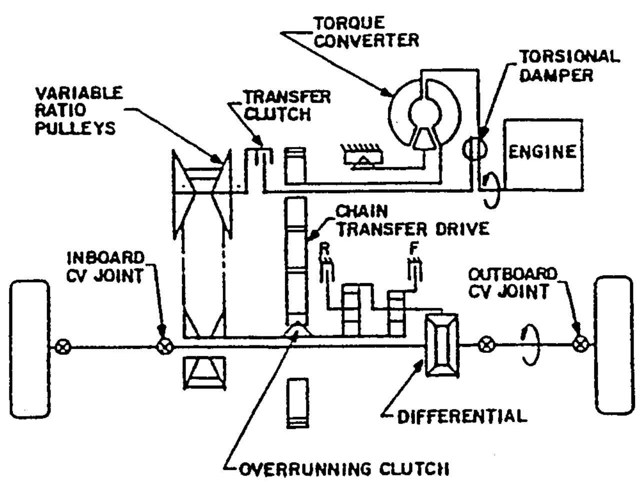


Figure III-10. 1957 Buick Flight Pitch Dynaflow transmission.



Dual mode CVT



Dual mode CVT schematic

Figure III-11a. Plan view and schematic of the Ford Dual Mode CVT.
Figure from Reference 32.

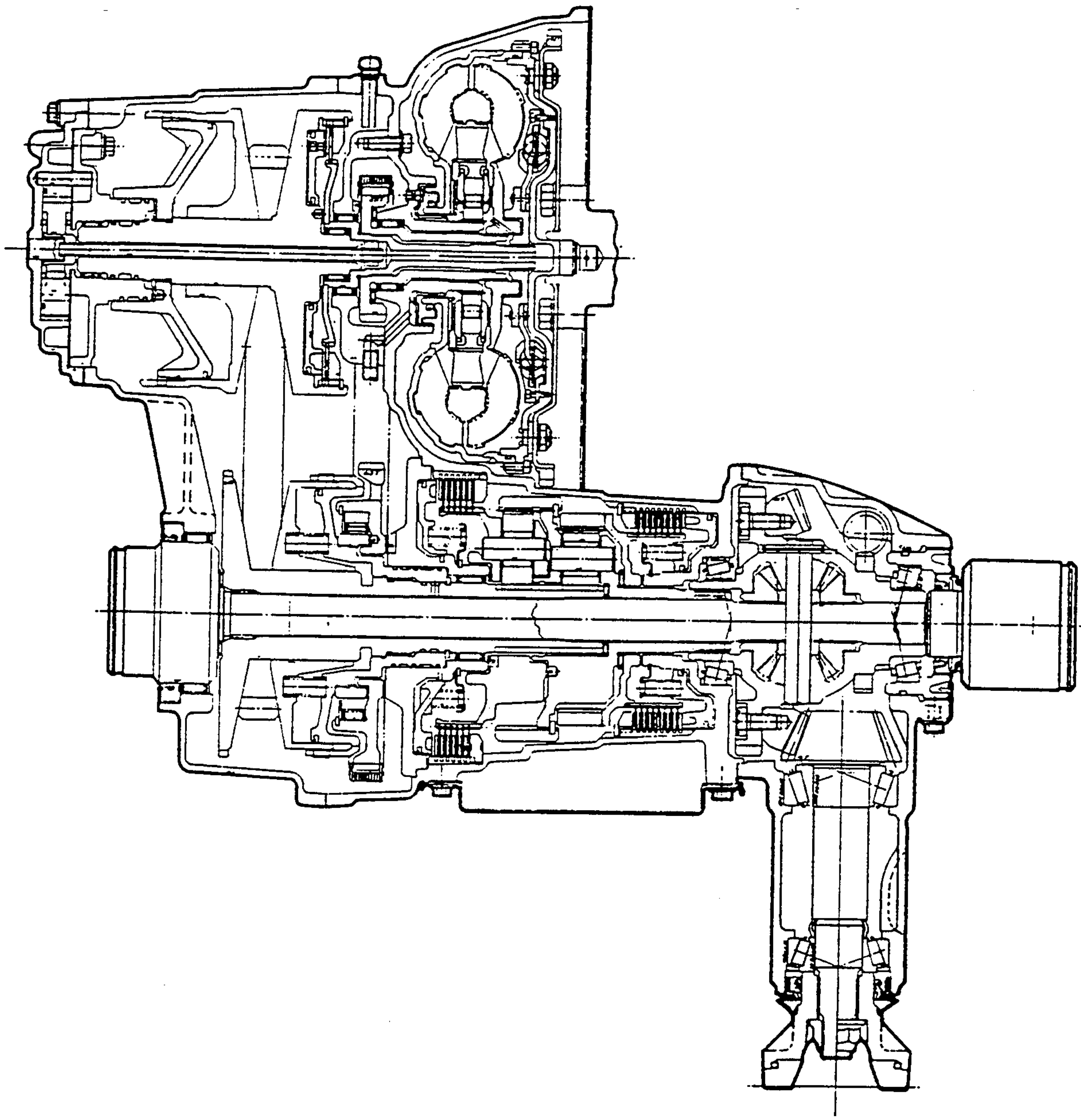


Figure III-11b. Plan view of Dual Mode CVT, 4 x 4 version.
Figure from Reference 32.

IV. ENGINE, VEHICLE AND CVT SYSTEM

A. BASE ENGINE, TRANSMISSION, AND VEHICLE COMBINATIONS

1. Base Engine

The base engine was a hypothetical 90° bank angle, 3.0 liter, port fuel injected, single spark ignition, V-6. A review of published contemporary engine design parameters (see for example Foss et. al.[10], Clark and Evans[7]) lead to the assumed specifications in Table IV-1. For this study the key parameters were: bore, stroke, rod length, compression ratio, 4 valves per cylinder (car), 2 valves per cylinder (truck), number of cylinders, intake and exhaust valve diameters and lift, and idle speed. It was these variables that were used for calculations of power, economy and NOx emissions. Engine intake and exhaust valve lift curves are shown in Figures IV-1 and IV-2 for the car engine and Figures IV-3 and IV-4 for the light truck engine. There are two curves shown on Figures IV-1 and IV-2. One is for the base engine and the other for the engine with the CVT. That engine, termed HITORC, is slightly different in that the valve lift curves are slightly different. This is discussed further below. For the truck, a HITORC engine was not assumed. Thus the truck employed the same engine for base and CVT applications. The valve lift curves were scaled from data for a current production 4 valve engine for the car and from Reference 11 for the light truck. For the car, the 3 liter engine parameters are scaled from the 3.5 liter engine adopted for the variable valve timing study of Reference 25. Likewise, the assumptions for the truck engine are the same except for the 2 valve per cylinder configuration and the valve lift curves discussed above.

2. Transmission

The base transmission is a production front-drive, electronically controlled, four speed automatic with lock-up torque converter of contemporary design. Figure IV-5 is a drawing of such a transaxle, the Ford Asynchronous AX4S used in Taurus and Sable automobiles. This transmission is used as the basis of comparison to the CVT in the cost, weight and leadtime study. The CVT selected is the Ford Dual Mode design discussed previously and described in Reference 32. Figure IV-6 is a perspective sketch of that transmission. The belt and pulley system are highlighted. Figure IV-7, redrawn from Reference 32, is a schematic showing the essential features of the Dual Mode CVT. It should be emphasized that for the present study, the details of a specific transmission are not used for the fuel economy calculations, only assumptions of relative efficiency. The details are used, however, for the cost, weight and leadtime study detailed in Chapter VI.

3. Vehicle

For both car and truck, the vehicle weight was taken as 3625 lb. The torque required at the engine to propel the vehicle at the various speeds on the EPA City and Highway Cycles is a function of the weight as well as the rolling resistance of the tires, frontal area of the vehicle and its drag coefficient, drivetrain efficiency including transmission, and the ratio of engine rotational speed to vehicle linear speed (N/V ratio). The EPA Cycles are a continuously varying pattern of vehicle speeds. For analysis purposes it is a common industry practice to quantify the Cycle into a few discrete speed, load points and the time spent at each point.

Engineers at Ford Research, in support of this study, selected a set of 16 speed and load values for both car and light truck appropriate to the specific base engine/vehicle combination. These are given in the two rightmost columns of Tables IV-2 to IV-4 for the car and IV-5 to IV-7 for the truck. The time spent (seconds) at each point for each vehicle on each Cycle is given in Columns 3 and 4 of these Tables. These times were provided by Ford Research and reflect values computed by proprietary Ford software. Column 4 reflects "corrected" times, times which add to 1372 seconds for the City and 765 for the Highway Cycles. Those values in Column 4 are the ones used for the fuel consumption calculations. The remaining values in these Tables are discussed later in the section below titled Transmission Assumptions and Calculations. With proper assumptions regarding engine fuel consumption at each speed and load point, the overall fuel usage and miles per gallon for the engine, vehicle and transmission combinations may be calculated. These additional assumptions are discussed below.

4. Additional Features

Because of the complex control required for the CVT system, it was deemed that a electronic engine throttle and transmission control system would be required for both car and light truck. The fuel control systems should be sequential port injection, and a conventional three-way catalyst would be employed without air pump along with a conventional EGR system. All these are presumed to be features of the base engines as well, at least by the time the CVT system enters production.

B. ENGINE SPEED AND LOAD ASSUMPTIONS

From a fuel economy point of view, the benefit of a CVT is to permit the engine to run relatively slowly and at relatively high loads compared to the 4SAT. Some assumptions are needed regarding the minimum engine speed permitted for high load operation with the CVT. In consideration of the base engine; 3 liter, V-6; that speed assumption was:

Minimum Engine Speed: 1100 rpm

Below 1100 rpm including idle, it is assumed that a "conventional" engine speed, vehicle speed relationship is retained. This would be the same as the 4SAT.

At low speeds and sustained high loads, engine knock is expected to be a problem. Also at these conditions the large intermittent torque pulsations may pose driveability problems and possibly noise problems. For these reasons the maximum sustained torque at any speed was taken to be 80% of the leanest mixture for best torque (LBT) of which the engine is capable.

Maximum Sustained Engine Torque @ Stoichiometric: 80% LBT

Further, this 80% torque limit was assumed to be produced with a stoichiometic fuel/air mixture and best economy spark timing, thus allowing a three-way catalytic converter for emission control throughout the EPA Cycle engine operating range.

The use of a CVT is expected to provide better acceleration because of the ability to dwell at the maximum power point of the engine. For this study it was desired only to match acceleration time. Engine downsizing or torque optimization for enhancing low speed torque are options. For this study the torque optimization route was chosen, leading to what has been termed the HITORC engine, an engine to be used with the CVT. The WOT torque curves are given in Figure IV-8 for both base and HITORC engines applied to the car. This represents a camshaft change for a fixed camshaft engine. The maximum torque is reduced 6% and the torque at 1100 rpm increased 3% for the HITORC engine. These torque curves were used for the four-valve per cylinder engine and reflect contemporary 4-valve engine design. The truck engine WOT torque curve, a two-valve per cylinder engine, is given in Figure IV-9. A HITORC version of that engine was not assumed. The general shape of these truck engine curves is based on the General Motors 4.3 liter engine, Graham et. al[11], scaled based on engine displacement.

C. TRANSMISSION ASSUMPTIONS AND CALCULATIONS

The various speed and load points in Tables IV-2 to IV-7 are the discrete combinations that reflect these vehicles on the EPA Cycles. The product of speed and bmep is proportional to the engine-out propulsive power required. At a given point and with a CVT, the engine speed is generally slower, but the load higher. The product of the two still provides the same power, and that is the exact power required if the CVT efficiency were the same as the 4SAT. It is difficult to ascribe a definite efficiency to the CVT because no published data exist for units designed for larger cars and a variety of values has been published in the literature for smaller vehicles. Consequently, based on the literature and discussions with industry experts, it was decided to assume a range of efficiencies. A 4SAT is thought to be about 84% efficient on the EPA City and somewhat higher on the Highway Cycle. Using data from Bishop and Kluger[3] from their Tables 4 and 5 and their Equation 1, the efficiency of a 4SAT computes to be 84% City and 89% Highway. For the present study, the CVT efficiency range was taken to be 84 - 90% with calculations made at equal efficiency (84%), +3% (87%) and +6% (90%). Some additional efficiency considerations are in the Appendix. Below are some sample calculations to demonstrate how engine speeds and loads were established with the CVT.

Sample Calculations of CVT Speed and Load Points - Car

1. Refer to Table IV-2 and consider the state of 1500 rpm and 2.62 bar bmep. The base engine, transmission vehicle combination requires engine power proportional to 1500x2.62. With a CVT of equal efficiency, the speed may be 1100 rpm (subject to

maximum torque check), yielding a load of 3.57 bar. In viewing Figure IV-8, this is less than 80% of the maximum torque (0.8x9.25 = 7.4 bar @ 1100 rpm) of the HITORC engine. Thus the engine with CVT may be operated at 1100 rpm at the load of 3.57 bar.

2. Suppose the transmission efficiency of the CVT were +6%, (90%), the load would be reduced to 3.57x84/90 = 3.33 bar, Table IV-4, even a more viable load for the HITORC engine at 1100 rpm.

3. Consider 2000 rpm and 5.5 bar. For equal transmission efficiencies, the HITORC engine at 1100 rpm would have to produce 10 bar torque. This is above its potential. Thus engine speed must be permitted to increase until a new speed and 80% torque at that speed are capable of providing the required power. The operating point is found by iteration to be 1405 rpm and 7.83 bar torque, Table IV-2.

Tables IV-2 to IV-7, rightmost columns, list the speed and load points calculated for the CVT equipped car and truck for the three CVT transmission efficiencies using the calculational procedures outlined above. The fifth column lists the maximum (80%) torque which must not be exceeded.

D. THE CVT OPERATING PATH

Using the values for the base car and transmission (leftmost two columns of Table IV-2) and the rightmost two columns for the CVT/HITORC combination, Figure IV-10 was generated. This Figure is a plot of speed versus relative power (speed x bmep) for the base CVT of equal efficiency. All 16 speed and load point are plotted except idle. A solid line is drawn between the operating points for the CVT.

For the CVT combination, the engine is run at 1100 rpm at increasing load until the 80% maximum power point of 7.4 bar is reached. Beyond that power, the speed is gradually increased while moving along the 80% maximum torque curve. For the base vehicle, the discrete operating points are plotted. At a given power level, the CVT equipped car always operates at a lower engine speed, often at a considerably lower speed. Reduction in friction and pumping losses provide better fuel economy for the CVT equipped vehicle because of the lower speed, higher load path. The benefits depend on a combination of the fuel rate and the operating time at the various points. These times (seconds) are indicated above each point for the EPA City and Highway Cycles. Points with a larger number of seconds which deviate the most from the CVT path yield the best economy gains for the CVT system. These are the points at 2000 rpm for the Highway and points at both 2000 and 1500 rpm for the City Cycles. Similar plots could be made for the other transmission efficiencies and for the truck. They would show a like advantage for the CVT equipped vehicles. In terms of torque versus engine speed, the path for the HITORC engine and CVT combination is shown in Figure IV-8.

E. POTENTIAL BENEFITS OF VARIABLE VALVE TIMING AND CVT

Although not a consideration of the present study, variable valve timing appears to offer a special advantage with CVT. This is because of the desirability of obtaining the highest possible torque at 1100 rpm (minimum speed of this study). With fixed valve timing, the high speed torque and maximum acceleration would be compromised. A VVT system would allow the CVT system to proceed through a more optimized path (subject to knock constraints). Internal EGR could be used to minimize knock at high loads as well as to control NOx. Since both VVT and CVT provide pumping loss reductions, that fuel economy benefit could only be realized once. A combined system would therefore provide reduced pumping losses: lower friction at moderate power levels; lower idle speed and engine downsizing. VVT could also lower engine intake noise at low speeds due to low overlap there. This could be a significant benefit for engines with four or fewer cylinders.

F. CONSIDERATIONS FOR CVT USE

An engine designed for CVT operation should have special attention devoted to friction and accessory drive power reduction at the minimum sustained speed, 1100 rpm in this study. Since valve train friction is very important at low engine speeds, it would be important to minimize that. Application of a CVT to a rear drive vehicle is somewhat constrained by packaging considerations resulting from the offset inherent in the CVT design. Poor weight distribution is a problem for a front-drive pickup truck. However, CVT application to a front-drive van appears practical.

TABLE IV-1

SPECIFICATIONS FOR BASE ENGINES AND TRANSMISSIONS

Configuration: 3.0 Liter; 90° V-6; 4 Valves Per Cylinder Car, 2 Valves Light Truck

Displacement per Cylinder: 0.5 Liters

Compression Ratio: 9.7:1

Idle Speed in Drive: 640 rpm with Automatic Transmission

Bore: 88.5 mm

Stroke: 81.3 mm

Ratio of Bore/Stroke: 1.089

Connecting Rod Length: 146 mm (L/R = 3.59)

Intake Valve Diameter and Lift: Car 31 mm, 9.4 mm, Light Truck - 42 mm, 11 mm

Exhaust Valve Diameter and Lift: Car - 27 mm, 8.6 mm, Light Truck - 34.5 mm, 11 mm

Cam and Followers: Individual for Each Intake and Exhaust Valve with Roller Followers

Camshaft: Single Overhead with Roller Chain Drive

Throttle Control: Electronic (Fly by Wire)

Fuel System: Sequential Port Injection

Manifold: Plastic

Emission Control: Three-Way Catalyst with Feedback Oxygen Sensor and Exhaust Recirculation System

Transmission: Four Speed, Electronically Controlled Automatic with Torque Converter Lock-up

TABLE IV-2

SPEEDS AND LOADS FOR BASE AND CVT ENGINES, EQUAL TRANSMISSION EFFICIENCIES - CAR

HITORC Engine, CVT of Equal Efficiency

1998 Taurus 3.0 L, 4-V, 4-Speed Auto. Trans., 3625 lb. Vehicle

EPA City Cycle

BASE TRANSMISSION AT 84%
CVT AT 84%

Nominal Engine BMEP (bar)	Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT CVT BMEP (bar)	CVT SPEED (rpm)
idle	700	537.1	551.86	idle	idle	700
1.50	1200	121.3	124.63	7.40	1.64	1100
1.50	1500	104.3	107.17	7.40	2.05	1100
1.50	2000	36.3	37.30	7.40	2.73	1100
2.62	1200	59.5	61.14	7.40	2.86	1100
2.62	1500	181.2	186.18	7.40	3.57	1100
2.62	2000	52.7	54.15	7.40	4.76	1100
4.00	1500	77.2	79.32	7.40	5.45	1100
4.00	2000	104.1	106.96	7.40	7.27	1100
4.00	2500	9.7	9.97	7.70	7.69	1300
5.50	1500	3.4	3.49	7.42	7.43	1110
5.50	2000	28.6	29.39	7.84	7.83	1405
5.50	2500	8.4	8.63	8.17	8.18	1680
7.00	1500	3.1	3.19	7.77	7.78	1350
7.00	2000	2.5	2.57	8.21	8.19	1710
7.00	2500	5.9	6.06	8.53	8.54	2050
		1335.3	1372.00			

EPA Highway Cycle

BMEP (bar)	Engine Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT CVT BMEP (bar)	CVT SPEED (rpm)
idle	700	41.8	41.54	idle	idle	700
1.50	1200	3.9	3.88	7.40	1.64	1100
1.50	1500	50.7	50.39	7.40	2.05	1100
1.50	2000	162.4	161.41	7.40	2.73	1100
2.62	1200	1.2	1.19	7.40	2.86	1100
2.62	1500	84.3	83.79	7.40	3.57	1100
2.62	2000	167.5	166.48	7.40	4.76	1100
4.00	1500	57.2	56.85	7.40	5.45	1100
4.00	2000	117.7	116.98	7.40	7.27	1100
4.00	2500	40.9	40.65	7.70	7.69	1300
5.50	1500	12.3	12.22	7.42	7.43	1110
5.50	2000	24	23.85	7.84	7.83	1405
5.50	2500	4.5	4.47	8.17	8.18	1680
7.00	1500	0.2	0.20	7.77	7.78	1350
7.00	2000	0.4	0.40	8.21	8.19	1710
7.00	2500	0.7	0.70	8.53	8.54	2050
		769.7	765.00			

TABLE IV-3

SPEEDS AND LOADS FOR BASE AND CVT ENGINES,
+3% CVT TRANSMISSION EFFICIENCY - CAR

HITORC Engine, CVT of +3% Efficiency

1998 Taurus 3.0 L, 4-V, 4-Speed Auto. Trans., 3625 lb. Vehicle

EPA City Cycle

BASE TRANSMISSION AT 84%
CVT AT 87%

Nominal Engine BMEP (bar)	Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT CVT BMEP (bar)	CVT SPEED (rpm)
idle	700	537.1	551.86	idle	idle	700
1.50	1200	121.3	124.63	7.40	1.58	1100
1.50	1500	104.3	107.17	7.40	1.97	1100
1.50	2000	36.3	37.30	7.40	2.63	1100
2.62	1200	59.5	61.14	7.40	2.76	1100
2.62	1500	181.2	186.18	7.40	3.45	1100
2.62	2000	52.7	54.15	7.40	4.60	1100
4.00	1500	77.2	79.32	7.40	5.27	1100
4.00	2000	104.1	106.96	7.40	7.02	1100
4.00	2500	9.7	9.97	7.64	7.63	1265
5.50	1500	3.4	3.49	7.40	7.24	1100
5.50	2000	28.6	29.39	7.78	7.78	1365
5.50	2500	8.4	8.63	8.13	8.12	1635
7.00	1500	3.1	3.19	7.72	7.71	1315
7.00	2000	2.5	2.57	8.15	8.14	1660
7.00	2500	5.9	6.06	8.48	8.47	1995
		1335.3	1372.00			

EPA Highway Cycle

BMEP (bar)	Engine Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT CVT BMEP (bar)	CVT SPEED (rpm)
idle	700	41.8	41.54	idle	idle	700
1.50	1200	3.9	3.88	7.40	1.58	1100
1.50	1500	50.7	50.39	7.40	1.97	1100
1.50	2000	162.4	161.41	7.40	2.63	1100
2.62	1200	1.2	1.19	7.40	2.76	1100
2.62	1500	84.3	83.79	7.40	3.45	1100
2.62	2000	167.5	166.48	7.40	4.60	1100
4.00	1500	57.2	56.85	7.40	5.27	1100
4.00	2000	117.7	116.98	7.40	7.02	1100
4.00	2500	40.9	40.65	7.64	7.63	1265
5.50	1500	12.3	12.22	7.40	7.24	1100
5.50	2000	24	23.85	7.78	7.78	1365
5.50	2500	4.5	4.47	8.13	8.12	1635
7.00	1500	0.2	0.20	7.72	7.71	1315
7.00	2000	0.4	0.40	8.15	8.14	1660
7.00	2500	0.7	0.70	8.48	8.47	1995
		769.7	765.00			

