REPORT NO. DOT-TSC-OST-77-34

AUTOMOBILE DRIVELINES

R.G. Colello

U.S. Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge MA 02142

MAY 1977

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
OFFICE OF THE SECRETARY
Office of the Assistant Secretary for
Systems Development and Technology
Office of Systems Engineering
Washington DC 20590

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. DOT-TSC-OST-77-34	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
AUTOMOBILE DRIVELINES

5. Report Date
May 1977

6. Performing Organization Code

7. Author(s)
R.G. Colello

8. Performing Organization Report No.
DOT-TSC-OST-75-35

9. Performing Organization Name and Address
U.S. Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge MA 02142

10. Work Unit No.
OS514/R7508

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Office of the Secretary
Office of the Asst. Sec. for Sys. Dev. and Tech.
Office of Systems Engineering
Washington DC 20590

13. Type of Report and Period Covered
Final Report
June 1974 - Dec. 1974

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This study assesses automobile driveline components and configurations, quantifying their performance as possible in the context of such current issues as fuel economy, exhaust emission reduction, safety, driveability, production costs and lead times, and engine life. The current and projected driveline technology is described. The results of simulation studies using the DOT/TSC Vehicle Simulation Program to analyze vehicles incorporating various driveline components and configurations in relation to fuel economy, acceleration, emissions and other factors of interest are also reported.

17. Key Words
AUTOMOBILES
DRIVELINES
DRIVETRAINS
TRANSMISSIONS
FUEL ECONOMY
FUEL CONSUMPTION

18. Distribution Statement
DOCUMENT IS AVAILABLE TO THE U.S. PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 56	22. Price

Form DOT F 1700.7 (8-69)

PREFACE

This report presents a study of the automobile driveline and its impact on fuel economy, exhaust emissions, driveability, gradeability, and acceleration performance. The study was conducted as part of the Component Evaluation Subproject of the Automotive Energy Efficiency Project at the Transportation Systems Center and sponsored by the Office of the Secretary of Transportation.

I wish to acknowledge Mr. Milton H. Scheiter and Mr. Herbert A. McAninch, consultants to Arthur D. Little, Inc., for their review of this report and for the suggestions and information that they provided.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

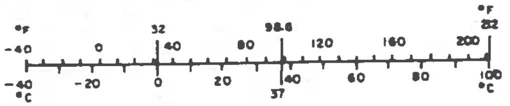


TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

This report assesses the current and projected performance of automobile driveline components and configurations, concentrating on fuel economy. It also discusses their impact on such important issues as exhaust emissions, acceleration, driveability, production costs and lead times, and engine life.

Drivelines as considered in this document consist of transmissions and drive axles through which the engine power flows to the driving wheels. Modern American production passenger cars employ either an automatic transmission consisting of a fluid torque converter and planetary gears or a manual transmission consisting of a dry, friction clutch and fully synchronized gears. The automatic transmission predominates in the American fleet of automobiles, accounting for 50% of all cars sold in 1953[1] and increasing to 91.3% of all cars sold in 1970.[2] Thus, it has been deemed logical to choose drivelines including an automatic transmission (three-speed with torque converter) as the reference for all performance comparisons.

2. SUMMARY

2.1 CONCLUSIONS

The information compiled in this study leads to the following conclusions:

1. Manual transmissions are more efficient than automatic transmissions. A three-speed manual transmission used in place of current production (1973) automatic transmissions can improve fuel economy by a computed average of 4% for urban driving and 3% for highway driving.

2. Selecting "tighter," i.e., low slip, torque converters can improve fuel economy for automobiles with automatic transmissions. The computed average improvement is of the order of 2% for urban and 1% for highway driving.

3. Wider range three-speed automatic transmissions can improve fuel economy at the expense of acceleration. The wide ratio three-speed configuration selected for this study gave a computed average improvement in fuel economy of 2% for urban and 8% for highway driving with a computed average increase of 4% in 0 to 60 mph acceleration time.

4. Wide range four-speed automatic transmissions can improve fuel economy with no sacrifice in 0 to 60 mph acceleration time. The four-speed configuration selected for this study gave a computed average improvement of 1% for urban and 11% for highway driving. A separate overdrive unit (0.7 to 1) can be added to a production three-speed automatic transmission to give similar results.

5. A torque converter lock-up can be added to automatic transmissions to improve fuel economy by eliminating torque converter slip whenever driving conditions are favorable. Adding a torque converter lock-up clutch to the wide ratio three-speed automatic transmission discussed above gives an overall improvement in computed

average fuel economy of 11% for urban driving and 16% for highway driving. Added to the four-speed automatic transmission discussed above, the torque converter lock-up clutch gives an overall computed average improvement of 7% for urban and 22% for highway driving.