TABLE IV-4

SPEEDS AND LOADS FOR BASE AND CVT ENGINES,
+6% CVT TRANSMISSION EFFICIENCY - CAR

HITORC Engine, CVT of +6% Efficiency

1998 Taurus 3.0 L, 4-V, 4-Speed Auto. Trans., 3625 lb. Vehicle

EPA City Cycle

BASE TRANSMISSION AT 84%
CVT AT 90%

Nominal Engine BMEP (bar)	Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT: CVT BMEP (bar)	CVT SPEED (rpm)
idle	700	537.1	551.86	idle	idle	700
1.50	1200	121.3	124.63	7.40	1.53	1100
1.50	1500	104.3	107.17	7.40	1.91	1100
1.50	2000	36.3	37.30	7.40	2.55	1100
2.62	1200	59.5	61.14	7.40	2.67	1100
2.62	1500	181.2	186.18	7.40	3.33	1100
2.62	2000	52.7	54.15	7.40	4.45	1100
4.00	1500	77.2	79.32	7.40	5.09	1100
4.00	2000	104.1	106.96	7.40	6.79	1100
4.00	2500	9.7	9.97	7.59	7.59	1230
5.50	1500	3.4	3.49	7.40	7.00	1100
5.50	2000	28.6	29.39	7.73	7.72	1330
5.50	2500	8.4	8.63	8.07	8.07	1590
7.00	1500	3.1	3.19	7.67	7.66	1280
7.00	2000	2.5	2.57	8.10	8.09	1615
7.00	2500	5.9	6.06	8.44	8.42	1940
		1335.3	1372.00			

EPA Highway Cycle

BMEP (bar)	Engine Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT: CVT BMEP (bar)	CVT SPEED (rpm)
idle	700	41.8	41.54	idle	idle	700
1.50	1200	3.9	3.88	7.40	1.53	1100
1.50	1500	50.7	50.39	7.40	1.91	1100
1.50	2000	162.4	161.41	7.40	2.55	1100
2.62	1200	1.2	1.19	7.40	2.67	1100
2.62	1500	84.3	83.79	7.40	3.33	1100
2.62	2000	167.5	166.48	7.40	4.45	1100
4.00	1500	57.2	56.85	7.40	5.09	1100
4.00	2000	117.7	116.98	7.40	6.79	1100
4.00	2500	40.9	40.65	7.59	7.59	1230
5.50	1500	12.3	12.22	7.40	7.00	1100
5.50	2000	24	23.85	7.73	7.72	1330
5.50	2500	4.5	4.47	8.07	8.07	1590
7.00	1500	0.2	0.20	7.67	7.66	1280
7.00	2000	0.4	0.40	8.10	8.09	1615
7.00	2500	0.7	0.70	8.44	8.42	1940
		769.7	765.00			

TABLE IV-5

SPEEDS AND LOADS FOR BASE AND CVT ENGINES, EQUAL TRANSMISSION EFFICIENCIES - LIGHT TRUCK

BASE Engine (2 valve), CVT of Equal Efficiency

1996 Ranger 3.0 L, 2-V, 4-Speed Auto. Trans., 3625 lb. Veh. Wt., Regular Cab

EPA City Cycle

BASE TRANSMISSION AT 84%
CVT AT 84%

Nominal Engine BMEP (bar)	Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT: CVT BMEP (bar)	CVT SPEED (rpm)
idle	700	539.1	561.91	idle	idle	700
1.50	1200	143.5	149.57	7.18	1.64	1100
1.50	1500	114.6	119.45	7.18	2.05	1100
1.50	2000	17.3	18.03	7.18	2.73	1100
2.62	1200	23.3	24.29	7.18	2.86	1100
2.62	1500	177.0	184.49	7.18	3.57	1100
2.62	2000	73.8	76.92	7.18	4.76	1100
4.00	1500	45.6	47.53	7.18	5.45	1100
4.00	2000	107.8	112.36	7.20	7.21	1110
4.00	2500	7.4	7.71	7.51	7.52	1330
5.50	1500	4.8	5.00	7.24	7.24	1140
5.50	2000	35.7	37.21	7.65	7.64	1440
5.50	2500	12.4	12.92	7.94	7.93	1735
7.00	1500	0.5	0.52	7.58	7.58	1385
7.00	2000	3.5	3.65	7.97	7.95	1760
7.00	2500	10.0	10.42	8.25	8.24	2125
		1316.3	1372.00			

EPA Highway Cycle

BMEP (bar)	Engine Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT: CVT BMEP (bar)	CVT SPEED (rpm)
idle	700	44.3	44.40	idle	idle	700
1.50	1200	3.9	3.91	7.18	1.64	1100
1.50	1500	39.0	39.09	7.18	2.05	1100
1.50	2000	59.6	59.73	7.18	2.73	1100
2.62	1200	1.8	1.80	7.18	2.86	1100
2.62	1500	86.3	86.49	7.18	3.57	1100
2.62	2000	145.2	145.52	7.18	4.76	1100
4.00	1500	70.6	70.76	7.18	5.45	1100
4.00	2000	179.2	179.60	7.20	7.21	1110
4.00	2500	35.3	35.38	7.51	7.52	1330
5.50	1500	24.8	24.86	7.24	7.24	1140
5.50	2000	50.3	50.41	7.65	7.64	1440
5.50	2500	7.7	7.72	7.94	7.93	1735
7.00	1500	5.0	5.01	7.58	7.58	1385
7.00	2000	6.6	6.61	7.97	7.95	1760
7.00	2500	3.7	3.71	8.25	8.24	2125
		763.3	765.00			

TABLE IV-6

SPEEDS AND LOADS FOR BASE AND CVT ENGINES,
+3% CVT TRANSMISSION EFFICIENCY - LIGHT TRUCK

BASE Engine (2 valve), CVT of +3% Efficiency

1996 Ranger 3.0 L, 2-V, 4-Speed Auto. Trans., 3625 lb. Veh. Wt., Regular Cab

EPA City Cycle

BASE TRANSMISSION AT 84%
CVT AT 87%

Nominal Engine BMEP (bar)	Nominal Engine Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT: CVT BMEP (bar)	Actual Engine with CVT: CVT SPEED (rpm)
idle	700	539.1	561.91	idle	idle	700
1.50	1200	143.5	149.57	7.18	1.58	1100
1.50	1500	114.6	119.45	7.18	1.97	1100
1.50	2000	17.3	18.03	7.18	2.63	1100
2.62	1200	23.3	24.29	7.18	2.76	1100
2.62	1500	177.0	184.49	7.18	3.45	1100
2.62	2000	73.8	76.92	7.18	4.60	1100
4.00	1500	45.6	47.53	7.18	5.27	1100
4.00	2000	107.8	112.36	7.18	7.02	1100
4.00	2500	7.4	7.71	7.46	7.46	1295
5.50	1500	4.8	5.00	7.20	7.18	1110
5.50	2000	35.7	37.21	7.60	7.59	1400
5.50	2500	12.4	12.92	7.90	7.90	1680
7.00	1500	0.5	0.52	7.53	7.54	1345
7.00	2000	3.5	3.65	7.93	7.93	1705
7.00	2500	10.0	10.42	8.21	8.20	2060
		1316.3	1372.00			

EPA Highway Cycle

BMEP (bar)	Engine Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT: CVT BMEP (bar)	Actual Engine with CVT: CVT SPEED (rpm)
idle	700	44.3	44.40	idle	idle	700
1.50	1200	3.9	3.91	7.18	1.58	1100
1.50	1500	39.0	39.09	7.18	1.97	1100
1.50	2000	59.6	59.73	7.18	2.63	1100
2.62	1200	1.8	1.80	7.18	2.76	1100
2.62	1500	86.3	86.49	7.18	3.45	1100
2.62	2000	145.2	145.52	7.18	4.60	1100
4.00	1500	70.6	70.76	7.18	5.27	1100
4.00	2000	179.2	179.60	7.18	7.02	1100
4.00	2500	35.3	35.38	7.46	7.46	1295
5.50	1500	24.8	24.86	7.20	7.18	1110
5.50	2000	50.3	50.41	7.60	7.59	1400
5.50	2500	7.7	7.72	7.90	7.90	1680
7.00	1500	5.0	5.01	7.53	7.54	1345
7.00	2000	6.6	6.61	7.93	7.93	1705
7.00	2500	3.7	3.71	8.21	8.20	2060
		763.3	765.00			

TABLE IV-7

SPEEDS AND LOADS FOR BASE AND CVT ENGINES,
+6% CVT TRANSMISSION EFFICIENCY - LIGHT TRUCK

BASE Engine (2 valve), CVT of +6% Efficiency

1996 Ranger 3.0 L, 2-V, 4-Speed Auto. Trans., 3625 lb. Veh. Wt., Regular Cab

EPA City Cycle

BASE TRANSMISSION AT 84%
CVT AT 90%

Nominal Engine BMEP (bar)	Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT CVT BMEP (bar)	CVT SPEED (rpm)
idle	700	539.1	561.91	idle	idle	700
1.50	1200	143.5	149.57	7.18	1.53	1100
1.50	1500	114.6	119.45	7.18	1.91	1100
1.50	2000	17.3	18.03	7.18	2.55	1100
2.62	1200	23.3	24.29	7.18	2.67	1100
2.62	1500	177.0	184.49	7.18	3.33	1100
2.62	2000	73.8	76.92	7.18	4.45	1100
4.00	1500	45.6	47.53	7.18	5.09	1100
4.00	2000	107.8	112.36	7.18	6.79	1100
4.00	2500	7.4	7.71	7.41	7.41	1260
5.50	1500	4.8	5.00	7.18	7.00	1100
5.50	2000	35.7	37.21	7.55	7.55	1360
5.50	2500	12.4	12.92	7.85	7.85	1635
7.00	1500	0.5	0.52	7.48	7.48	1310
7.00	2000	3.5	3.65	7.88	7.87	1660
7.00	2500	10.0	10.42	8.16	8.17	2000
		1316.3	1372.00			

EPA Highway Cycle

BMEP (bar)	Engine Speed (rpm)	Allocated Time (sec)	Corrected Time (sec)	Allowed Tq. (.8xmax bmep) (bar)	Actual Engine with CVT CVT BMEP (bar)	CVT SPEED (rpm)
idle	700	44.3	44.40	idle	idle	700
1.50	1200	3.9	3.91	7.18	1.53	1100
1.50	1500	39.0	39.09	7.18	1.91	1100
1.50	2000	59.6	59.73	7.18	2.55	1100
2.62	1200	1.8	1.80	7.18	2.67	1100
2.62	1500	86.3	86.49	7.18	3.33	1100
2.62	2000	145.2	145.52	7.18	4.45	1100
4.00	1500	70.6	70.76	7.18	5.09	1100
4.00	2000	179.2	179.60	7.18	6.79	1100
4.00	2500	35.3	35.38	7.41	7.41	1260
5.50	1500	24.8	24.86	7.18	7.00	1100
5.50	2000	50.3	50.41	7.55	7.55	1360
5.50	2500	7.7	7.72	7.85	7.85	1635
7.00	1500	5.0	5.01	7.48	7.48	1310
7.00	2000	6.6	6.61	7.88	7.87	1660
7.00	2500	3.7	3.71	8.16	8.17	2000
		763.3	765.00			

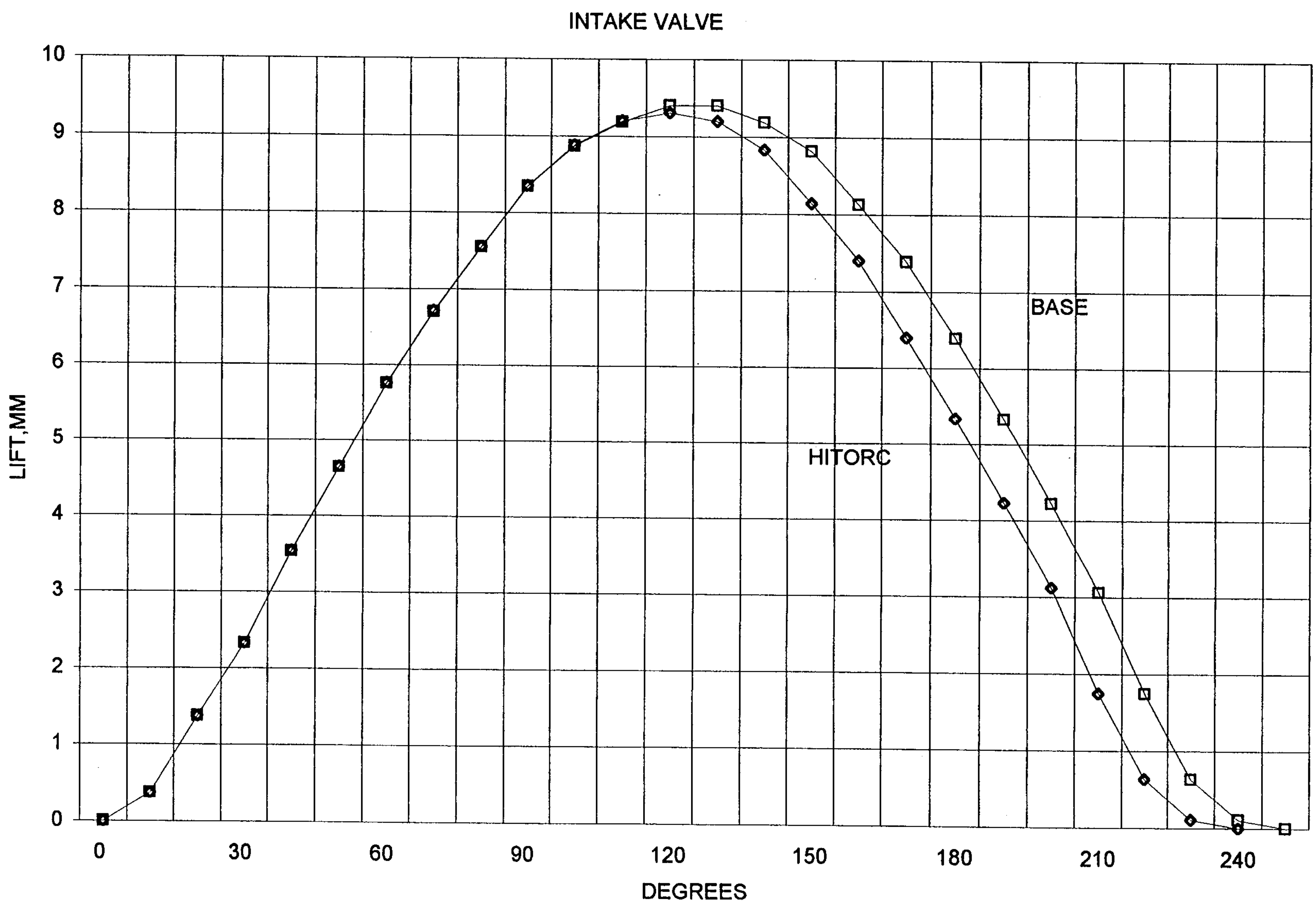


Figure IV-1. Intake valve lift for base and HITORC engines - Car.

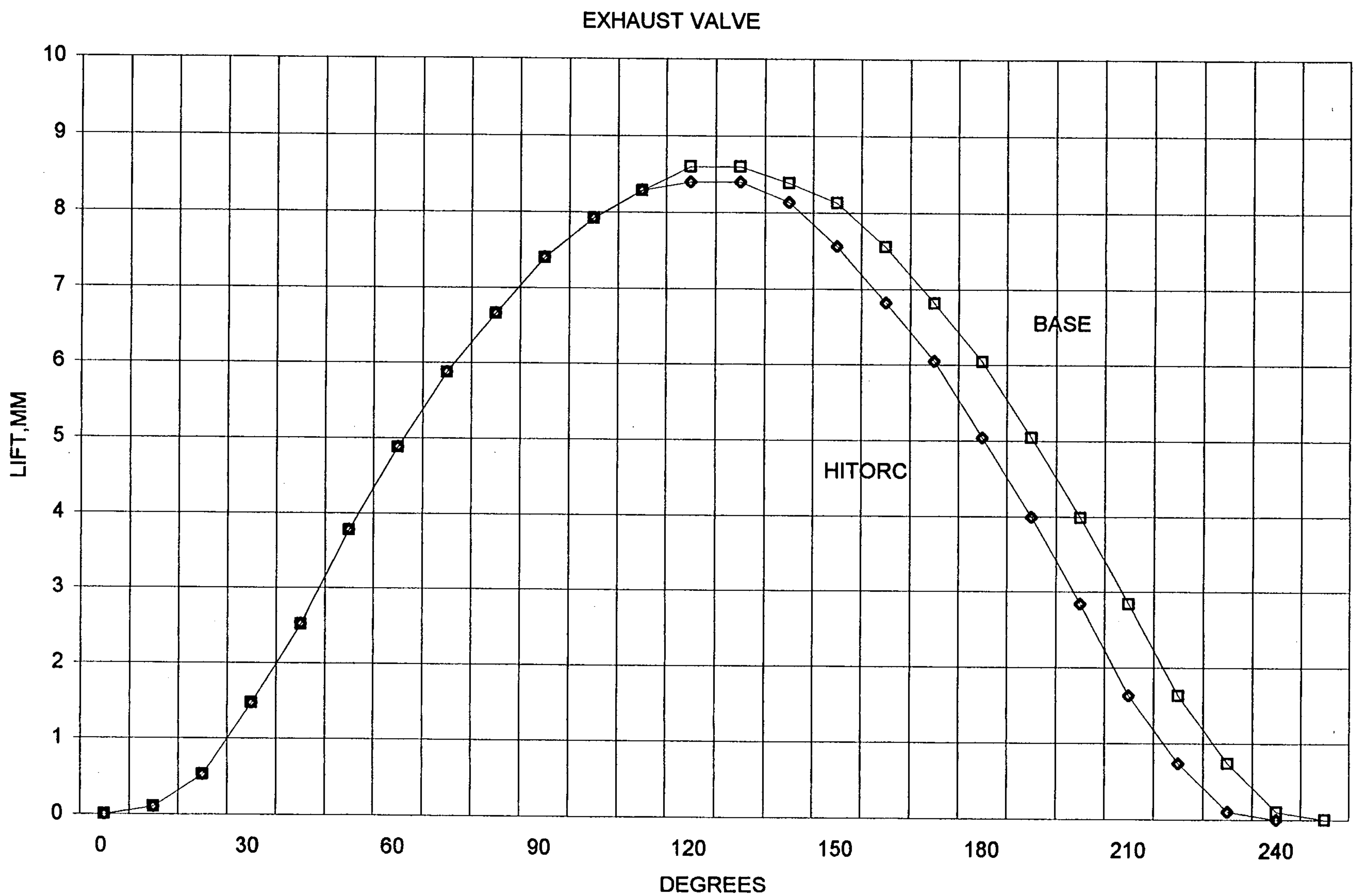


Figure IV-2. Exhaust valve lift for base and HITORC engines - Car.

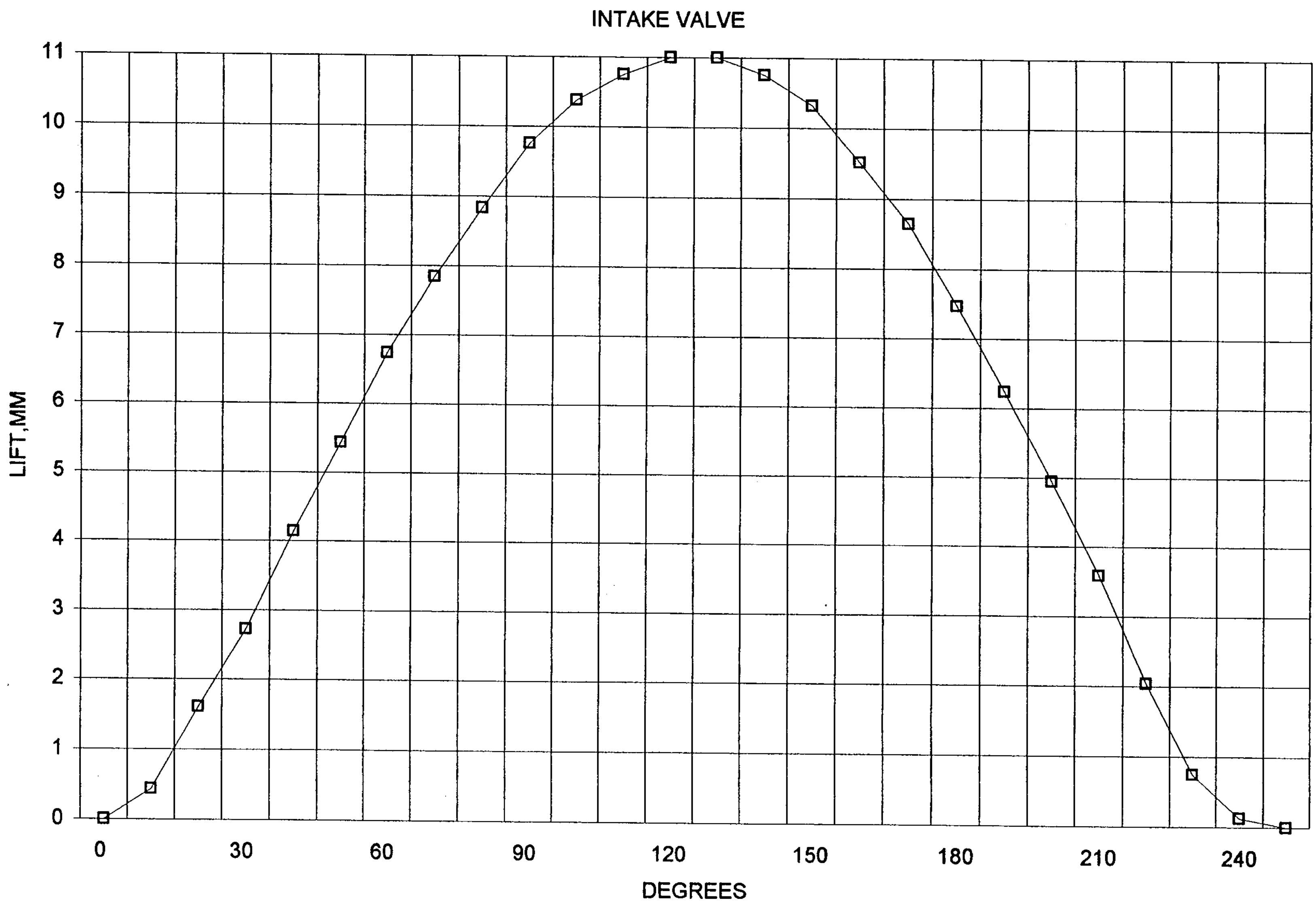


Figure IV-3. Intake valve lift for light truck engine.