Torque converter lock-up clutches for automobiles are not currently in production. Development of the component involves negligible technological risk.

6. The full potential of drivelines to improve fuel economy, exhaust emissions, driveability, and/or acceleration will be achieved only when a continuously variable ratio transmission (CVRT) is developed that is cost effective and exhibits high component efficiency, low weight, and adequate durability. The potential improvement in fuel economy with the CVRT is 20 to 40%. Development of the CVRT involves relatively high technological risk.

7. Transmission efficiency is reduced by power lost in driving the automatic transmission oil pump. Variable displacement pumps require about half the power of constant displacement pumps currently used. Cost effectiveness is the only issue in question.

8. Selecting lower drive axle ratios improves fuel economy at the sacrifice of acceleration. A 10% reduction in axle ratio gives a computed average improvement of 1% for urban and 5% for highway driving.

2.2 RECOMMENDATIONS

1. The torque converter lock-up clutch used with a wide ratio three- or four-speed automatic transmission offers near-term fuel economy improvement of about 12 to 13%. It is recommended that these driveline configurations be evaluated by test in order to determine the impact on exhaust emissions, driveability, acceleration, and engine life and to validate predicted fuel economy improvements.

2. The most significant improvement in fuel economy that can be derived from automobile drivelines is associated with the successful development of a continuously variable ratio transmission (CVRT). Development of various CVRT configurations is currently being sponsored by government and industry. State-of-the-art problems include efficiency, durability, noise (in some cases), weight, and cost effectiveness. It is recommended that promising designs be supported as necessary.
3. Fuel economy can be readily traded-off against acceleration capability through appropriate selection of current production engines and drivelines; e.g., lower numerical axle ratio. It is recommended that further study be conducted to determine the lowest maximum acceleration required for driving safety, and the fuel economy achieveable if engines/drivelines were matched to provide that level of acceleration.
4. It is recommended that further study be given to methods of predicting exhaust emissions through computerized vehicle simulation. An accurate technique will allow prediction of emissions for various engine/driveline combinations in a manner currently accomplished for fuel economy predictions.

2.3 DRIVELINES THAT IMPROVE FUEL ECONOMY

Significant improvements in fuel economy can be achieved for current (1973) automobiles through transmission and rear axle changes. The Department of Transportation, Transportation Systems Center vehicle simulation program, was used to compute fuel economies for nine 1973 production automobiles, ranging in weight from 2750 to 5000 pounds, and operating over a composite of the EPA Urban and Highway Driving Cycles. Fuel economy improvements, shown in Table 2-1, are in comparison to the fuel economy of the cars equipped with one of their production drivelines picked for

TABLE 2-1. FUEL ECONOMY IMPROVEMENTS FOR VARIOUS TRANSMISSIONS*

ITEM	PERCENT COMPUTED FUEL ECONOMY IMPROVEMENT
BENCHMARK-THEORETICAL, IDEAL TRANSMISSION (100% EFFICIENCY, ALLOWING ENGINE OPERATION AT CONSTANT THERMAL EFFICIENCY OF 23%)	56-112
CONTINUOUSLY VARIABLE RATIO TRANSMISSIONS (CVRT)	20-40
MODIFICATIONS TO CONVENTIONAL TRANSMISSIONS	
3-SPD WIDE RATIO MANUAL OR AUTOMATIC WITH TORQUE CONVERTER LOCK-UP CLUTCH	8-13
4-SPD MANUAL OR AUTOMATIC WITH TORQUE CONVERTER LOCK-UP CLUTCH	8-13
3-SPD WIDE RATIO AUTOMATIC WITH LOW SLIP TORQUE CONVERTER	3-6
4-SPD AUTOMATIC	3-6
3-SPD MANUAL OR AUTOMATIC WITH TORQUE CONVERTER LOCK-UP CLUTCH	3-6
3-SPD WIDE-RATIO AUTOMATIC	3-6
3-SPD AUTOMATIC WITH LOW-SLIP TORQUE CONVERTER	2-3

*Continuously variable tranmission data are from references 4 and 5. All other data are computed averages for nine 1973 vehicles operating over a composite of EPA Urban and Highway Driving Cycles comparison purposes and consisting of a three-speed transmission with a fluid torque converter. This table also includes, as a theoretical 'benchmark', an ideal transmission assumed to be 100% efficient while permitting the engine to operate at a constant brake thermal efficiency of 23%. Production vehicles of weights up through 3000 pounds are in general designed for modest acceleration and, with the ideal transmission, show 56 to 80% computed improvement. Production vehicles of 3500 to 4500 pounds exhibit 80 to 112% improvement with the ideal transmission. Vehicle operation is computer-simulated over a composite of the EPA Urban and Highway driving cycles. No production or development hardware exists that approaches the theoretical, ideal transmission performance.