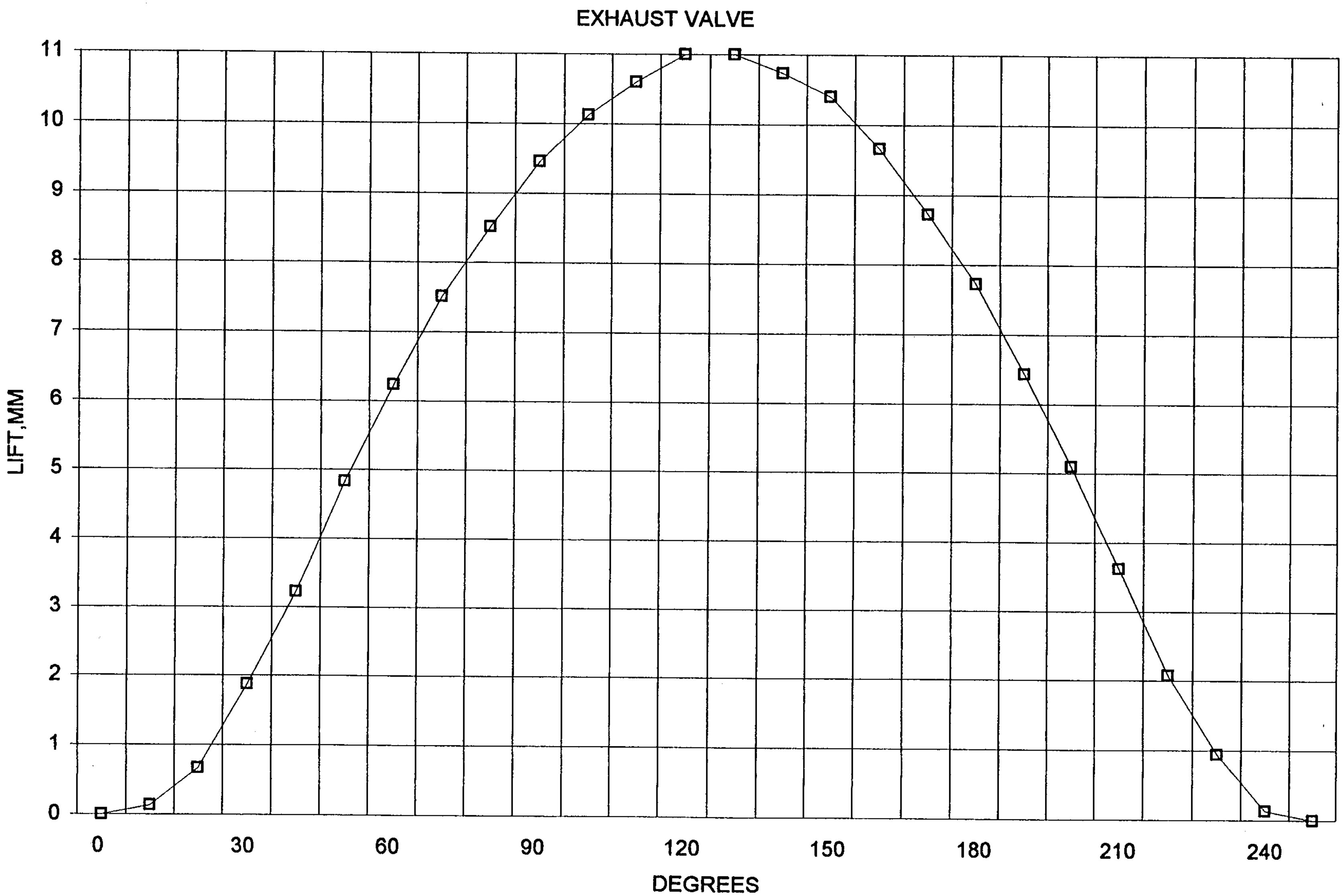
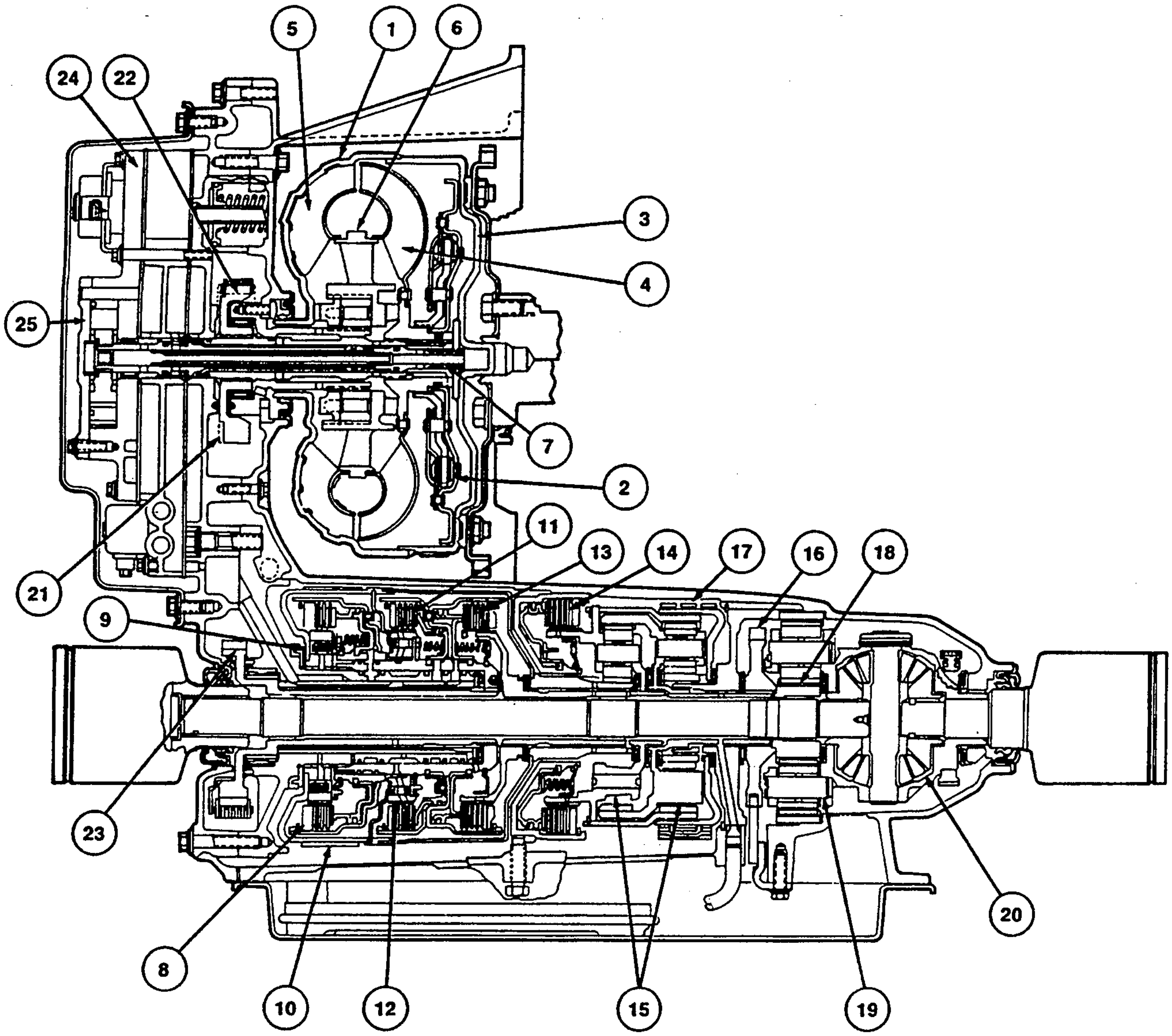


Figure IV-4. Exhaust valve lift for light truck engine.

AX4S Main Components



Item	Description	Item	Description	Item	Description
1	Torque Converter	9	Low One-Way Clutch	17	Low/Intermediate Band
2	Converter Clutch	10	Overdrive Band	18	Final Drive Sun Gear
3	Converter Cover	11	Direct Clutch	19	Final Drive Planet and Carrier
4	Turbine	12	Direct One Way Clutch	20	Diff. Thrust Bearing and Race
5	Impeller	13	Intermediate Clutch	21	Drive Sprocket
6	Reactor	14	Reverse Clutch	22	Drive Chain
7	Pump Driveshaft	15	Front/Rear Planets	23	Driven Sprocket
8	Front Clutch Cylinder	16	Park Gear	24	Main Control Valve Body
				25	Pump Assembly

Figure IV-5. Ford AX4S four speed automatic transaxle with lock-up converter.[9]

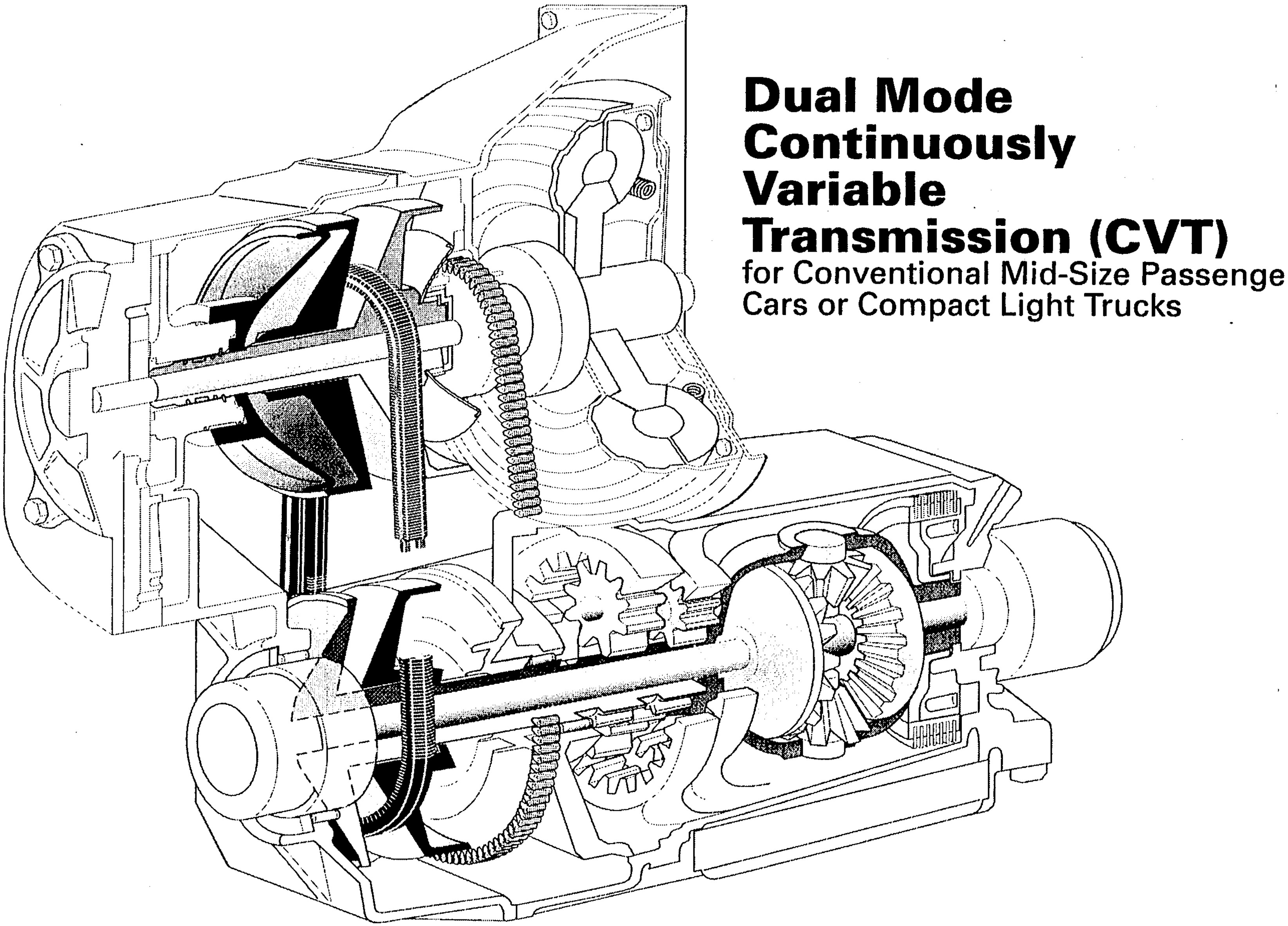


Figure IV-6. Perspective view of the Dual Mode CVT.

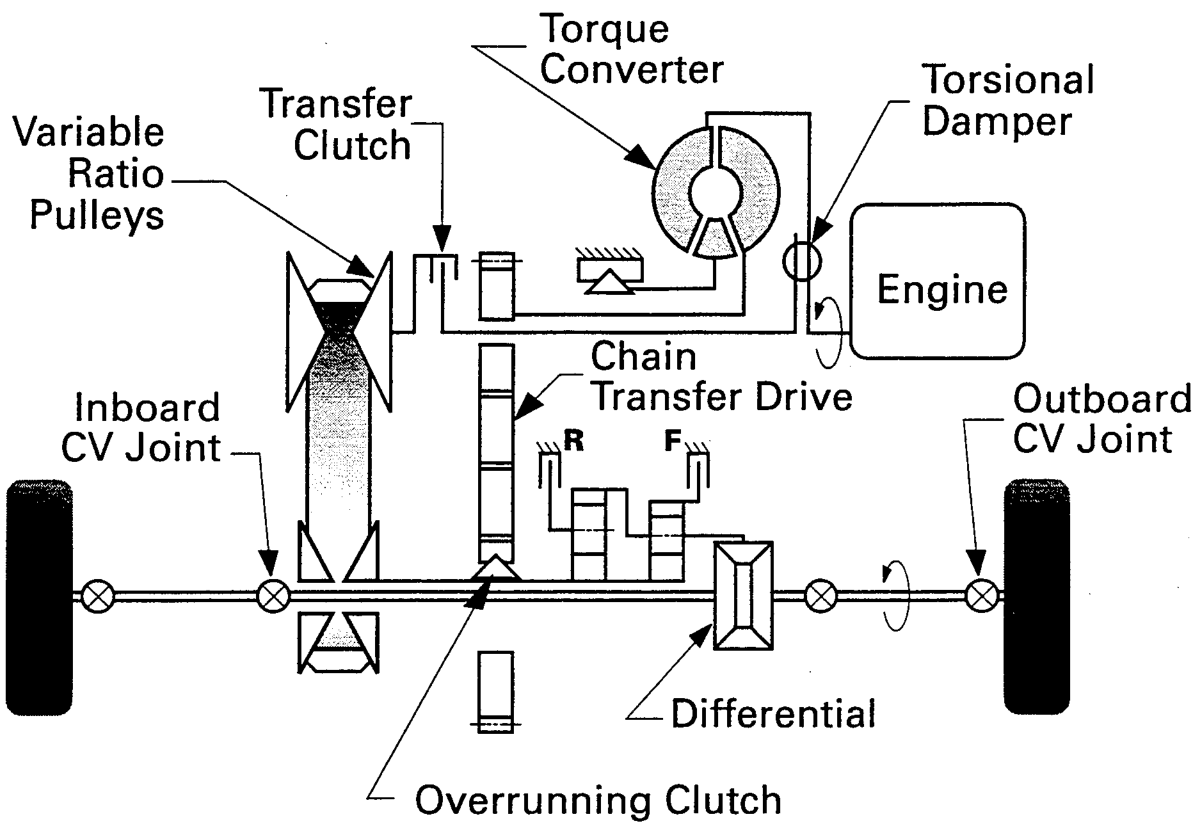


Figure IV-7. Schematic of the Dual Mode CVT Transmission.

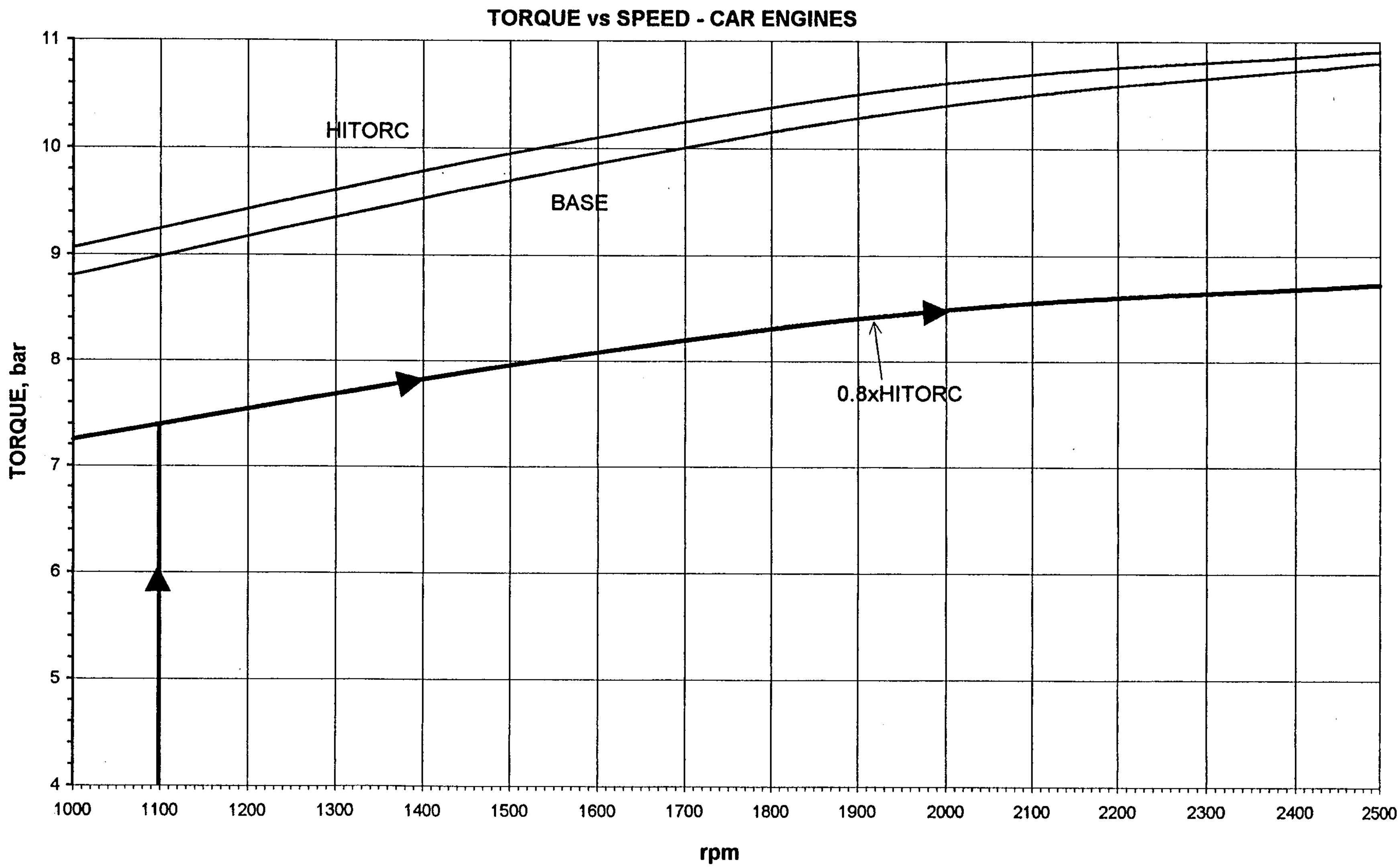


Figure IV-8. WOT torque curves for base and HITORC engines for car - above.
Lower curve with arrows gives the operating path for the CVT engine.

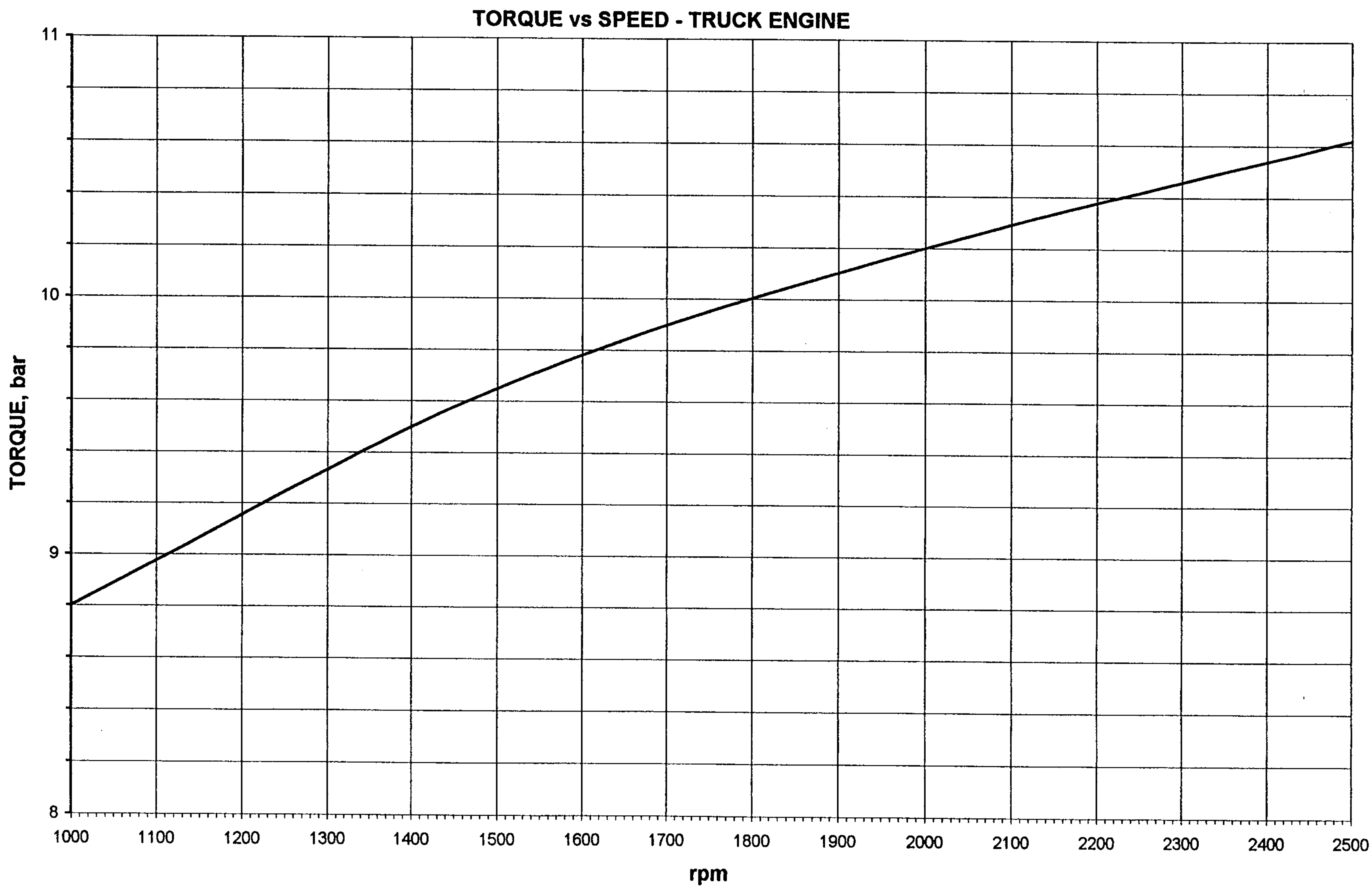


Figure IV-9. WOT torque curve for truck engine.

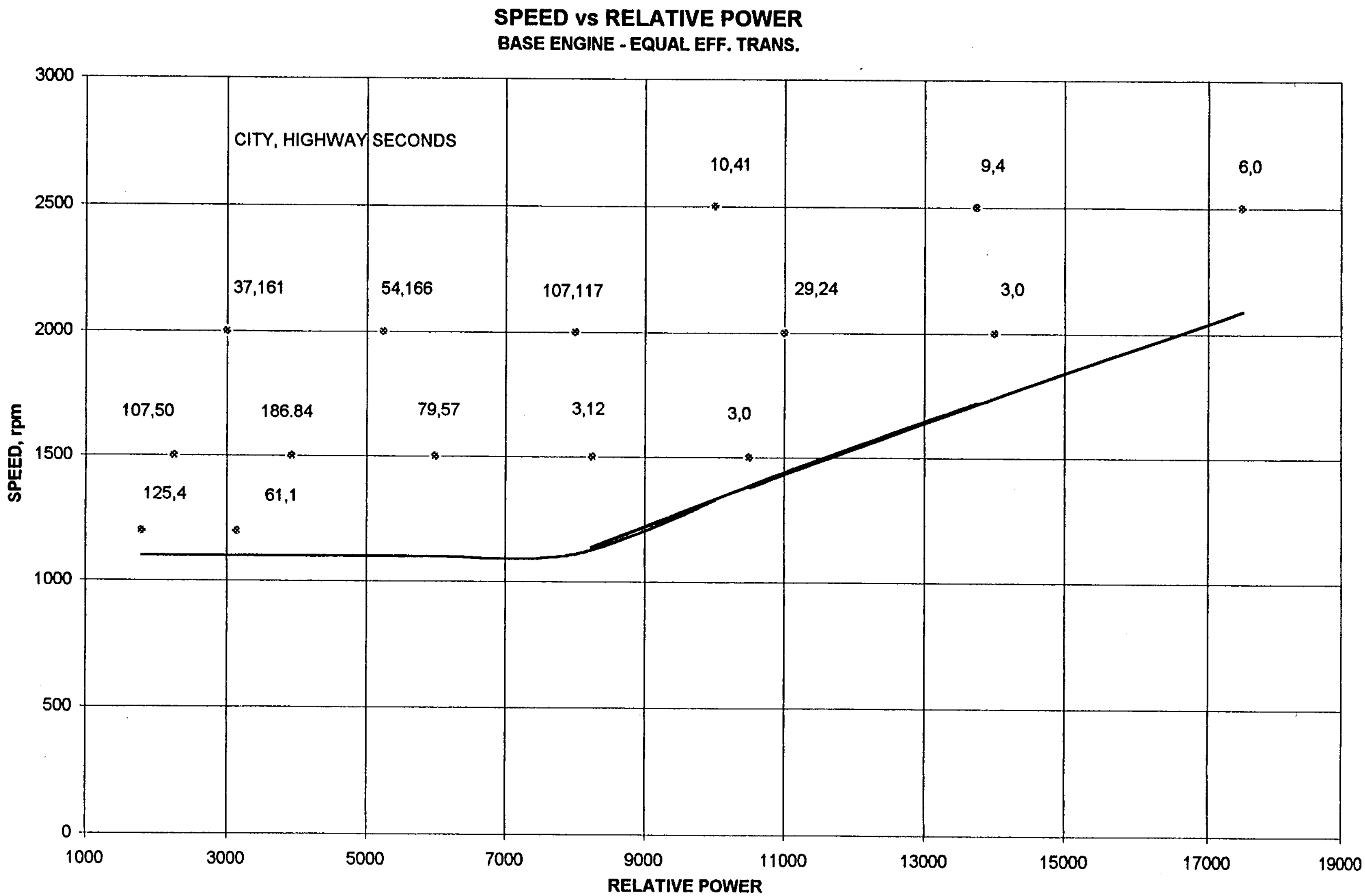


Figure IV-10. The CVT and base system path.

V. FUEL ECONOMY ANALYSIS AND RESULTS

A. SOURCES OF FUEL ECONOMY GAIN

The sources of fuel economy gain with a CVT are significant reductions in friction and pumping work plus some gain in transmission efficiency itself. The magnitude of the gain is very dependent on the operating point of the engine.

B. ASSUMPTIONS FOR THE FUEL ECONOMY CALCULATIONS

1. Residual Gas Considerations

When determining fuel economy benefits of the CVT system, it was assumed that 10% EGR was added to the charge for NOx control. Under some operating conditions, it was not possible to achieve 80% torque with that level and with stoichiometric fuel/air ratio. In those cases lower amounts of EGR were used. EGR amounts, if different from 10%, are given at the bottom of Tables V-1 to V-5.

2. HITORC Engine and Friction for the CVT System

As was discussed in Chapter IV, the HITORC engine was assumed for use with the CVT system in the car. Thus all car fuel economy calculation with the CVT were made with this engine. It was different from the base engine due to a camshaft change which provided higher torque at low engine speeds. In every other respect, the engines were identical. For the truck, the base engine was used with the CVT. The friction mean effective pressures were assumed to be the same for the 4-valve and 2-valve engines, both base and HITORC. The friction values were the same as those used in the VVT study, Reference 25.

3. Engine Speed Considerations

The idle speed of both HITORC and base engines was assumed to be 640 rpm. The idle fuel rate was taken to be 0.327 g/s for both engines. This value was derived from measured industry data for a 4-valve production, 2-liter engine adjusted for displacement differences in the ratio of 3.0/2.0.

Lowering engine speed when using a CVT may produce problems with engine accessories such as inadequate cooling or inadequate alternator speed. This possibility was not considered in this study. The authors believe that the lower speeds with the CVT can be achieved within the parameters of existing engine accessories.

C. COMPUTER CALCULATIONS OF PART LOAD FUEL ECONOMY

1. The GM Single Cylinder Engine Program

In Chapter IV, the 16 idle and part load points around which City and Highway Cycle fuel economy calculations were to be made were discussed. The assumptions with respect to idle fuel rate were discussed above.

The indicated fuel economy of the remaining 15 points was calculated using the "Export Version" of the General Motors Research Laboratory Single Cylinder Engine Computer Model (Meintjes[22]). Below are the first two paragraphs from the report Abstract which describe its features and usefulness.

<u>Abstract</u>

"The General Motors engine simulation is a comprehensive computer model of a four-stroke, spark ignited, homogeneous charge engine cycle. The model is based primarily on the first law of thermodynamics; differential equations (for pressure, temperature, etc.) are integrated for each of a number of thermodynamic zones (or control volumes) to obtain predictions of engine performance. Submodels describe heat and mass transfer to or from each zone.

This version of the simulation is being released by GM to academic institutions for use as a teaching aid in advanced undergraduate and graduate courses in thermodynamics and internal combustion engines. It is ideally suited to illustrate aspects of engine behavior beyond the ideal cycle analyses found in textbooks, for example, the effect of valve timing on engine torque and the influence of heat transfer on engine efficiency."

In this study the following were assumed at the 15 engine speed and load points:

1. Combustion rate as in supplied program (Wiebe function) with peak pressure at 14^{o} ATC.
2. Heat transfer coefficients and cylinder temperatures as in supplied program.
3. Gasoline properties as in supplied program.
4. NOx calculation as in supplied program.
5. Engine parameters as in Table IV-1.
6. Valve lift and duration as in Figures IV-1 to IV-4.
7. EGR of 10% at 550 K except as noted.
8. Equivalence ratio of 1.0.

9. Intake Mixture temperature of 325 K.

10. Combustion efficiency of 98%.

11. Five iterations were run to reach stable values.

2. Calculated Fuel Economy Results

Tables V-1 and V-2 give the results of the GM Program calculations for the car with 3.0 liter base engine and 4SAT transmission (Table V-1) and HITORC engine with CVT, (Table V-2). Tables V-3 and V-4 give the results for the light truck. In each table, the leftmost two columns list the 16-speed, load points from top to bottom. At each speed and load point are listed the manifold air pressure (MAP), imep, pmep, net imep = imep-pmep, friction mep estimate generated by the GM program (not used), friction mep projected from experimental industry engine data termed FM friction (used), brake mep based on FM friction, power, fuel rate, net indicated efficiency, mechanical efficiency, brake efficiency, bsfc, bsNOx and residual dilution.

The fuel consumption rate result at each speed and load combination in Tables V-1 to V-4 has been carried to Tables V-5 to V-10 in which the City, Highway, and Combined Cycle fuel economy results are presented. Tables V-5, 6, and 7 give results for the car with the three assumed transmission efficiencies of equal to the production 4SAT, +3% and +6%. Tables V-8, 9, and 10 give results for the light truck. In those tables, the first three columns list the base engine speed, load, and fuel consumption. The fourth through sixth columns list the CVT system speed, load, and fuel consumption. The next two columns repeat the times on both City and Highway Cycles. The next four columns list the total fuel consumed at each point for the Base and CVT systems. Finally, the rightmost column lists the percent fuel consumption gain at that point with the CVT system. For the car, the greatest percentage gains (16-19%) came at 2000 rpm, 1.5, and 2.62 bar load, key points which contribute about 35% of the fuel consumption on the Highway Cycle. For the light truck, 2000 rpm and 4-bar load yielded the greatest absolute economy increase on the City Cycle, up to 25% of the benefit. Several points yielded double digit economy increases.

3. Cycle Fuel Economy Benefit Considerations

Fuel economy results have been graphed in Figures V-1 to V-3 for the car and V-4 to V-6 for the light truck. Figure V-1 shows the absolute economy comparison for the car. Plotted are City, Highway, and Combined Cycle fuel economy for base engine and transmission (leftmost bar), CVT, and HITORC engine with equal, +3%, and +6% efficiencies (rightmost three bars). The base car achieves 20.1 mpg on the City, 32.5 mpg on the Highway, and 24.3 mpg on the Combined Cycle. With the CVT, this ranges upward to 22, 37.2, and 26.9 mpg depending on the transmission efficiency assumption. Figure V-4 shows similar results for the light truck. In general, fuel economy is somewhat lower for the truck, especially on the Highway Cycle. This is due to the higher aerodynamic drag of the light truck.

Figure V-2 shows the absolute incremental improvement for the various CVT efficiency assumptions with the car and Figure V-5 shows the improvements for the truck. Note the relatively large incremental gains on the Highway Cycle for both vehicles. This reflects the reduced friction with the CVT operating at lower speeds, an effect which is amplified under conditions where the engine and conventional transmission run at relatively high speeds. Finally, Figures V-3 and V-6 show the Combined Cycle percentage gains over the base engine and transmission for the various CVT efficiency assumptions. For the car these range from 6.6% with equal transmission efficiency to 8.7% (+3% efficiency) to 11% (+6% efficiency). The light truck gains are quite similar, ranging from 6% to 10.8%. The Highway Cycle contribution to the fuel economy increase is larger than the City, especially for the car. It should be noted that the economy gain with each 3% transmission efficiency increase increment is less than 3% because the engine load is reduced and engine operation moves to a lower load, higher bsfc point. This is illustrated in Figure V-7, a plot of engine bsfc versus brake power. To the extent that improved transmission efficiency reduces power requirement, the operating point moves to the left, to a higher bsfc. This is especially significant at the lower power outputs where the slope of the bsfc curve is steep.

D. EMISSIONS

A constraint of this study was that emissions not increase beyond those of the base engine which was assumed to meet Tier I EPA regulations. Emissions are discussed below.

1. Hydrocarbon and Oxygenate Emissions

There are no reliable means to accurately estimate HC or oxygenate emissions analytically. It is projected that they will be no higher with the CVT system based on the following logic.

a. Mixture strength is maintained at stoichiometric with the three-way catalyst.

b. The literature indicates that the effect of load on engine-out HC emissions at a given speed and MBT timing is approximately zero in terms of ppm at a constant mixture strength. On the other hand, lowering engine speed typically increases HC emissions in terms of ppm. At a given HC emission level in ppm, to the extent that transmission efficiency is increased with the CVT, mass flow and HC mass emissions would be reduced. The higher engine loads with CVT are expected to increase exhaust temperature. This may improve catalyst efficiency, if it is not already at about 100%, except for the initial cold-start period of 15-20 seconds. If necessary, the HC emissions in this period can be made identical to those of the base vehicle by adjusting the speed and loads on the engine to be the same as those of the base vehicle. The impact on CVT fuel economy would be negligible.

2. Carbon Monoxide Emissions

Carbon monoxide emissions are primarily a function of the engine air-fuel ratio. That is assumed to be the same for the CVT and the base system. Therefore it is likely that CO emissions remain unchanged, or may decrease a little to the extent that increased transmission efficiency lowers exhaust mass flow.

3. Oxides of Nitrogen Emissions

NOx emission trends can be approximated reasonably well by engine simulation programs like the GM Single Cylinder Engine Program used in this study which uses the Zeldovich mechanism for NOx prediction. The calculations show NOx to be generally higher with the CVT. This results from the generally higher engine loads with the CVT. Tables V-11, 12, 13 and 14 show engine-out NOx emission results for both car and light truck at both equal and +6% transmission efficiency. At each of the 15 non-idle operating points, the grams of NOx emitted are calculated. Idle NOx emission is negligible. The grams at each point are totaled for the EPA City Cycle and the g/mi. determined. Emissions are not assessed on the Highway Cycle. Significantly there was a 43.7% increase in engine-out NOx with the CVT system of equal transmission efficiency. This reduced to 34.1% with the 6% CVT efficiency increase. Higher transmission efficiency reduces the engine load which causes less NOx to be generated. Results for the light truck show a somewhat higher level of NOx initially, but only a 17.6% increase with equal and a 9.6% increase with a 6% more efficient CVT.

Because of the many assumptions and simplifications used to calculate the NOx emissions, the results should be viewed as directional only. The large difference in the increase of emissions between the car and truck is probably not real. Some of the difference is explained by the lower, low speed maximum torque of the truck engine, which was the base rather than the HITORC version, together with the exponential sensitivity of NOx emission to load. The best conclusion to be reached from these numbers is that NOx emissions may be expected to be significantly higher with use of a CVT.

From the above it is clear that NOx emission control poses a challenge to the use of the CVT. Actually, the problem is not as serious as it appears. Today's NOx catalysts are capable of up to 98% efficiency. The calculations in Tables V-11 to V-14 show that the needed catalyst efficiency to reach TLEV standards of 0.4 g/mile increases from about 88% with the 4SAT to 92% with the CVT. This suggests that the increased NOx is not a problem. Furthermore, some minor load reduction at high NOx CVT points might be expected to lower NOx significantly without a major impact on fuel consumption. More and more, the largest accumulation of emissions is occurring in the first 15 to 20 seconds on the Cycle. The CVT control software might be programmed to set engine speeds and loads more like the conventional 4SAT. This would lower NOx significantly and would not reduce fuel economy very much on a cycle of total length 1320 seconds.

TABLE V-1

RESULTS FROM GM SINGLE CYLINDER MODEL, BASE ENGINE AND TRANSMISSION - CAR

CAR - BASE ENGINE AND TRANSMISSION

HEATING VALUE OF FUEL WAS 45.59 MJ/kg

NOMINAL SPEED rpm	LOAD bar	MAP kpa	GM IMEP kpa	GM PMEP kpa	GM NET IMEP kpa	GM FRICTIO kpa	FM FRICTIO kpa	FM BRAKE kpa	FM POWER bKw	FM FUEL RATE, g/s	GM NET IN EFF, %	FM MECH EFF, %	FM BRAKE EFF, %	FM BSFC g/kW-hr	GM NOx g/kw-hr	GM NOx g/sx100	GM DILUT. %
IDLE	X	X	X	X	X	X	X	X	IDLE	0.327	X	X	X	X	X	0.0	X
1200	1.50	40.0	265.0	61.4	203.6	66.6	56.6	147.0	4.55	0.570	24.2	72.2	17.5	451.81	5.8	0.732	22.9
1200	2.62	51.5	365.3	50.1	315.2	68.8	57.9	257.3	7.94	0.781	27.3	81.6	22.3	354.30	8.5	1.874	20.0
1500	1.50	38.5	268.7	63.1	205.6	72.8	59.2	146.4	5.68	0.694	25.2	71.2	17.9	440.02	5.4	0.852	22.5
1500	2.62	50.0	373.7	51.8	321.9	74.9	59.4	262.5	9.92	0.937	28.5	81.6	23.2	339.75	8.0	2.205	19.5
1500	4.00	63.5	499.4	38.5	460.9	77.5	64.1	396.8	15.15	1.253	30.8	86.1	26.5	297.82	10.1	4.250	17.3
1500	5.50	78.0	636.8	24.2	612.6	80.2	66.7	545.9	20.83	1.582	32.4	89.1	28.9	273.48	11.4	6.597	15.9
1500	7.00	94.5	796.1	7.8	788.3	83.2	69.4	718.9	26.51	1.901	33.5	91.2	30.6	258.16	13.6	10.016	14.6
2000	1.50	39.5	297.2	62.5	234.7	84.0	72.5	162.2	7.58	0.877	27.4	69.1	18.9	416.70	8.5	1.789	21.3
2000	2.62	48.5	384.0	53.8	330.2	85.7	72.8	257.4	13.23	1.233	30.2	77.9	23.5	335.45	7.3	2.690	19.0
2000	4.00	63.0	526.0	39.6	486.4	88.5	78.0	408.4	20.20	1.622	32.5	84.0	27.3	289.02	11.6	6.509	16.9
2000	5.50	77.0	665.2	25.9	639.3	91.0	82.8	556.5	27.78	2.065	33.9	87.0	29.5	267.60	10.8	8.333	15.5
2000	7.00	91.0	806.0	12.2	793.8	93.6	85.7	708.1	35.35	2.489	34.9	89.2	31.1	253.50	13.1	12.863	14.5
2500	4.00	62.5	541.5	40.9	500.6	99.7	87.4	413.2	25.25	2.005	33.5	82.5	27.6	285.83	11.0	7.715	16.6
2500	5.50	xxx	xxx	xxx	xxx	xxx	xxx	xxx	34.72	2.584	xxx	xxx	29.6	267.9	11.8	11.380	xxx
2500	7.00	89.5	819.0	14.9	804.1	104.6	96.0	708.1	44.19	3.068	35.9	88.1	31.6	249.99	12.6	15.466	14.4

ALL POINTS HAVE 10% EGR

TABLE V-2

RESULTS FROM GM SINGLE CYLINDER ENGINE MODEL, HITORC ENGINE AND CVT - CAR

CAR - HITORC ENGINE AND CVT TRANSMISSION

HEATING VALUE OF FUEL WAS 45.59 MJ/kg

NOMINAL SPEED rpm	LOAD bar	MAP kpa	GM IMEP kpa	GM PMEP kpa	GM NET IMEP kpa	GM FRICTIO kpa	FM FRICTIO kpa	FM BRAKE kpa	FM ACTUA POWER bKw	FM FUEL RATE, g/s	GM NET IN EFF, %	FM MECH EFF, %	FM BRAKE EFF, %	FM BSFC g/kW-hr	GM NOx g/kw-hr	GM NOx g/sx100	GM DILUT. %
IDLE	X	X	X	X	X	X	X	X	IDLE	0.327	X	X	X	X	X	0.0	X
1100	1.53	40.5	278.0	60.9	217.1	64.6	54.5	162.6	4.47	0.543	24.1	74.9	18.1	437.48	10.2	1.267	21.6
1100	2.40	50.0	360.9	51.5	309.4	66.4	54.5	254.9	7.01	0.702	26.6	82.4	21.9	360.33	12.0	2.337	19.3
1100	3.40	60.0	449.6	41.7	408.0	68.3	58.3	349.7	9.62	0.867	28.4	85.7	24.3	324.40	13.1	3.499	17.8
1100	4.40	70.0	539.4	31.8	507.6	70.2	61.8	445.8	12.26	1.034	29.6	87.8	26.0	303.75	13.8	4.699	16.6
1100	5.40	80.0	630.1	21.9	608.2	72.0	63.3	544.9	14.98	1.203	30.5	89.6	27.3	288.98	14.1	5.869	15.7
1100	6.40	90.0	721.5	12.0	709.5	73.9	65.0	644.5	17.72	1.367	31.3	90.8	28.4	277.73	14.3	7.040	15.0
1100	7.40	100.0	814.1	2.0	812.1	75.8	66.7	745.4	20.50	1.536	31.9	91.8	29.3	269.69	14.3	8.142	14.4
1200	7.55	99.0	834.6	3.2	831.4	77.7	70.7	760.7	22.82	1.694	32.3	91.5	29.6	267.19	14.7	9.319	13.5
1400	7.80	99.5	868.4	3.1	865.3	82.0	71.3	794.0	27.79	1.983	33.5	91.8	30.7	256.88	14.7	11.348	13.3
1600	8.10	100.0	896.7	3.0	893.7	86.4	75.4	818.3	32.73	2.293	34.2	91.6	31.3	252.17	14.3	13.002	13.2
1800	8.30	100.0	929.5	3.6	925.9	90.8	81.9	844.0	37.98	2.626	34.8	91.2	31.7	248.93	14.8	15.614	12.2
2000	8.50	100.0	945.1	4.3	940.8	95.2	88.6	852.2	42.61	2.915	35.4	90.6	32.1	246.26	14.7	17.399	12.2
2100	8.60	99.5	961.1	5.2	955.9	97.4	91.0	864.9	45.41	3.101	35.5	90.5	32.1	245.84	15.2	19.172	11.3

EGR: 10% @ 1100, 9% @ 1200 - 1700, 8% @ 1800 - 2000, 7% @ 2100 rpm

TABLE V-3

RESULTS FROM GM SINGLE CYLINDER MODEL, BASE ENGINE AND TRANSMISSION - LT. TRUCK

TRUCK - BASE ENGINE AND TRANSMISSION

HEATING VALUE OF FUEL WAS 45.59 MJ/kg

NOMINAL SPEED rpm	LOAD bar	MAP kpa	GM IMEP kpa	GM PMEP kpa	GM NET IMEP kpa	GM FRICTIO kpa	FM FRICTIO kpa	FM BRAKE kpa	FM POWER bKw	FM FUEL RATE, g/s	GM NET IN EFF, %	FM MECH EFF, %	FM BRAKE EFF, %	FM BSFC g/kW-hr	GM NOx g/kw-hr	GM NOx g/sx100	GM DILUT. %
IDLE	X	X	X	X	X	X	X	X	IDLE	0.327	X	X	X	X	X	0.0	X
1200	1.50	39.5	268.0	62.4	205.6	55.3	56.6	149.0	4.55	0.571	24.1	72.5	17.5	452.34	7.9	0.997	22.6
1200	2.62	51.0	369.1	51.2	317.9	57.5	57.9	260.0	7.94	0.783	27.2	81.8	22.2	354.91	10.4	2.293	19.6
1500	1.50	38.5	275.4	63.9	211.5	62.1	59.2	152.3	5.68	0.685	25.3	72.0	18.2	433.79	7.8	1.231	22.1
1500	2.62	50.0	381.6	52.7	328.9	64.3	59.4	269.5	9.92	0.931	28.5	81.9	23.4	337.79	10.0	2.756	19.2
1500	4.00	63.5	508.5	39.6	468.9	66.8	64.1	404.8	15.15	1.251	30.8	86.3	26.6	297.26	11.8	4.966	17.2
1500	5.50	78.0	647.0	25.5	621.5	69.5	66.7	554.8	20.83	1.585	32.3	89.3	28.8	273.87	12.8	7.407	15.7
1500	7.00	92.0	782.6	11.8	770.8	72.1	69.4	701.4	26.51	1.919	33.3	91.0	30.3	260.56	13.3	9.795	14.7
2000	1.50	38.0	288.3	65.3	223.0	74.0	72.5	150.5	7.58	0.920	26.8	67.5	18.1	437.11	7.7	1.620	21.5
2000	2.62	49.0	395.1	54.9	340.2	72.0	72.8	267.4	13.23	1.232	30.0	78.6	23.6	335.26	9.5	3.492	18.8
2000	4.00	62.0	523.3	42.6	480.7	78.4	78.0	402.7	20.20	1.643	32.2	83.8	27.0	292.81	11.1	6.228	16.9
2000	5.50	76.0	663.0	29.2	633.8	81.0	82.8	551.0	27.78	2.079	33.7	86.9	29.3	269.40	12.2	9.413	15.5
2000	7.00	89.5	799.2	16.4	782.8	83.5	85.7	697.1	35.35	2.507	34.7	89.1	30.9	255.36	12.8	12.569	14.6
2500	4.00	61.5	535.7	44.9	490.8	90.6	87.4	403.4	25.25	2.034	33.1	82.2	27.2	290.05	10.6	7.435	16.7
2500	5.50	75.0	674.0	32.5	641.5	93.1	91.7	549.8	34.72	2.584	34.4	85.7	29.5	267.90	11.7	11.284	15.5
2500	7.00	88.5	813.4	20.3	793.1	95.6	96.0	697.1	44.19	3.097	35.6	87.9	31.3	252.34	12.4	15.220	14.6