In comparison with the ideal transmission, fuel economy improvement claims based on computer simulation of continuously variable ratio automobile transmissions (CVRT), now in development, range from 20 to 40%. Design problems that must be solved before the CVRT becomes a viable candidate for production automobiles include: increasing efficiency, reducing weight, decreasing noise, improving durability, and decreasing cost.

Table 2-2 offers a more detailed breakdown of the computed fuel economy improvement percentages achievable by modifying production transmissions. Three families of transmissions are presented for illustration. The three-speed transmission shown has a first gear ratio of 2.5, second gear 1.5, and third 1.0 combined with rear axle ratios which range from 2.8 to 3.2. The four-speed transmission family considered has the same first, second, and third gear ratios and the same rear axle ratios as the three-speed family, with the added fourth gear ratio being 0.7 (overdrive). The wide ratio three-speed transmission family has been simulated by providing the transmission with gear ratios of 3.2, 1.8, and 1, giving a maximum gear ratio step of 1.8 which is about the practical limit for acceptable shift feel. The corresponding rear axle ratios have been reduced to the range 2.2 to 2.5, which is about the practical limit for lowering hypoid rear axle ratios.

TABLE 2-2. COMPUTED FUEL ECONOMY IMPROVEMENTS FOR VARIOUS TRANSMISSIONS

A. THREE-SPEED TRANSMISSION						
DRIVING CYCLE	PRODUCTION 3-SPEED AUTOMATIC*	LOW-SLIP CONVERTER	LOCK-UP IN 3RD	LOCK-UP IN 2ND AND 3RD		MANUAL
EPA URBAN	BASELINE	2.2%	2.9%	4.9%		3.9%
EPA HIGH-WAY		1.3	4.3	4.5		2.8
COMPOSITE		1.9	3.4	4.7		3.5
B. WIDE RATIO THREE-SPEED TRANSMISSION**						
DRIVING CYCLE	3-SPD WIDE-RATIO AUTOMATIC	LOW-SLIP CONVERTER	LOCK-UP IN 3RD	LOCK-UP IN 2ND AND, 3RD		MANUAL
EPA URBAN	1.9%	5.2%	8.6%	10.7%		10.3%
EPA HIGH-WAY	8.1	4.9	15.8	16.1		14.7
COMPOSITE	4.0	5.2	11.0	12.7		11.8
C. FOUR-SPEED TRANSMISSION						
DRIVING CYCLE	4-SPD AUTOMATIC		LOCK-UP IN 4TH	LOCK-UP IN 3RD and 4TH	LOCK-UP IN 2ND, 3RD 4TH	
EPA URBAN	1.3%		2.9%	5.1%	6.9%	
EPA HIGH-WAY	10.7		21.1	21.7	21.9	
COMPOSITE	4.5		8.7	10.4	11.8	

* Average for nine 1973 production vehicles operating over a composite of EPA Urban and Highway Driving Cycles.

** The computed 0 to 60 mph acceleration time provided by the wide ratio three-speed transmission family (B) considered in this illustration is approximately 4% greater than that provided by (A) or (C). See Table 2-3.

The overall transmission/rear axle ratio in first gear for the wide-ratio three-speed transmission family was kept the same as that of the three-speed and four-speed transmission families studied in order to maintain vehicle start-up torque. In practice, similar wide-ratio three-speed drivelines could be accomplished by a number of practical gearing combinations. A torque converter lock-up clutch, used to provide 100% efficiency for the torque converter in several gear ratio combinations, was also included in the investigation.

Table 2-2 indicates that the greatest improvements in fuel economy, 12 to 13%, are given by drivelines that include the wide-ratio three-speed and the four-speed transmissions with torque converter lock-up in all gears but first. The percentage improvements represent a calculated average for nine 1973 production automobiles ranging in weight from 2750 to 5000 lbs and therefore indicate the general merit of various drivelines to improve fuel economy. Selection of the most advantageous driveline for a specific vehicle specification requires separate design analysis for each individual case.