ALL POINTS HAVE 10% EGR

TABLE V-4

RESULTS FROM GM SINGLE CYLINDER ENGINE MODEL, BASE ENGINE AND CVT - LT. TRUCK

TRUCK - BASE ENGINE AND CVT TRANSMISSION

HEATING VALUE OF FUEL WAS 45.59 MJ/kg

NOMINAL SPEED rpm	LOAD bar	MAP kpa	GM IMEP kpa	GM PMEP kpa	GM NET IMEP kpa	GM FRICTIO kpa	FM FRICTIO kpa	FM BRAKE kpa	FM ACTUA POWER bKw	FM FUEL RATE, g/s	GM NET IN EFF, %	FM MECH EFF, %	FM BRAKE EFF, %	FM BSFC g/kW-hr	GM NOx g/kw-hr	GM NOx g/sx100	GM DILUT. %
IDLE	X	X	X	X	X	X	X	X	IDLE	0.327	X	X	X	X	X	0.0	X
1100	1.53	40.5	269.6	61.3	208.3	53.2	54.5	153.8	4.23	0.529	23.8	73.8	17.6	449.92	8.1	0.952	22.6
1100	2.42	50.0	351.3	52.0	299.3	55.0	54.5	244.8	6.73	0.685	26.3	81.8	21.5	366.54	10.3	1.926	20.1
1100	3.36	60.0	438.8	42.2	396.6	56.9	58.3	338.3	9.30	0.850	28.1	85.3	24.0	329.07	11.8	3.049	18.3
1100	4.3	70.0	527.7	32.3	495.4	58.8	61.8	433.6	11.92	1.016	29.4	87.5	25.7	306.88	12.8	4.240	17.0
1100	5.29	80.0	617.8	22.5	595.3	60.7	63.3	532.0	14.63	1.183	30.3	89.4	27.1	291.16	13.3	5.405	16.1
1100	6.28	90.0	709.0	12.6	696.4	62.5	65.0	631.4	17.36	1.351	31.1	90.7	28.2	280.04	13.6	6.560	15.3
1100	6.77	95.0	755.2	7.6	747.6	63.5	66.7	680.9	18.72	1.436	31.4	91.1	28.6	276.03	13.7	7.126	14.9
1100	7.08	98.0	783.3	4.7	778.6	64.0	66.7	711.9	19.58	1.487	31.6	91.4	28.9	273.42	13.8	7.505	14.7
1200	7.27	98.5	805.4	4.5	800.9	66.4	70.7	730.2	21.91	1.635	32.2	91.2	29.4	268.72	13.7	8.336	14.6
1400	7.51	98.5	834.3	5.1	829.2	71.0	71.3	757.9	26.53	1.914	33.3	91.4	30.4	259.73	13.5	9.947	14.4
1600	7.73	99.0	862.3	5.4	856.9	75.8	75.4	781.5	31.26	2.205	34.1	91.2	31.1	253.95	13.4	11.636	14.3
1800	7.91	99.5	885.9	5.9	880.0	80.6	81.9	798.1	35.91	2.498	34.8	90.7	31.5	250.40	13.2	13.169	14.2
2000	8.1	100.0	906.1	6.5	899.6	85.5	88.6	811.0	40.55	2.794	35.3	90.2	31.8	248.03	13.1	14.756	14.1
2200	8.21	100.0	927.6	8.3	919.3	90.2	91.0	828.3	45.56	3.112	35.6	90.1	32.1	245.95	13.7	17.337	13.1

ALL POINT HAVE 10% EGR EXCEPT AT 2200 RPM WHICH IS 9%.

TABLE V-5

FUEL ECONOMY PREDICTIONS ON EPA CYCLES - BASE AND CVT COMPARED, EQUAL TRANSMISSION EFFICIENCIES - CAR

BASE ENGINE/TRANS PTS SPEED	LOAD bar	FUEL g/s	HITORC ENGINE/CVT PTS SPEED	LOAD bar	FUEL g/s	CYCLE TIMES CITY sec	HWY sec	BASE CITY TOTAL FUEL, g	CVT CITY TOTAL FUEL, g	BASE HWY TOTAL FUEL, g	CVT HWY TOTAL FUEL, g	CVT GAIN %
IDLE	X	0.327	IDLE	X	0.327	551.9	41.5	180.46	180.46	13.58	13.58	0.0
1200	1.5	0.570	1100	1.64	0.552	124.6	3.9	71.04	68.80	2.21	2.14	3.2
1200	2.62	0.781	1100	2.86	0.772	61.1	1.2	47.75	47.20	0.93	0.92	1.2
1500	1.5	0.694	1100	2.05	0.631	107.2	50.4	74.38	67.63	34.97	31.80	9.1
1500	2.62	0.937	1100	3.57	0.890	186.2	83.8	174.45	165.70	78.51	74.57	5.0
1500	4	1.253	1100	5.45	1.208	79.3	56.9	99.39	95.82	71.23	68.67	3.6
1500	5.5	1.582	1110	7.43	1.557	3.5	12.2	5.52	5.43	19.33	19.03	1.6
1500	7	1.901	1350	7.78	1.907	3.2	0.2	6.06	6.08	0.38	0.38	-0.3
2000	1.5	0.877	1100	2.73	0.739	37.3	161.4	32.71	27.56	141.56	119.28	15.7
2000	2.62	1.233	1100	4.76	1.095	54.2	166.5	66.77	59.29	205.27	182.30	11.2
2000	4	1.622	1100	7.27	1.504	107.0	117.0	173.49	160.87	189.74	175.94	7.3
2000	5.5	2.065	1405	7.83	1.983	29.4	23.9	60.69	58.28	49.25	47.29	4.0
2000	7	2.489	1710	8.19	2.455	2.6	0.4	6.40	6.31	1.00	0.98	1.4
2500	4	2.005	1300	7.69	1.838	10.0	40.7	19.99	18.32	81.50	74.71	8.3
2500	5.5	2.536	1680	8.18	2.419	8.6	4.5	21.89	20.88	11.34	10.81	4.6
2500	7	3.068	2050	8.54	3.020	6.1	0.7	18.59	18.30	2.15	2.11	1.6
						1372.0	765.0	1059.6	1006.9	903.0	824.5	

	BASE CITY	CVT CITY	BASE HWY	CVT HWY
LITERS CONSUMED @ SP. GR.=0.735	1.44	1.37	1.23	1.12
GALLONS = l/3.864	0.373	0.355	0.318	0.290
MILES	7.50	7.50	10.32	10.32
MPG	20.10	21.15	32.46	35.54
DEL FE, MPG		1.05		3.09
LITERS/100 KM	12.01	11.42	7.44	6.79
GRAMS DIFFERENCE	52.63		78.42	
% FE GAIN WITH CVT	**5.23**		**9.51**	

COMBINED CYCLE	24.26	25.87	MPG
COMBINED GAIN	1.61	MPG	
% GAIN	**6.63**		

TABLE V-6

FUEL ECONOMY PREDICTIONS ON EPA CYCLES - BASE AND CVT COMPARED, +3% CVT TRANSMISSION EFFICIENCY - CAR

BASE ENGINE/TRANS PTS			**HITORC ENGINE/CVT PTS**			**CYCLE TIMES**		**BASE CITY**	**CVT CITY**	**BASE HWY**	**CVT HWY**	**CVT GAIN**
SPEED	LOAD bar	FUEL g/s	SPEED	LOAD bar	FUEL g/s	CITY sec	HWY sec	TOTAL FUEL, g	TOTAL FUEL, g	TOTAL FUEL, g	TOTAL FUEL, g	%
IDLE	X	0.327	IDLE	X	0.327	551.9	41.5	180.46	180.46	13.58	13.58	0.0
1200	1.5	0.570	1100	1.59	0.539	124.6	3.9	71.04	67.18	2.21	2.09	5.4
1200	2.62	0.781	1100	2.77	0.742	61.1	1.2	47.75	45.37	0.93	0.88	5.0
1500	1.5	0.694	1100	1.98	0.620	107.2	50.4	74.38	66.45	34.97	31.24	10.7
1500	2.62	0.937	1100	3.47	0.872	186.2	83.8	174.45	162.35	78.51	73.06	6.9
1500	4	1.253	1100	5.29	1.188	79.3	56.9	99.39	94.23	71.23	67.54	5.2
1500	5.5	1.582	1100	7.28	1.515	3.5	12.2	5.52	5.29	19.33	18.51	4.2
1500	7	1.901	1315	7.75	1.863	3.2	0.2	6.06	5.94	0.38	0.37	2.0
2000	1.5	0.877	1100	2.65	0.719	37.3	161.4	32.71	26.82	141.56	116.05	18.0
2000	2.62	1.233	1100	4.62	1.069	54.2	166.5	66.77	57.89	205.27	177.97	13.3
2000	4	1.622	1100	7.05	1.481	107.0	117.0	173.49	158.41	189.74	173.25	8.7
2000	5.5	2.065	1365	7.82	1.928	29.4	23.9	60.69	56.66	49.25	45.98	6.6
2000	7	2.489	1660	8.18	2.392	2.6	0.4	6.40	6.15	1.00	0.96	3.9
2500	4	2.005	1265	7.67	1.797	10.0	40.7	19.99	17.92	81.50	73.05	10.4
2500	5.5	2.536	1635	8.16	2.359	8.6	4.5	21.89	20.36	11.34	10.54	7.0
2500	7	3.068	1995	8.51	2.943	6.1	0.7	18.59	17.83	2.15	2.06	4.1
						1372.0	765.0	1059.6	989.3	903.0	807.1	

	BASE CITY	CVT CITY	BASE HWY	CVT HWY
LITERS CONSUMED @ SP. GR.=0.735	1.44	1.35	1.23	1.10
GALLONS = l/3.864	0.373	0.348	0.318	0.284
MILES	7.50	7.50	10.32	10.32
MPG	20.10	21.53	32.46	36.31
DEL FE, MPG		1.43		3.85
LITERS/100 KM	12.01	11.22	7.44	6.65
GRAMS DIFFERENCE	70.28		95.80	
% FE GAIN WITH CVT	**7.10**		**11.87**	

COMBINED CYCLE	24.26	26.36	MPG
COMBINED GAIN	2.10	MPG	
% GAIN	**8.66**		

TABLE V-7

FUEL ECONOMY PREDICTIONS ON EPA CYCLES - BASE AND CVT COMPARED, +6% CVT TRANSMISSION EFFICIENCY - CAR

BASE ENGINE/TRANS PTS SPEED	LOAD bar	FUEL g/s	HITORC ENGINE/CVT PTS SPEED	LOAD bar	FUEL g/s	CYCLE TIMES CITY sec	HWY sec	BASE CITY TOTAL FUEL, g	CVT CITY TOTAL FUEL, g	BASE HWY TOTAL FUEL, g	CVT HWY TOTAL FUEL, g	CVT GAIN %
IDLE	X	0.327	IDLE	X	0.327	551.9	41.5	180.46	180.46	13.58	13.58	0.0
1200	1.5	0.570	1100	1.59	0.528	124.6	3.9	71.04	65.80	2.21	2.05	7.4
1200	2.62	0.781	1100	2.77	0.729	61.1	1.2	47.75	44.57	0.93	0.87	6.7
1500	1.5	0.694	1100	1.98	0.604	107.2	50.4	74.38	64.73	34.97	30.44	13.0
1500	2.62	0.937	1100	3.47	0.849	186.2	83.8	174.45	158.07	78.51	71.14	9.4
1500	4	1.253	1100	5.29	1.155	79.3	56.9	99.39	91.61	71.23	65.66	7.8
1500	5.5	1.582	1100	7.28	1.479	3.5	12.2	5.52	5.16	19.33	18.07	6.5
1500	7	1.901	1280	7.96	1.821	3.2	0.2	6.06	5.81	0.38	0.36	4.2
2000	1.5	0.877	1100	2.65	0.707	37.3	161.4	32.71	26.37	141.56	114.12	19.4
2000	2.62	1.233	1100	4.62	1.044	54.2	166.5	66.77	56.53	205.27	173.81	15.3
2000	4	1.622	1100	7.05	1.445	107.0	117.0	173.49	154.56	189.74	169.04	10.9
2000	5.5	2.065	1330	8.02	1.886	29.4	23.9	60.69	55.43	49.25	44.98	8.7
2000	7	2.489	1615	8.41	2.326	2.6	0.4	6.40	5.98	1.00	0.93	6.5
2500	4	2.005	1230	7.89	1.754	10.0	40.7	19.99	17.49	81.50	71.30	12.5
2500	5.5	2.536	1590	8.39	2.283	8.6	4.5	21.89	19.70	11.34	10.21	10.0
2500	7	3.068	1940	8.75	2.850	6.1	0.7	18.59	17.27	2.15	2.00	7.1
						1372.0	765.0	1059.6	969.5	903.0	788.5	

	BASE CITY	CVT CITY	BASE HWY	CVT HWY
LITERS CONSUMED @ SP. GR.=0.735	1.44	1.32	1.23	1.07
GALLONS = l/3.864	0.373	0.341	0.318	0.278
MILES	7.50	7.50	10.32	10.32
MPG	20.10	21.97	32.46	37.17
DEL FE, MPG		1.87		4.71
LITERS/100 KM	12.01	10.99	7.44	6.50
GRAMS DIFFERENCE	90.02		114.41	
% FE GAIN WITH CVT	**9.29**		**14.51**	

COMBINED CYCLE	24.26	26.92	MPG
COMBINED GAIN	2.67	MPG	
% GAIN	**10.99**		

TABLE V-8

FUEL ECONOMY PREDICTIONS ON EPA CYCLES - BASE AND CVT COMPARED
EQUAL TRANSMISSION EFFICIENCIES - LT. TRUCK

BASE ENGINE/TRANS PTS SPEED	LOAD bar	FUEL g/s	BASE ENGINE/CVT PTS SPEED	LOAD bar	FUEL g/s	CYCLE TIMES CITY sec	HWY sec	BASE CITY TOTAL FUEL, g	CVT CITY TOTAL FUEL, g	BASE HWY TOTAL FUEL, g	CVT HWY TOTAL FUEL, g	CVT GAIN %
IDLE	X	0.327	IDLE	X	0.327	561.9	44.4	183.74	183.74	14.52	14.52	0.0
1200	1.5	0.571	1100	1.64	0.552	149.6	3.9	85.40	82.56	2.23	2.16	3.3
1200	2.62	0.783	1100	2.86	0.759	24.3	1.8	19.02	18.44	1.41	1.37	3.1
1500	1.5	0.685	1100	2.05	0.628	119.5	39.1	81.82	75.01	26.78	24.55	8.3
1500	2.62	0.931	1100	3.57	0.890	184.5	86.5	171.76	164.20	80.52	76.98	4.4
1500	4	1.251	1100	5.45	1.220	47.5	70.8	59.46	57.99	88.52	86.33	2.5
1500	5.5	1.585	1110	7.43	1.574	5.0	24.9	7.93	7.87	39.40	39.13	0.7
1500	7	1.919	1350	7.78	1.915	0.5	5.0	1.00	1.00	9.61	9.59	0.2
2000	1.5	0.920	1100	2.73	0.758	18.0	59.7	16.59	13.67	54.95	45.28	17.6
2000	2.62	1.232	1100	4.76	1.103	76.9	145.5	94.77	84.84	179.28	160.51	10.5
2000	4	1.643	1100	7.27	1.526	112.4	179.6	184.61	171.46	295.08	274.07	7.1
2000	5.5	2.079	1405	7.83	1.991	37.2	50.4	77.36	74.09	104.80	100.37	4.2
2000	7	2.507	1710	8.19	2.430	3.7	6.6	9.15	8.87	16.57	16.06	3.1
2500	4	2.034	1300	7.69	1.838	7.7	35.4	15.68	14.17	71.96	65.03	9.6
2500	5.5	2.584	1680	8.18	2.465	12.9	7.7	33.39	31.85	19.95	19.03	4.6
2500	7	3.097	2050	8.54	3.032	10.4	3.7	32.27	31.59	11.49	11.25	2.1
						1372.0	765.0	1073.9	1021.3	1017.09	946.21	

	BASE CITY	CVT CITY	BASE HWY	CVT HWY
LITERS CONSUMED @ SP. GR.=0.735	1.46	1.39	1.38	1.29
GALLONS = l/3.864	0.378	0.360	0.358	0.333
MILES	7.50	7.50	10.32	10.32
MPG	19.83	20.86	28.81	30.97
DEL FE, MPG		1.02		2.16
LITERS/100 KM	12.18	11.58	8.38	7.80
GRAMS DIFFERENCE	52.60		70.88	
% FE GAIN WITH CVT	**5.15**		**7.49**	

COMBINED CYCLE	23.07	24.45	MPG
COMBINED GAIN	1.38	MPG	
% GAIN	**5.98**		

TABLE V-9

FUEL ECONOMY PREDICTIONS ON EPA CYCLES - BASE AND CVT COMPARED +3% CVT TRANSMISSION EFFICIENCY - LT. TRUCK

BASE ENGINE/TRANS PTS			BASE ENGINE/CVT PTS			CYCLE TIMES		BASE CITY	CVT CITY	BASE HWY	CVT HWY	CVT GAIN
SPEED	LOAD bar	FUEL g/s	SPEED	LOAD bar	FUEL g/s	CITY sec	HWY sec	TOTAL FUEL, g	TOTAL FUEL, g	TOTAL FUEL, g	TOTAL FUEL, g	%
IDLE	X	0.327	IDLE	X	0.327	561.9	44.4	183.74	183.74	14.52	14.52	0.0
1200	1.5	0.571	1100	1.64	0.545	149.6	3.9	85.40	81.52	2.23	2.13	4.6
1200	2.62	0.783	1100	2.86	0.742	24.3	1.8	19.02	18.03	1.41	1.34	5.2
1500	1.5	0.685	1100	2.05	0.620	119.5	39.1	81.82	74.05	26.78	24.23	9.5
1500	2.62	0.931	1100	3.57	0.875	184.5	86.5	171.76	161.39	80.52	75.66	6.0
1500	4	1.251	1100	5.45	1.192	47.5	70.8	59.46	56.67	88.52	84.37	4.7
1500	5.5	1.585	1110	7.43	1.526	5.0	24.9	7.93	7.63	39.40	37.94	3.7
1500	7	1.919	1350	7.78	1.863	0.5	5.0	1.00	0.97	9.61	9.33	2.9
2000	1.5	0.920	1100	2.73	0.723	18.0	59.7	16.59	13.04	54.95	43.18	21.4
2000	2.62	1.232	1100	4.76	1.076	76.9	145.5	94.77	82.77	179.28	156.58	12.7
2000	4	1.643	1100	7.27	1.486	112.4	179.6	184.61	166.97	295.08	266.89	9.6
2000	5.5	2.079	1405	7.83	1.935	37.2	50.4	77.36	72.00	104.80	97.54	6.9
2000	7	2.507	1710	8.19	2.401	3.7	6.6	9.15	8.76	16.57	15.87	4.2
2500	4	2.034	1300	7.69	1.790	7.7	35.4	15.68	13.80	71.96	63.33	12.0
2500	5.5	2.584	1680	8.18	2.359	12.9	7.7	33.39	30.48	19.95	18.21	8.7
2500	7	3.097	2050	8.54	2.943	10.4	3.7	32.27	30.67	11.49	10.92	5.0
						1372.0	765.0	1073.9	1002.5	1017.09	922.04	

	BASE CITY	CVT CITY	BASE HWY	CVT HWY
LITERS CONSUMED @ SP. GR.=0.735	1.46	1.36	1.38	1.25
GALLONS = l/3.864	0.378	0.353	0.358	0.325
MILES	7.50	7.50	10.32	10.32
MPG	19.83	21.25	28.81	31.78
DEL FE, MPG		1.41		2.97
LITERS/100 KM	12.18	11.37	8.38	7.60
GRAMS DIFFERENCE	71.47		95.05	
% FE GAIN WITH CVT	**7.13**		**10.31**	

COMBINED CYCLE	23.07	24.97	MPG
COMBINED GAIN	1.90	MPG	
% GAIN	**8.25**		

TABLE V-10

FUEL ECONOMY PREDICTIONS ON EPA CYCLES - BASE AND CVT COMPARED
+6% CVT TRANSMISSION EFFICIENCY - LT. TRUCK

BASE ENGINE/TRANS PTS			BASE ENGINE/CVT PTS			CYCLE TIMES		BASE CITY	CVT CITY	BASE HWY	CVT HWY	CVT GAIN
SPEED	LOAD bar	FUEL g/s	SPEED	LOAD bar	FUEL g/s	CITY sec	HWY sec	TOTAL FUEL, g	TOTAL FUEL, g	TOTAL FUEL, g	TOTAL FUEL, g	%
IDLE	X	0.327	IDLE	X	0.327	561.9	44.4	183.74	183.74	14.52	14.52	0.0
1200	1.5	0.571	1100	1.64	0.533	149.6	3.9	85.40	79.72	2.23	2.08	6.7
1200	2.62	0.783	1100	2.86	0.729	24.3	1.8	19.02	17.72	1.41	1.31	6.8
1500	1.5	0.685	1100	2.05	0.607	119.5	39.1	81.82	72.47	26.78	23.72	11.4
1500	2.62	0.931	1100	3.57	0.847	184.5	86.5	171.76	156.19	80.52	73.22	9.1
1500	4	1.251	1100	5.45	1.159	47.5	70.8	59.46	55.09	88.52	82.01	7.4
1500	5.5	1.585	1110	7.43	1.485	5.0	24.9	7.93	7.43	39.40	36.92	6.3
1500	7	1.919	1350	7.78	1.814	0.5	5.0	1.00	0.94	9.61	9.09	5.5
2000	1.5	0.920	1100	2.73	0.703	18.0	59.7	16.59	12.68	54.95	42.00	23.6
2000	2.62	1.232	1100	4.76	1.047	76.9	145.5	94.77	80.54	179.28	152.36	15.0
2000	4	1.643	1100	7.27	1.451	112.4	179.6	184.61	163.03	295.08	260.60	11.7
2000	5.5	2.079	1405	7.83	1.893	37.2	50.4	77.36	70.44	104.80	95.43	8.9
2000	7	2.507	1710	8.19	2.326	3.7	6.6	9.15	8.49	16.57	15.37	7.2
2500	4	2.034	1300	7.69	1.748	7.7	35.4	15.68	13.48	71.96	61.84	14.1
2500	5.5	2.584	1680	8.18	2.293	12.9	7.7	33.39	29.63	19.95	17.70	11.3
2500	7	3.097	2050	8.54	2.862	10.4	3.7	32.27	29.82	11.49	10.62	7.6
						1372.0	765.0	1073.9	981.4	1017.1	898.8	

	BASE CITY	CVT CITY	BASE HWY	CVT HWY
LITERS CONSUMED @ SP. GR.=0.735	1.46	1.34	1.38	1.22
GALLONS = l/3.864	0.378	0.346	0.358	0.316
MILES	7.50	7.50	10.32	10.32
MPG	19.83	21.70	28.81	32.61
DEL FE, MPG		1.87		3.79
LITERS/100 KM	12.18	11.13	8.38	7.41
GRAMS DIFFERENCE	92.55		118.30	
% FE GAIN WITH CVT	**9.43**		**13.16**	

COMBINED CYCLE	23.07	25.55	MPG
COMBINED GAIN	2.48	MPG	
% GAIN	**10.75**		

TABLE V-11

NOx PREDICTIONS ON EPA CITY CYCLE - BASE AND CVT SYSTEMS COMPARED, EQUAL TRANSMISSION EFFICIENCIES - CAR

BASE ENGINE/TRANS PTS			HITORC ENGINE/CVT PTS			CYCLE TIMES		BASE CITY	CVT CITY	BASE HWY	CVT HWY	CVT INCREASE
SPEED	LOAD bar	NOx g/s	SPEED	LOAD bar	NOx g/s	CITY sec	HWY sec	TOTAL NOx, g	TOTAL NOx, g	TOTAL NOx, g	TOTAL NOx, g	%
IDLE	X	0.0000	IDLE	X	0.0000	551.9	41.5	0.00	0.00	0.00	0.00	0.0
1200	1.5	0.0073	1100	1.64	0.0129	124.6	3.9	0.91	1.61	0.03	0.05	76.2
1200	2.62	0.0187	1100	2.86	0.0273	61.1	1.2	1.15	1.67	0.02	0.03	45.7
1500	1.5	0.0085	1100	2.05	0.0174	107.2	50.4	0.91	1.86	0.43	0.88	104.2
1500	2.62	0.0221	1100	3.57	0.0362	186.2	83.8	4.11	6.74	1.85	3.03	64.2
1500	4	0.0425	1100	5.45	0.0593	79.3	56.9	3.37	4.70	2.42	3.37	39.5
1500	5.5	0.0660	1110	7.43	0.0836	3.5	12.2	0.23	0.29	0.81	1.02	26.7
1500	7	0.1002	1350	7.78	0.1082	3.2	0.2	0.32	0.35	0.02	0.02	8.0
2000	1.5	0.0179	1100	2.73	0.0258	37.3	161.4	0.67	0.96	2.89	4.16	44.2
2000	2.62	0.0269	1100	4.76	0.0511	54.2	166.5	1.46	2.77	4.48	8.51	90.0
2000	4	0.0651	1100	7.27	0.0811	107.0	117.0	6.96	8.67	7.61	9.49	24.6
2000	5.5	0.0833	1405	7.83	0.1134	29.4	23.9	2.45	3.33	1.99	2.70	36.1
2000	7	0.1286	1710	8.19	0.1448	2.6	0.4	0.33	0.37	0.05	0.06	12.6
2500	4	0.0772	1300	7.69	0.1028	10.0	40.7	0.77	1.02	3.14	4.18	33.2
2500	5.5	0.1138	1680	8.18	0.1442	8.6	4.5	0.98	1.24	0.51	0.64	26.7
2500	7	0.1547	2050	8.54	0.1841	6.1	0.7	0.94	1.12	0.11	0.13	19.0
						1372.0	765.0	25.6	36.7	26.3	38.3	

	BASE	CVT	
CYCLE MILES	7.50	7.50	
ENGINE OUT NOx	3.41	4.90	g/mi
DELTA NOx		1.49	g/mi
CATALYST EFFICIENCY TO REACH 0.4 g/mi (TLEV), %	88.3	91.8	
TOTAL GRAMS NOx INCREASE	11.16		
% TOTAL NOx INCREASE - URBAN CYCLE	43.69		

TABLE V-12

NOx PREDICTIONS ON EPA CITY CYCLE - BASE AND CVT SYSTEMS COMPARED, +6% CVT TRANSMISSION EFFICIENCY - CAR

BASE ENGINE/TRANS PTS			HITORC ENGINE/CVT PTS			CYCLE TIMES		BASE CITY	CVT CITY	BASE HWY	CVT HWY	CVT INCREASE
SPEED	LOAD bar	NOx g/s	SPEED	LOAD bar	NOx g/s	CITY sec	HWY sec	TOTAL NOx, g	TOTAL NOx, g	TOTAL NOx, g	TOTAL NOx, g	%
IDLE	X	0.0000	IDLE	X	0.0000	551.9	41.5	0.00	0.00	0.00	0.00	0.0
1200	1.5	0.0073	1100	1.64	0.0120	124.6	3.9	0.91	1.50	0.03	0.05	63.9
1200	2.62	0.0187	1100	2.86	0.0253	61.1	1.2	1.15	1.55	0.02	0.03	35.0
1500	1.5	0.0085	1100	2.05	0.0160	107.2	50.4	0.91	1.71	0.43	0.81	87.8
1500	2.62	0.0221	1100	3.57	0.0337	186.2	83.8	4.11	6.27	1.85	2.82	52.8
1500	4	0.0425	1100	5.45	0.0554	79.3	56.9	3.37	4.39	2.42	3.15	30.4
1500	5.5	0.0660	1110	7.43	0.0784	3.5	12.2	0.23	0.27	0.81	0.96	18.8
1500	7	0.1002	1350	7.78	0.1012	3.2	0.2	0.32	0.32	0.02	0.02	1.0
2000	1.5	0.0179	1100	2.73	0.0239	37.3	161.4	0.67	0.89	2.89	3.86	33.6
2000	2.62	0.0269	1100	4.76	0.0479	54.2	166.5	1.46	2.59	4.48	7.97	78.1
2000	4	0.0651	1100	7.27	0.0760	107.0	117.0	6.96	8.13	7.61	8.89	16.8
2000	5.5	0.0833	1405	7.83	0.1063	29.4	23.9	2.45	3.12	1.99	2.54	27.6
2000	7	0.1286	1710	8.19	0.1362	2.6	0.4	0.33	0.35	0.05	0.05	5.9
2500	4	0.0772	1300	7.69	0.0963	10.0	40.7	0.77	0.96	3.14	3.91	24.8
2500	5.5	0.1138	1680	8.18	0.1337	8.6	4.5	0.98	1.15	0.51	0.60	17.5
2500	7	0.1547	2050	8.54	0.1714	6.1	0.7	0.94	1.04	0.11	0.12	10.8
						1372.0	765.0	25.6	34.3	26.3	35.8	

CYCLE MILES	7.50	7.50	
ENGINE OUT NOx	3.41	4.57	g/mi
DELTA NOx		1.16	g/mi
CATALYST EFFICIENCY TO REACH 0.4 g/mi (TLEV), %	88.3	91.2	
TOTAL GRAMS NOx INCREASE	8.71		
% TOTAL NOx INCREASE - URBAN CYCLE	**34.10**		

TABLE V-13

NOx PREDICTIONS ON EPA CITY CYCLE - BASE AND CVT SYSTEMS COMPARED, EQUAL TRANSMISSION EFFICIENCIES - TRUCK

BASE ENGINE/TRANS PTS			BASE ENGINE/CVT PTS			CYCLE TIMES		BASE CITY	CVT CITY	BASE HWY	CVT HWY	CVT INCREASE
SPEED	LOAD bar	NOx g/s	SPEED	LOAD bar	NOx g/s	CITY sec	HWY sec	TOTAL NOx, g	TOTAL NOx, g	TOTAL NOx, g	TOTAL NOx, g	%
IDLE	X	0.0000	IDLE	X	0.0000	551.9	41.5	0.00	0.00	0.00	0.00	0.0
1200	1.5	0.0100	1100	1.64	0.0105	124.6	3.9	1.24	1.31	0.04	0.04	5.3
1200	2.62	0.0229	1100	2.86	0.0243	61.1	1.2	1.40	1.49	0.03	0.03	6.0
1500	1.5	0.0123	1100	2.05	0.0147	107.2	50.4	1.32	1.58	0.62	0.74	19.4
1500	2.62	0.0276	1100	3.57	0.0331	186.2	83.8	5.13	6.16	2.31	2.77	20.1
1500	4	0.0497	1100	5.45	0.0562	79.3	56.9	3.94	4.46	2.82	3.19	13.2
1500	5.5	0.0741	1110	7.43	0.0778	3.5	12.2	0.26	0.27	0.91	0.95	5.0
1500	7	0.0980	1350	7.78	0.0990	3.2	0.2	0.31	0.32	0.02	0.02	1.1
2000	1.5	0.0162	1100	2.73	0.0215	37.3	161.4	0.60	0.80	2.61	3.47	32.7
2000	2.62	0.0349	1100	4.76	0.0480	54.2	166.5	1.89	2.60	5.81	7.99	37.5
2000	4	0.0623	1100	7.27	0.0755	107.0	117.0	6.66	8.08	7.29	8.83	21.2
2000	5.5	0.0941	1405	7.83	0.1038	29.4	23.9	2.77	3.05	2.25	2.48	10.3
2000	7	0.1257	1710	8.19	0.1321	2.6	0.4	0.32	0.34	0.05	0.05	5.1
2500	4	0.0744	1300	7.69	0.0943	10.0	40.7	0.74	0.94	3.02	3.83	26.8
2500	5.5	0.1128	1680	8.18	0.1297	8.6	4.5	0.97	1.12	0.50	0.58	14.9
2500	7	0.1522	2050	8.54	0.1651	6.1	0.7	0.92	1.00	0.11	0.12	8.5
						1372.0	765.0	28.5	33.5	28.4	35.1	

CYCLE MILES	7.50	7.50	
ENGINE OUT NOx	3.80	4.47	g/mi
DELTA NOx		0.67	g/mi
CATALYST EFFICIENCY TO REACH 0.4 g/mi (TLEV), %	89.5	91	
TOTAL GRAMS NOx INCREASE	5.02		
% TOTAL NOx INCREASE - URBAN CYCLE	17.61		

TABLE V-14

NOx PREDICTIONS ON EPA CITY CYCLE - BASE AND CVT SYSTEMS COMPARED, +6% CVT TRANSMISSION EFFICIENCY - TRUCK

BASE ENGINE/TRANS PTS			BASE ENGINE/CVT PTS			CYCLE TIMES		BASE CITY	CVT CITY	BASE HWY	CVT HWY	CVT INCREASE
SPEED	LOAD bar	NOx g/s	SPEED	LOAD bar	NOx g/s	CITY sec	HWY sec	TOTAL NOx, g	TOTAL NOx, g	TOTAL NOx, g	TOTAL NOx, g	%
IDLE	X	0.0000	IDLE	X	0.0000	551.9	41.5	0.00	0.00	0.00	0.00	0.0
1200	1.5	0.0100	1100	1.64	0.0097	124.6	3.9	1.24	1.21	0.04	0.04	-2.7
1200	2.62	0.0229	1100	2.86	0.0224	61.1	1.2	1.40	1.37	0.03	0.03	-2.3
1500	1.5	0.0123	1100	2.05	0.0131	107.2	50.4	1.32	1.40	0.62	0.66	6.4
1500	2.62	0.0276	1100	3.57	0.0305	186.2	83.8	5.13	5.68	2.31	2.56	10.7
1500	4	0.0497	1100	5.45	0.0526	79.3	56.9	3.94	4.17	2.82	2.99	5.9
1500	5.5	0.0741	1110	7.43	0.0732	3.5	12.2	0.26	0.26	0.91	0.89	-1.2
1500	7	0.0980	1350	7.78	0.0931	3.2	0.2	0.31	0.30	0.02	0.02	-5.0
2000	1.5	0.0162	1100	2.73	0.0210	37.3	161.4	0.60	0.78	2.61	3.39	29.6
2000	2.62	0.0349	1100	4.76	0.0446	54.2	166.5	1.89	2.42	5.81	7.43	27.7
2000	4	0.0623	1100	7.27	0.0709	107.0	117.0	6.66	7.58	7.29	8.29	13.8
2000	5.5	0.0941	1405	7.83	0.0975	29.4	23.9	2.77	2.87	2.25	2.33	3.6
2000	7	0.1257	1710	8.19	0.1242	2.6	0.4	0.32	0.32	0.05	0.05	-1.2
2500	4	0.0744	1300	7.69	0.0887	10.0	40.7	0.74	0.88	3.02	3.61	19.3
2500	5.5	0.1128	1680	8.18	0.1219	8.6	4.5	0.97	1.05	0.50	0.54	8.0
2500	7	0.1522	2050	8.54	0.1552	6.1	0.7	0.92	0.94	0.11	0.11	2.0
						1372.0	765.0	28.5	31.2	28.4	32.9	

CYCLE MILES	7.50	7.50	
ENGINE OUT NOx	3.80	4.16	g/mi
DELTA NOx		0.37	g/mi
CATALYST EFFICIENCY TO REACH 0.4 g/mi (TLEV), %	89.5	90.4	
TOTAL GRAMS NOx INCREASE	2.74		
% TOTAL NOx INCREASE - URBAN CYCLE	**9.62**		

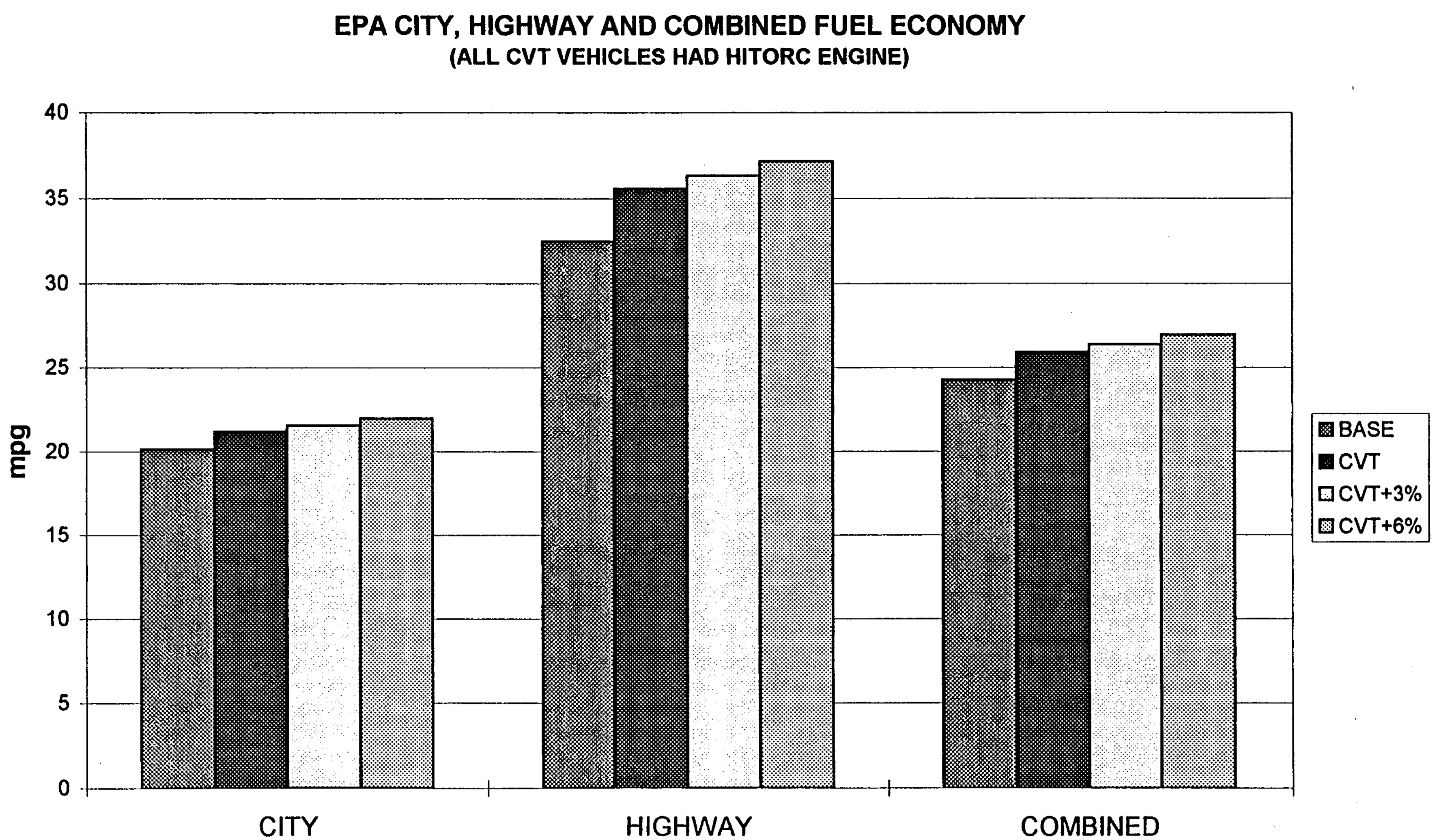


Figure V-1. Fuel economy of 3625 lb. car with Base and CVT Transmissions. Three CVT efficiencies of equal, +3% and +6%.

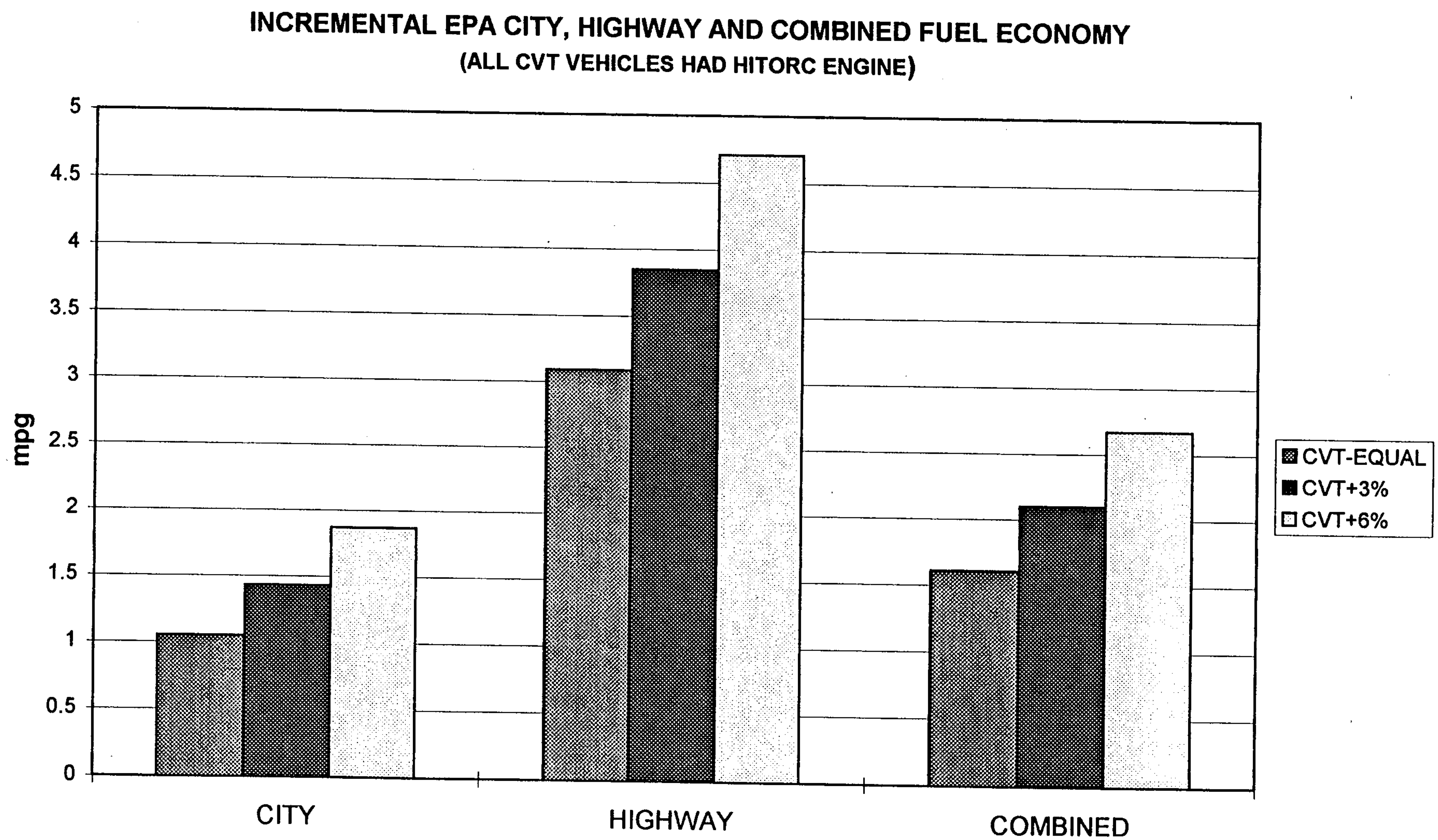


Figure V-2. Incremental fuel economy with CVT's of equal, +3% and +6% efficiency - Car.

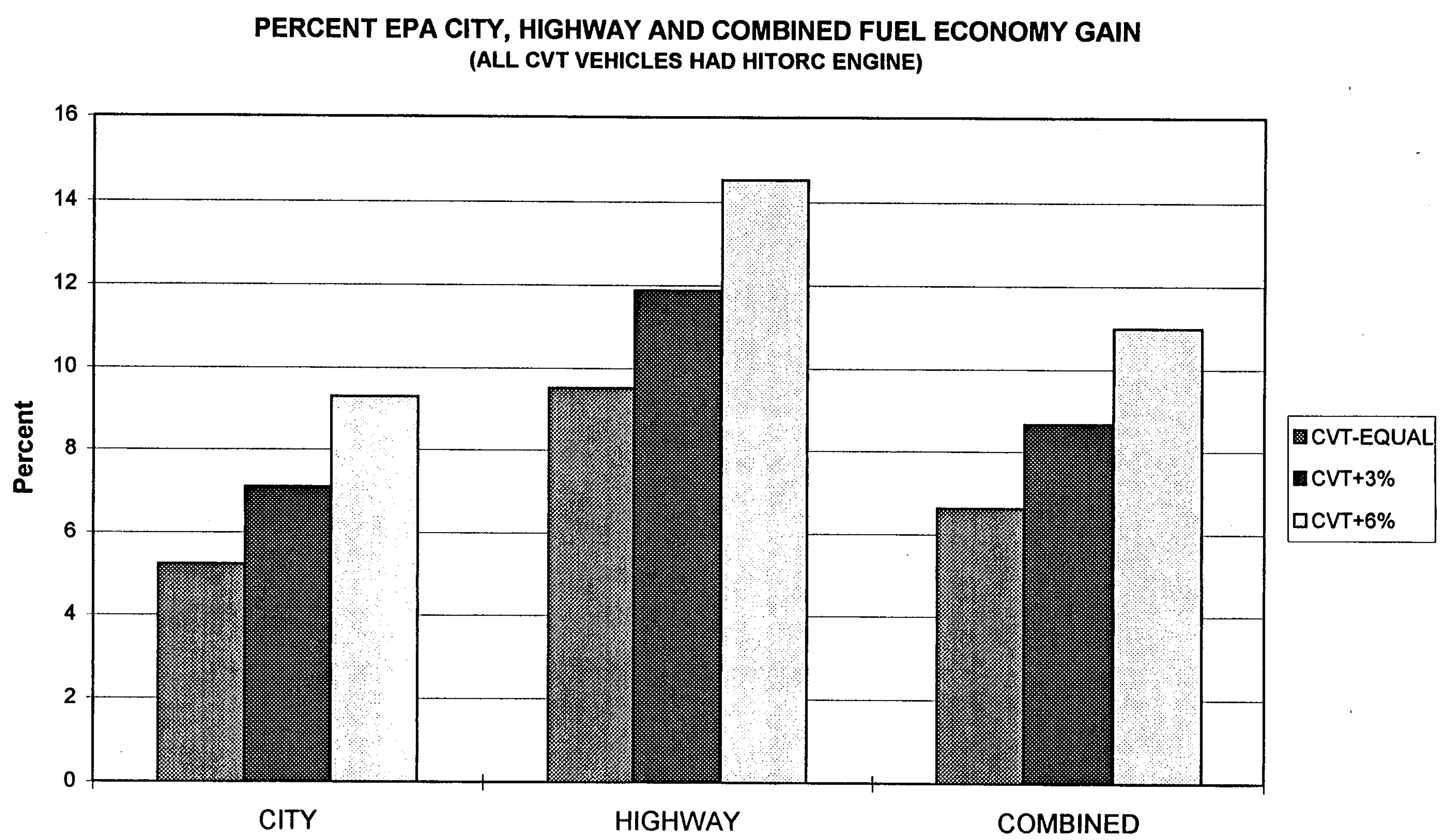


Figure V-3. Percent fuel economy increase with CVT's of equal, +3% and +6% efficiency - Car.

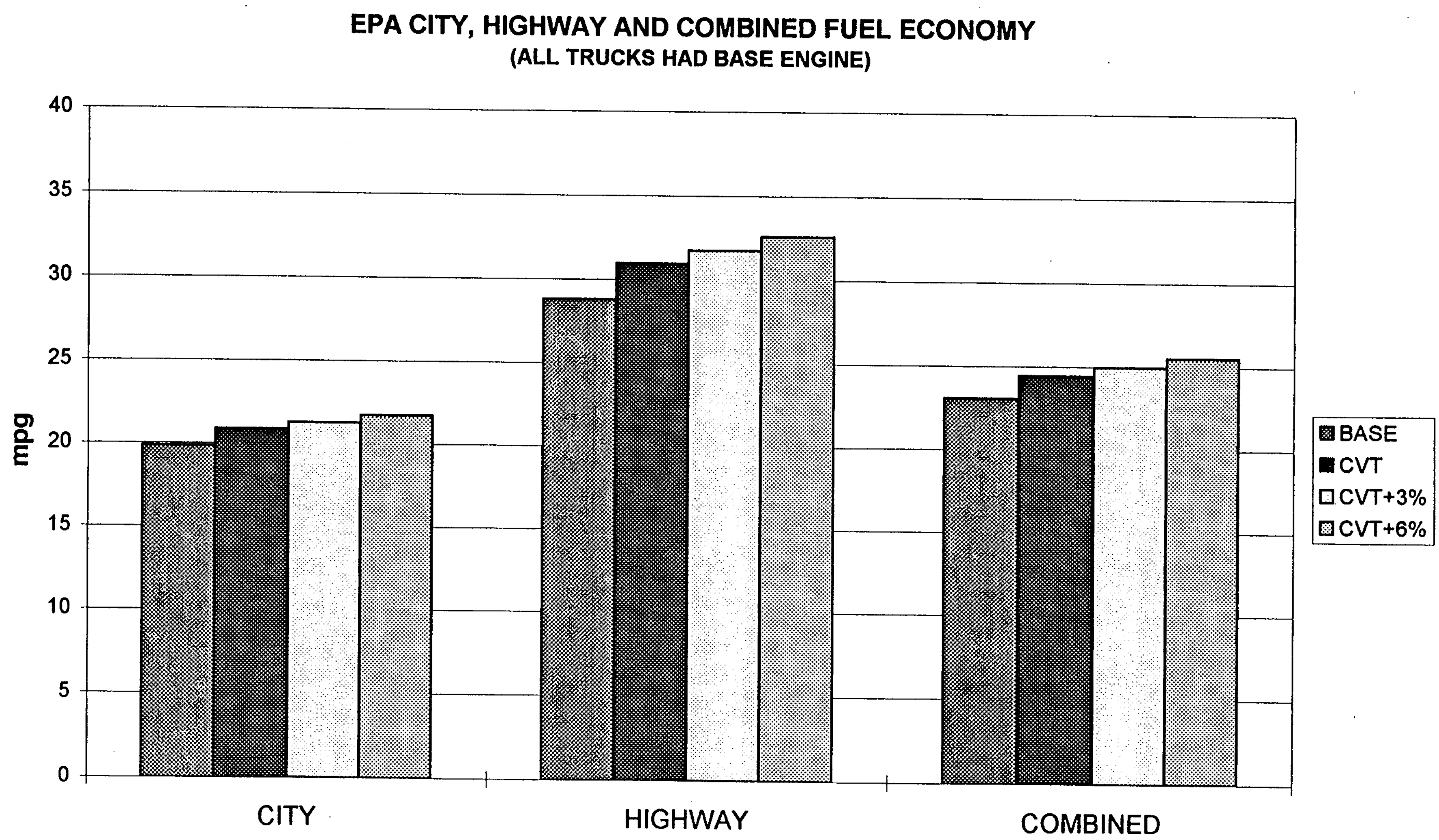


Figure V-4. Fuel economy of 3625 lb. light truck with Base and CVT transmissions. Three CVT efficiencies of equal, +3% and +6%.

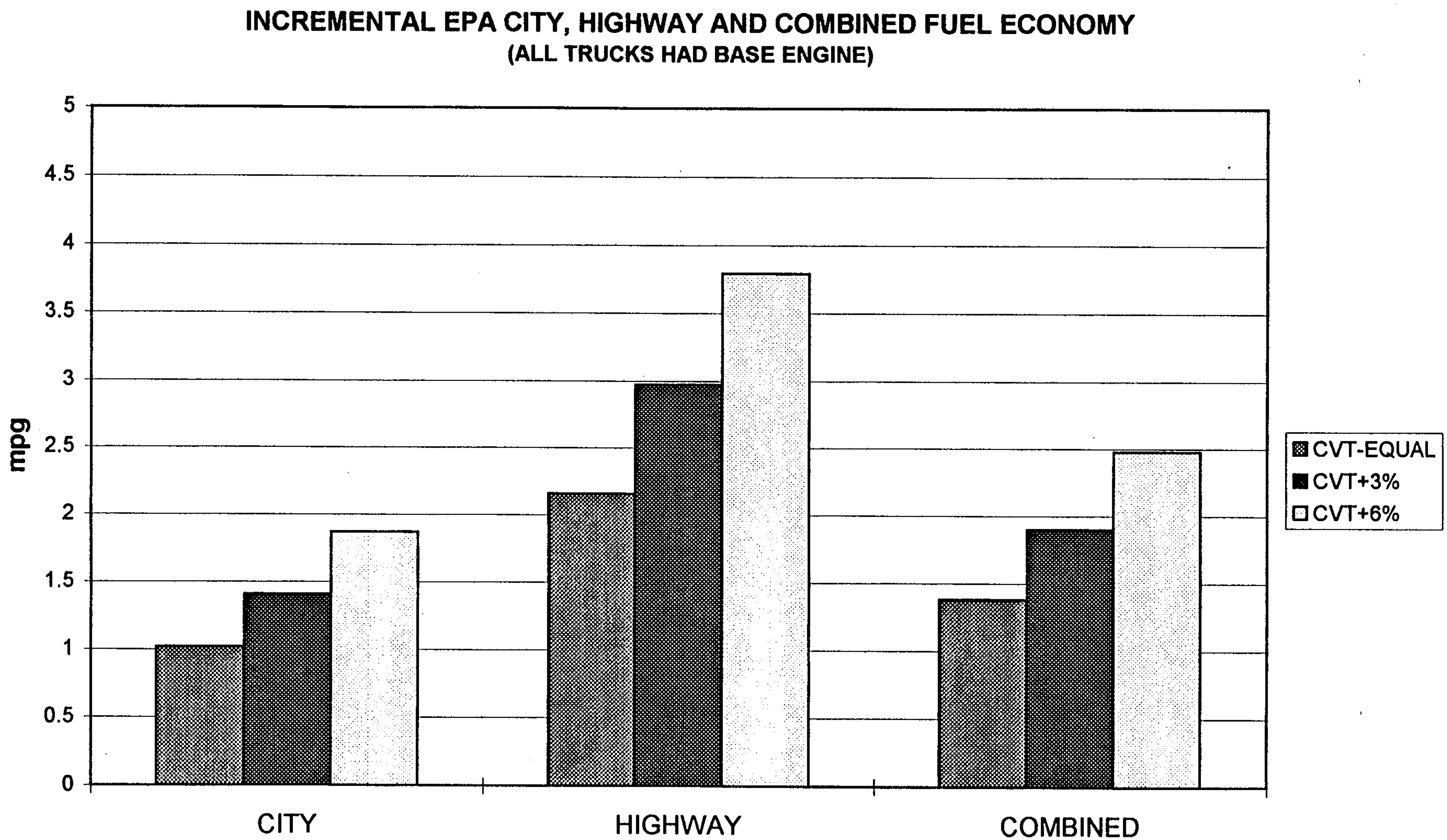


Figure V-5. Incremental fuel economy with CVT's of equal, +3% and +6% efficiency - Light Truck.

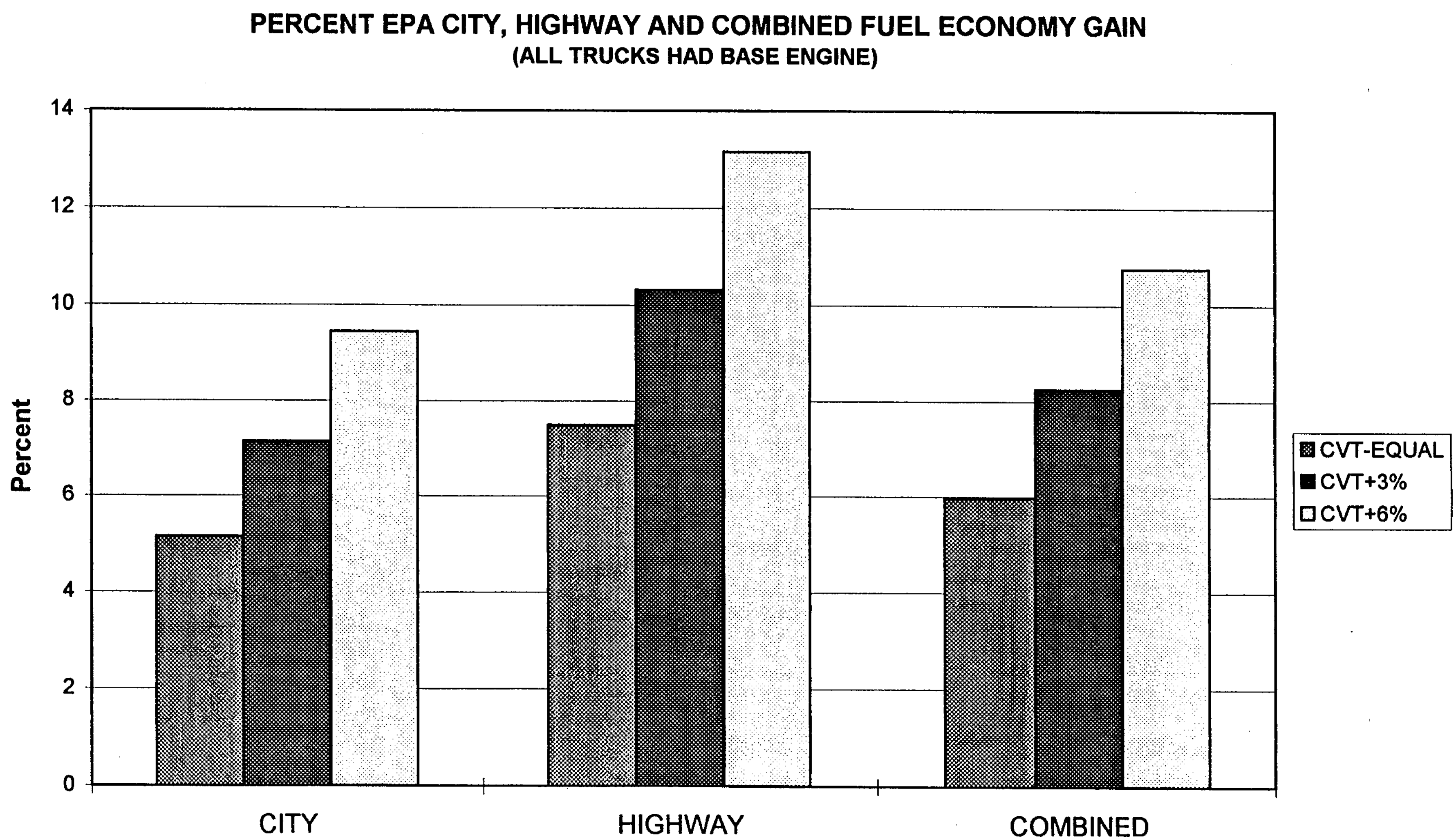


Figure V-6. Percent fuel economy increase with CVT's of equal, +3% and +6% efficiency - Light Truck.

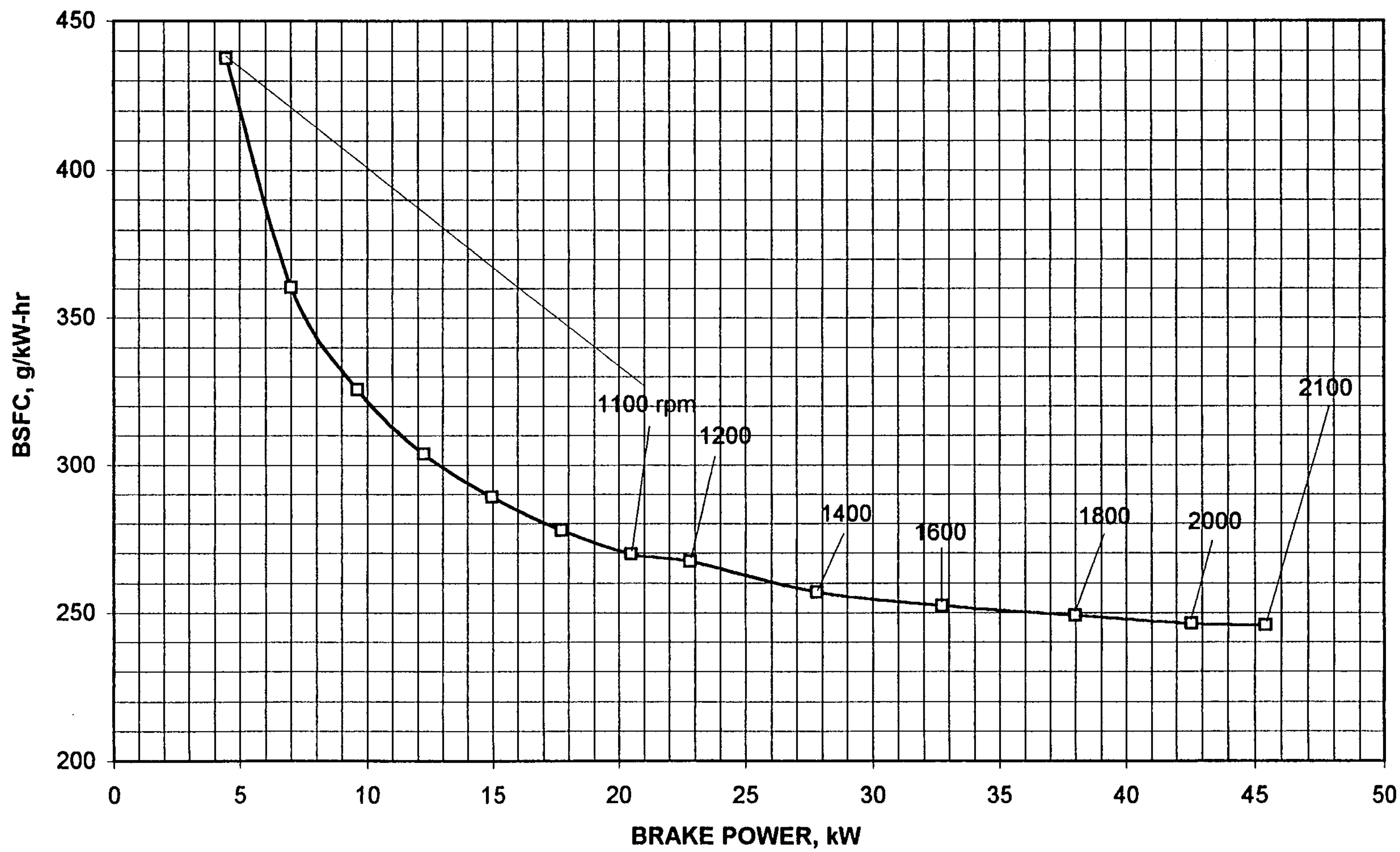


Figure V-7. Bsfc versus brake power for HITORC engine and CVT of equal efficiency - Car.

VI. COST, WEIGHT, CAPITAL INVESTMENT, AND LEADTIME

A. INCREMENTAL COST AND WEIGHT METHODOLOGY

Estimates of the incremental cost and weight of the CVT system described in Chapter IV are presented here. These are relative to a conventional 4SAT with lock-up torque converter. The production Ford AX4S was taken as the specific base transmission for this comparison. The CVT design was that of the Dual Mode. Compared to other CVT's, this transmission has an additional overrunning clutch and chain transfer drive, features that permit the transmission to be used with the larger engines and vehicles envisioned in this study, especially under conditions of sustained high load and low speed operation such as hill climbing or trailer towing. These features make the Dual Mode a somewhat more expensive and heavier transmission relative to those CVT's of simpler design, particularly those not employing torque converters. The Dual Mode was described by Stockton in Reference 32. What was available from that publication were diagrams which did not have dimensions or complete details. 4SAT information was limited to shop manuals, some published longitudinal cross sections, discussions with experienced 4SAT engineers, and one disassembled 4SAT for inspection. The disassembled transmission provided actual deletion weights and served as basis for added and changed weights and costs.

Total manufacturing costs are reflected in this evaluation (material, labor, variable and fixed costs). SG&A (Sales, General & Administrative) and Profit are excluded. For estimating purposes, all estimates are based on OEM rates that are higher than those of the suppliers, which cover supplier SG&A and Profit in the total manufacturing cost calculations. The methodology used reflects current typical practices used in the automotive (and most other) industries to project the costs, timing, weights, and other benefits and liabilities of advanced concepts.

B. INCREMENTAL COST AND WEIGHT RESULTS

Figure VI-1 shows a comparison of both the conventional and Dual Mode transmissions. The major parts added for the CVT are colored in red and the major parts deleted from the 4SAT are in blue. For the purposes of illustration in this report, the base transmission shown in Figure VI-1 is a Ford AX4N. The drawing of the AX4N has been modified to represent the AX4S, for which a suitable drawing was not available. Figure VI-2 highlights the CVT pulley system and belt. Listed are the principal deletions, additions and changes to the base 4SAT needed to "convert" it to the Dual Mode CVT. Table VI-1 adds numbers to these additions, deletions, and changes, numbers which are further detailed in Table VI-2. The net cost and weight difference between the two transmissions is given, at the top of Table VI-1, indicating that the Dual Mode is approximately comparable in cost and weight to the 4SAT. Details of the cost and weight analysis are presented below.

The manufacturing cost and weight details of the CVT relative to the 4SAT are given in Table VI-2. Listed are 40 parts deleted from the 4SAT which are sorted into 8 major categories. A planetary gear set, associated clutch pack and band and drum system are the major deletions in terms of both cost and weight. There are 45 parts added for the CVT which are sorted into 3 major categories. These are the CVT chain, driver pulley system and driven pulley system. Finally, there are 9 items that are neither additions or deletions but are changes to 4SAT components needed to convert to the CVT. These are items which either increase or decrease or become larger or smaller. There are no major cost or weight items in this category.

Table VI-1 gives a summary of the individual incremental costs and weights. The net incremental cost of the CVT was $1.62 more and weight was 0.2 pounds less than the 4SAT. Clearly the weight increment is negligible as is the cost relative to a production 4SAT which is estimated between $600 and $1000.

The authors believe that in the production implementation of the Dual Mode transmission there might actually be some cost and weight saving because the whole transmission would be redesigned to take advantage of new concepts, materials, and manufacturing technologies. Prospects for ongoing productivity improvements, and cost and weight reductions will be greater for a new CVT than for a new 4SAT because of its newer technology and increasing sales volume.

C. CAPITAL, TOOLS, AND LEADTIME CONSIDERATIONS

The Dual Mode CVT described in this report combines the basic Van Doorne CVT which is in production by several manufacturers with a few additional components, each of which are currently in production for other applications. The present system is unique only in that no transmission manufacturer produces a system with all the components proposed. Therefore it is believed that there are no technical uncertainties with respect to leadtime. There is no "fundamental" research required or invention or breakthrough needed. What is needed is engineering development which includes design, building prototypes, optimization, final designs and durability demonstration. Once the designs are finalized, then tooling can be ordered.

It is the judgment of the authors that capital expenditures, tooling costs and leadtime are no different for an all-new Dual Mode CVT than for and all-new 4SAT.

TABLE VI-1

COST AND WEIGHT COMPARISON SUMMARY

Continuously Variable Transmission (CVT)
(over)/under
Conventional Transmission (4SAT)

	change	qty/ unit	Description	$ per unit	$ total /trans	lbs	variable cost ($) mat	variable cost ($) labor	variable cost ($) other variable
			TOTAL Transmission Difference		($1.62)	0.2	3.83	(1.92)	(2.59)
DELETIONS									
1	delete	1 set	one way clutch		$5.72	1.8	5.40	0.11	0.09
2	delete	1 set	planetary gear		$29.40	9.0	7.02	4.25	7.03
3	delete	1 set	clutch pack		$23.40	7.0	17.62	1.53	2.01
4	delete	2 set	band/drum sys tot		$22.14	10.0	13.79	1.80	2.47
5	delete	6 part	needle thrust bearings	$0.60	$3.60	0.6	3.60	0.00	0.00
6	delete	3 part	solenoid systems	$3.40	$10.20	2.2	10.20	0.00	0.00
7	delete	1 sys	converter lockup clutch		$4.50	1.7	4.50	0.00	0.00
8	delete	1 part	oil transfer sleeve		$3.10	2.2	1.24	0.35	0.57
ADDITIONS									
9	add	1 part	CV chain		($28.19)	(5.5)	(28.19)	0.00	0.00
10	add	1 sys	CV driver pulley sys		($36.23)	(15.9)	(13.14)	(5.08)	(7.03)
11	add	1 sys	CV driven pulley sys		($34.20)	(13.8)	(11.71)	(5.61)	(8.20)
CHANGES									
12	decrease	3 lbs	main shaft length 156mm		$2.40	2.3	1.60	0.18	0.28
13	less	1 lbs	housing mat'l		$1.44	1.0	1.20	0.05	0.09
14	larger	1 size	left shaft seal		($0.40)	(0.1)	(0.40)	0.00	0.00
15	larger	2 lbs	left case extention		($3.78)	(2.0)	(3.78)	0.00	0.00
16	replace	1 part	stamped cover w/casting		($2.00)	(0.8)	(2.40)	0.50	0.10
17	increase	1 sys	chain length and sprocket		($2.72)	0.5	(2.72)	0.00	0.00

TABLE VI-2

COST AND WEIGHT COMPARISON - DETAILS

Continuously Variable Transmission (CVT)
(over)/under
Conventional Transmission (4SAT)

	change	qty / unit	Description	$ per unit	total /trans	lbs	variable cost ($) mat	labor	other variable
DELETIONS									
1.00	**delete**	**1 set**	**one way clutch**		**5.72**	**1.8**	**5.40**	**0.11**	**0.09**
1.01		1 set	one way clutch		5.40		5.40	0.00	0.00
1.02			asm'y		0.32		0.00	0.11	0.09
2.00	**delete**	**1 set**	**planitary gear**		**29.40**	**9.0**	**7.02**	**4.25**	**7.03**
2.01		1 part	ring gear		7.00		2.45	0.90	1.54
2.02		3 part	pinion gears	2.80	8.40		0.56	1.30	2.45
2.03		3 part	pinion bushings	0.80	2.40		2.40	0.00	0.00
2.04		3 part	pinion pins	0.70	2.10		0.15	0.52	0.60
2.05		1 part	pinion carrier		5.00		0.82	0.90	1.32
2.06		1 part	sun gear		4.50		0.64	0.63	1.12
3.00	**delete**	**1 set**	**clutch pack**		**23.40**	**7.0**	**17.62**	**1.53**	**2.01**
3.01		1 part	cyclinder		4.00		0.64	0.90	1.10
3.02		1 part	hub		3.00		0.48	0.63	0.91
3.03		4 part	plates	1.20	4.80		4.80	0.00	0.00
3.04		1 part	backing-plate		0.80		0.80	0.00	0.00
3.05		4 part	separators	0.70	2.80		2.80	0.00	0.00
3.06		1 part	backing-separator		0.90		0.90	0.00	0.00
3.07		1 part	backing retainer		0.80		0.90	0.00	0.00
3.08		1 part	piston		2.60		2.60	0.00	0.00
3.09		1 part	inner seal		0.40		0.40	0.00	0.00
3.10		1 part	outer seal		0.70		0.70	0.00	0.00
3.11		6 part	springs	0.25	1.50		1.50	0.00	0.00
3.12		1 part	sping plate		0.70		0.70	0.00	0.00
3.13		1 part	spring plate retainer		0.40		0.40	0.00	0.00
4.00	**delete**	**2 set**	**band/drum sys tot**		**22.14**	**10.0**	**13.79**	**1.80**	**2.47**
4.01		1 oper	asm band/drum sys	1.23	2.46		0.00	0.52	0.80
4.02		1 part	band asmy	3.40	6.80		6.80	0.00	0.00
4.03		1 part	drum matl	0.64	1.28		1.28	0.00	0.00
4.04		1 oper	stamp	0.56	1.12		0.00	0.23	0.18
4.05		1 part	hub matl	0.40	0.80		0.80	0.00	0.00
4.06		1 oper	turn hub blanc	0.74	1.48		0.00	0.32	0.50
4.07		1 oper	join hub & drum	0.40	0.80		0.00	0.21	0.20
4.08		1 oper	mach OD-ID-faces	0.77	1.54		0.00	0.32	0.54
4.09		1 part	driver pin	0.42	0.84		0.84	0.00	0.00

TABLE VI-2: CONTINUED

Continuously Variable Transmission (CVT)
(over)/under
Conventional Transmission (4SAT)

	change	qty / unit	Description	$ per unit	total /trans	lbs	variable cost ($) mat	labor	other variable
DELETIONS CONTINUED									
4.10		1 part	piston	0.48	0.96		0.96	0.00	0.00
4.11		1 part	piston seal	0.29	0.58		0.58	0.00	0.00
4.12		1 part	cover	0.31	0.62		0.62	0.00	0.00
4.13		1 part	cover seal	0.23	0.46		0.46	0.00	0.00
4.14		1 lbs	cylinder wall	1.20	2.40		1.45	0.20	0.25
4.15		0 oper	machine in-line		0.00		0.00	0.00	0.00
5.00	**delete**	**6 part**	**needle thrust bearings**	**0.60**	**3.60**	**0.6**	**3.60**	**0.00**	**0.00**
6.00	**delete**	**3 parts**	**solenoid systems**	**3.40**	**10.20**	**2.2**	**10.20**	**0.00**	**0.00**
7.00	**delete**	**1 sys**	**converter lockup clutch**		**4.50**	**1.7**	**4.50**	**0.00**	**0.00**
8.00	**delete**	**1 part**	**oil transfer sleeve**		**3.10**	**2.2**	**1.24**	**0.35**	**0.57**
ADDITIONS									
9.00	**add**	**1 part**	**CV chain**		**(28.19)**	**(5.5)**	**(28.19)**	**0.00**	**0.00**
		270 parts	friction plates	0.037	(9.99)	(3.5)	(9.99)	0.00	0.00
		20 parts	steel bands	0.65	(13.00)	(2.0)	(13.00)	0.00	0.00
		1 asmy	asmy & asmy aid		(5.20)		(5.20)	0.00	0.00
10.00	**add**	**1 sys**	**CV driver pulley sys**		**(36.23)**	**(15.9)**	**(13.14)**	**(5.08)**	**(7.03)**
10.01		1 part	fixed cone face		(2.60)	(3.0)	(1.20)	(0.30)	(0.45)
10.02		1 part	fix cone shaft		(2.40)	(2.9)	(1.10)	(0.40)	(0.32)
10.03		1 oper	weld cone face & shaft		(3.20)		(0.07)	(0.90)	(1.34)
10.04		1 oper	machine		(0.98)		0.00	(0.23)	(0.33)
10.05		1 oper	finish cone-shaft asmy		(1.52)		0.00	(0.32)	(0.37)
10.06		1 oper	harden		(1.40)		0.00	(0.23)	(0.70)
10.07		1 part	clutch piston -cast al.		(1.80)	(0.4)	(1.80)	0.00	0.00
10.08		1 oper	machine		(0.40)		0.00	(0.13)	(0.14)
10.09		2 parts	seals-inner & outer		(1.80)	(0.2)	(1.80)	0.00	0.00
10.10		1 part	plate asmy		(1.10)	(0.3)	(1.10)	0.00	0.00
10.11		1 part	backing plate		(0.90)	(0.2)	(0.90)	0.00	0.00
10.12		1 part	retainer ring		(0.80)	(0.1)	2.80	0.00	0.00
10.13		1 oper	asmy		(1.30)		0.00	(0.28)	(0.40)
10.14		2 sets	roller bearings	1.10	(2.20)		(2.20)	0.00	0.00
10.15		1 part	moveable cone face		(2.80)	(3.4)	(1.60)	(0.30)	(0.35)
10.16		1 part	moveable cone hub		(0.88)	(0.8)	(0.42)	(0.20)	(0.11)
10.17		1 oper	weld cone & face		(3.20)	(3.7)	(0.07)	(0.90)	(1.34)
10.18		1 oper	machine		(0.37)		0.00	(0.13)	(0.12)

TABLE VI-2: CONTINUED

Continuously Variable Transmission (CVT)
(over)/under
Conventional Transmission (4SAT)

	change	qty / unit	Description	$ per unit	total /trans	lbs	variable cost ($) mat	labor	other variable
ADDITIONS CONTINUED									
10.19		1 oper	finish cone-hub asmy		(0.70)		0.00	(0.26)	(0.20)
10.20		1 oper	harden		(0.80)		0.00	(0.13)	(0.39)
10.21		1 part	piston -cast al.		(2.70)	(0.7)	(2.70)	0.00	0.00
10.22		1 oper	machine		(0.40)		0.00	(0.12)	(0.12)
10.23		1 part	seal		(0.70)	(0.1)	(0.70)	0.00	0.00
10.24		1 part	retainer		(0.28)	(0.1)	(0.28)	0.00	0.00
10.25		1 oper	asmy		(1.00)		0.00	(0.25)	(0.35)
11.00	**add**	**1 sys**	**CV driven pulley sys**		**(34.20)**	**(13.8)**	**(11.71)**	**(5.61)**	**8.20**
11.01		1 part	fixed cone		(2.00)	(2.4)	(0.75)	(0.25)	(0.37)
11.02		1 part	fix cone shaft		(3.90)	(5.3)	(0.13)	(0.85)	(1.37)
11.03		1 oper	weld cone face & shaft		(3.20)		(0.07)	(0.90)	(1.34)
11.04		1 oper	machine		(1.70)		0.00	(0.38)	(0.50)
11.05		1 oper	finish cone-shaft asmy		(2.25)		0.00	(0.51)	(0.60)
11.06		1 oper	harden		(2.20)		0.00	(0.33)	(1.05)
11.07		2 part	roller bearings	1.10	(2.20)	(0.1)	(2.20)	0.00	0.00
11.08		1 parts	moveable cone face		(2.80)	(2.9)	(1.60)	(0.30)	(0.35)
11.09		1 parts	moveable cone hub		(0.95)	(0.8)	(0.49)	(0.20)	(0.11)
11.10		1 oper	weld cone & face		(3.20)		(0.07)	(0.90)	(1.34)
11.11		1 oper	machine		(0.90)		0.00	(0.31)	(0.28)
11.12		1 oper	finish cone-hub asmy		(1.10)		0.00	(0.37)	(0.32)
11.13		1 oper	harden		(0.80)		0.00	(0.13)	(0.39)
11.14		1 parts	piston -cast al.		(2.60)	(0.7)	(2.60)	0.00	0.00
11.15		1 oper	machine		(0.60)		0.00	(0.18)	(0.18)
11.16		2 parts	seals		(1.80)	(1.5)	(1.80)	0.00	0.00
11.17		8 parts	springs	0.25	(2.00)	(0.1)	(2.00)	0.00	0.00
CHANGES									
12.00	**decrease**	**2 lbs**	**main shft length 156mm**	**0.80**	**2.40**	**2.3**	**1.60**	**0.18**	**0.28**
13.00	**less**	**1 lbs**	**housing mat'l**	**1.20**	**1.44**	**1.0**	**1.20**	**0.05**	**0.09**
14.00	**larger**	**1 size**	**left shaft seal**	**0.40**	**(0.40)**	**(0.1)**	**(0.40)**	**0.00**	**0.00**
15.00	**larger**	**2 lbs**	**left case extenstion**	**2.10**	**(3.78)**	**(2.0)**	**(3.78)**	**0.00**	**0.00**
16.00	**replace**	**1 part**	**stamped cover w/casting**	**2.00**	**(2.00)**	**(0.8)**	**(2.40)**	**0.50**	**0.10**
17.00	**increase**	**1 sys**	**chain length and sprocket**		**(2.72)**	**(0.5)**	**(2.72)**	**0.00**	**0.00**
17.01	increase	1 chg	chain length		(1.80)	(0.3)	(1.80)	0.00	0.00
17.02	increase	1 chg	driven sprocket dia		(1.30)	(0.4)	(1.30)	0.00	0.00
17.03	decrease	1 chg	driving sprocket dia		0.38	0.2	0.38	0.00	0.00

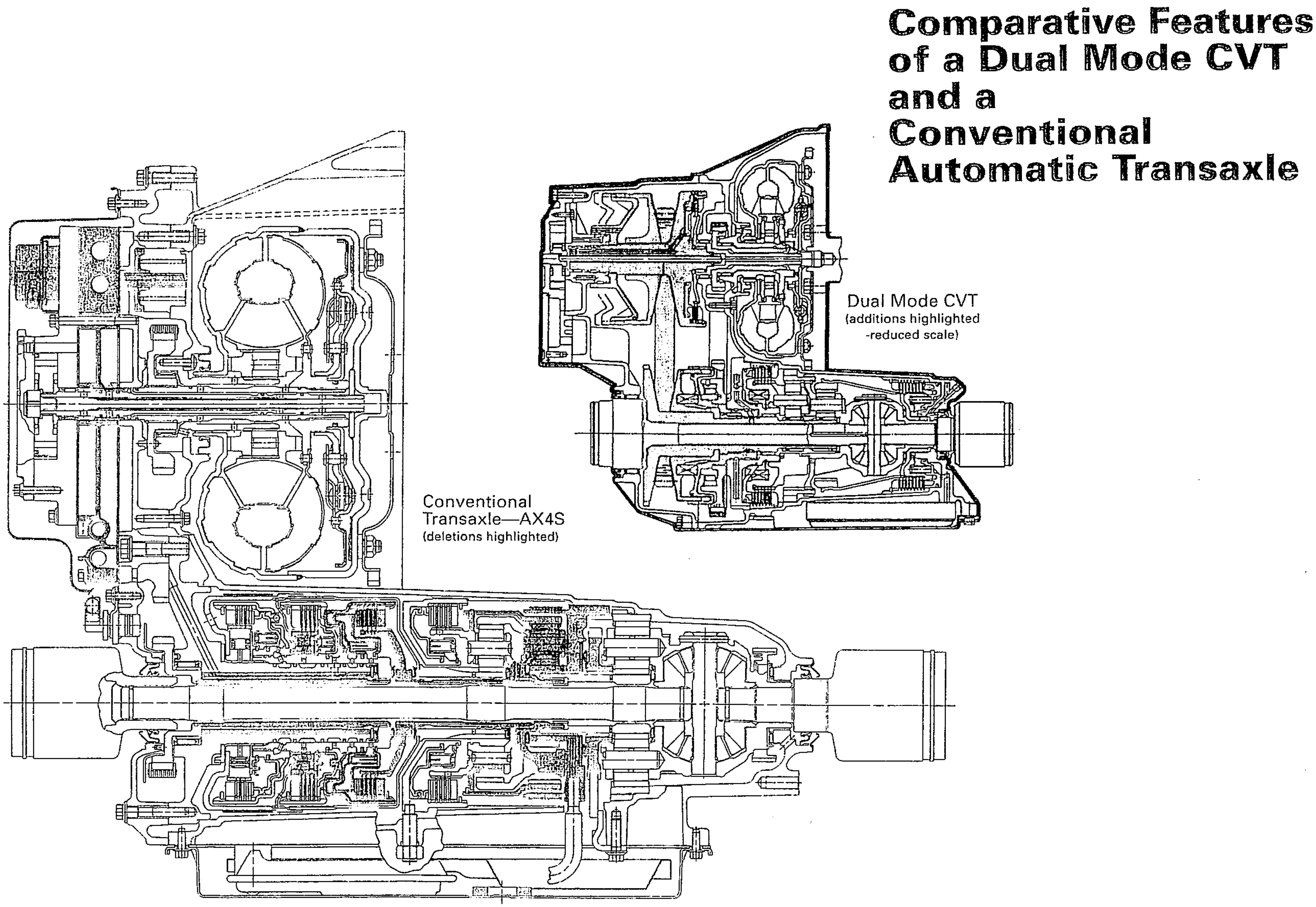
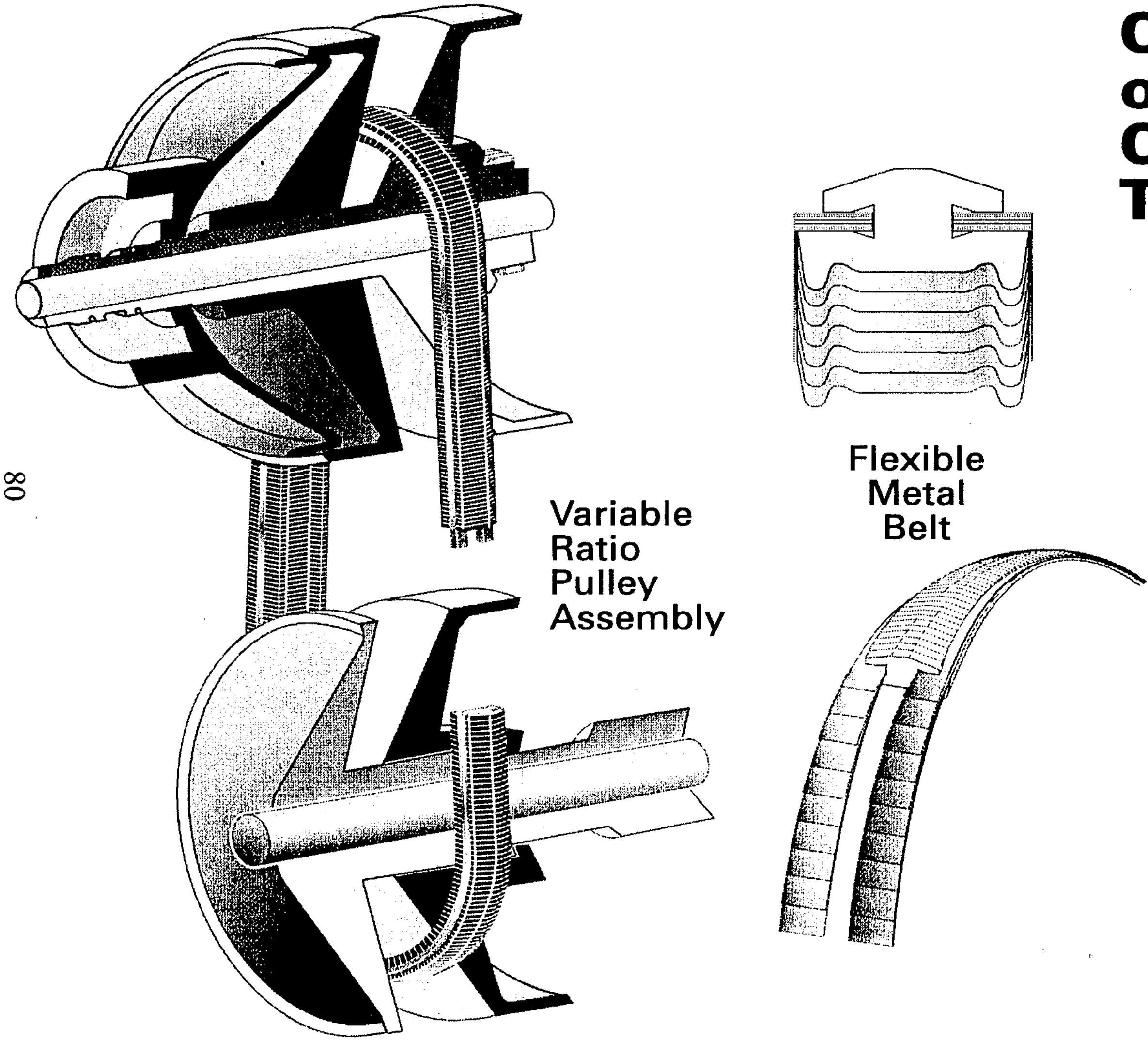


Figure VI-1. View of both conventional transmission, 4SAT, and Dual Mode CVT showing major items deleted from the 4SAT and those added for the CVT. The 4SAT drawing is constructed from the Ford AX4N transaxle and modified to represent the AX4S.



Comparative Features of a Dual Mode Continuously Variable Transmission (CVT)

----DELETIONS----
1-one way clutch
1-planetary gear set
1-clutch pack set
2-drum & band systems
6-needle thrust bearings
3-solenoid systems
1-converter lockup clutch
1-oil transfer sleeve

----ADDITIONS---
1-CV chain
1-CV driver pulley system
1-CV driven pulley system

----CHANGES----
-decrease main shaft length
-less housing material
-larger left shaft seal
-larger left case extension
-replace stamped cover with casting
-increase drive chain length & sprocket diameter

Figure VI-2. Belt and Pulley Assembly for the CVT. These are the principal CVT additions.

APPENDIX

TRANSMISSION AND COMPONENT LOSSES AND EFFICIENCY
Prepared by Thomas Stockton

Reference	% Steel Belt	% CVT	% 4SAT	% of Total Power Losses: Oil Pump	Gears	Clutch Drag	Windage
15	90-97						
8	70-95	50-92					
24			87-91	22-30	14-28	22-32	3-10
2	95						
4	85-93						
14				45	6	35	8
16	90-95						

Observations

- Five papers address efficiency of the steel belt and pulley system. The efficiency curves characteristically quickly rise from around 70% at light torque and flatten out around 95% at medium to heavy torque loading. The overall CVT efficiency follows this trend from 50-93%.

- Three papers address component losses for a 4SAT, which would be comparable to the CVT depending upon the number of active gear meshes and inactive dragging clutches. The Dual Mode CVT selected for this study has only one active gear mesh and one clutch dragging in the high mode, considerably less than a conventional 4SAT and some other CVT arrangements.

- Typical automatic transmission oil pumps have a torque efficiency and a volumetric efficiency of approximately 70%, resulting in an overall efficiency of 50%. The pump portion of total losses is the most significant at 30-45%. Pump displacement is first sized to satisfy transmission leakage and/or satisfactory N-D-R clutch engagement time at engine idle speeds as well as pressure requirements. The CVT pump must also be able to provide the necessary flow rate to either pulley for quick filling of the clamping cylinder during a rapid ratio change. There is little potential for significantly reducing pump losses, although the lower engine speeds with the CVT reduce the losses accordingly. The CVT selected has an advantage during vehicle start up, as the 2:1 converter torque multiplication not only provides a smooth vehicle launch, but also reduces the maximum torque imposed on the steel belt.

Conclusion

In reviewing the literature it is concluded that the overall CVT efficiency of 84% used for predicting fuel economy is considered conservative in relation to the above findings. The assumption of the 6% potential improvement to 90% is also considered reasonable over the EPA City and Highway Cycles.

GLOSSARY

bar	Measure of Pressure, 1 bar = 101 kPa (14.7 psi)
bmep	Brake Mean Effective Pressure
bsfc	Brake Specific Fuel Consumption
fmep	Friction Mean Effective Pressure
imep	Indicated Mean Effective Pressure
isfc	Indicated Specific Fuel Consumption
netimep	Indicated mep - Pumping mep
pmep	Pumping Mean Effective Pressure
rpm	Revolutions per Minute Engine Speed
AX4S	Ford Production Transaxle Used as Base Transmission
CO	Carbon Monoxide Emissions
CVT	Continuously Variable Transmission
EGR	Exhaust Gas Recirculation
DEL FE	Fuel Economy Incremental Change
ETW	Equivalent Test Weight as Defined in EPA Regulations
FM	Indicates Values Derived from Ford Provided Data
GM	Indicates Values Derived from General Motors Research Single Cylinder Engine Simulation Program
HC	Hydrocarbon Emissions
IND	Indicated Quantity
LBT	Leanest Mixture for Best Torque
MAP	Manifold Air Pressure
MBT	Minimum Spark Advance for Best Torque
MPG	Miles per Gallon
NOx	Oxides of Nitrogen
SG&A	Sales, General and Administrative
SP. GR.	Specific Gravity
TDC	Top Dead Center Piston Position
VVT	Variable Valve Timing
WOT	Wide Open Throttle
4SAT	Four Speed Automatic Transmission with Torque Converter Lock-up

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