Fuel economy changes cannot be considered alone. Any driveline change will also affect acceleration, driveability, and exhaust emissions. The transmission modifications summarized in Table 2-2 were selected for fuel economy improvement. In order to establish the effect of the modifications on acceleration performance, the time to accelerate from 0 to 60 mph was calculated. The average times for the nine 1973 automobiles considered are summarized in Table 2-3. The 0 to 60 mph acceleration performance of the three-speed and the four-speed transmission families are essentially identical. The 0 to 60 mph acceleration time for the particular wide-ratio three-speed transmission family selected for analysis is greater than that of the above mentioned families by about 4%. Fuel economy can be traded-off against acceleration capability in any driveline system. The fuel economy improvements of the wide-range three-speed transmission family given in Table 2-2 are thus partially attributable to reduced acceleration capability.

TABLE 2-3. CALCULATED WIDE-OPEN THROTTLE ACCELERATION FROM 0 TO 60 MPH

TRANSMISSION	TIME 0 TO 60 MPH (SEC)
PRODUCTION 3-SPEED AUTOMATIC	12.6
WIDE-RATIO 3-SPEED AUTOMATIC	13.1
4-SPEED AUTOMATIC	12.6
CONVENTIONAL 3-SPEED WITH TORQUE CONVERTER LOCK-UP IN 2ND AND 3RD	12.7
WIDE-RATIO 3-SPEED WITH TORQUE CONVERTER LOCK-UP IN 2ND AND 3RD	13.3

The effects of driveline modifications on driveability and emissions require evaluation by vehicle test since they are not amenable to study by computer simulation. It is expected that emissions and driveability of vehicles employing the wide ratio three-speed transmissions would deviate from those of the standard three-speed transmission equipped vehicles by a greater degree than those of four-speed transmission equipped vehicles.

The first three gears of the four-speed transmission of Table 2-2 have ratios identical to those of the production three-speed transmission. Much vehicle operation over the EPA Urban Driving Cycle, where driveability and emissions are of primary concern, involves the first three gears. The wide-ratio three-speed transmission family, however, provides overall transmission/rear axle ratios that differ substantially from the overall second and third gears of the production three-speed transmission.

Table 2-4 summarizes the impact of transmission changes proposed in Table 2-2 on the issues of cost, emissions, driveability and production lead time. However, vehicle power trains must be considered as a complete system by the automotive designer. A change in one component may dictate changes in interacting components. As an illustration, Table 2-5 summarizes design considerations that a change in transmission may dictate.

TABLE 2-4. AUTOMATIC TRANSMISSION MODIFICATIONS

MODIFICATION	LOW SLIP CONVERTER (1)	*THREE SPEED WITH LOCK-UP CLUTCH IN 3RD (2)	THREE-SPEED WITH LOCK-UP CLUTCH IN 2ND-3RD (3)	WIDE-RANGE 3-SPEED (4)	ADD FOURTH GEAR (5)	FOURTH-SPEED WITH LOCK-UP CLUTCH IN 4TH (6)	FOURTH SPEED WITH LOCK-UP CLUTCH IN 2ND-3RD-4TH (7)
COST	No cost increase (already available)	Additional $ over (1) because of lock-up clutch and controls.	Additional $ over (2) because of vibration damper needed	Additional $ for expendable cooling (less than (2))	Additional $ over (3) because of 4TH gear	Additional $ over (5) for clutch and controls	Additional $ over (6) because of vibration damper and additional controls to cover other ratios
EMISSIONS	Increase	Increase over low slip converter at low speed but not at high speeds	Same or more than (2)	Higher gear ratio permits carb. calibration for emission improvement	Improved emission condition over speed range	Same as (3)	Same as (3)
ACCELERATION DRIVEABILITY	Reduced engine power at stall reduces acceleration	Engine rough, prone to stumble at low speed	Mid-range acceleration significantly reduced over (2) requires more shifting	Same as production or conventional (max upspeed ratio of 1.8)	Excellent for optimizing performance	Engine rough prone to stumble at low speeds	Low speed problems same as (3)
LEAD-TIME TO PRODUCTION	Available on some installations	Approximately 2 yrs (18 mos for new tools)	Approximately 2 yrs (18 mos for new tools)	Short lead time for some transmissions	Approximately 4 yrs min (complete redesign) **	Approximately 4 yrs min (complete redesign) **	Approximately 4 yrs min (complete redesign) **

*Torque converter limited slip clutch permits less than 5% slip at any speed (when engaged).

**On redesign the decision would be made as to which way to go, and time is not relevant for component development.

TABLE 2-5. DESIGN IMPACTS OF AUTOMATIC TRANSMISSION IMPROVEMENTS

MODIFICATION	LOW SLIP CONVERTER (1)	*THREE-SPEED WITH LIMITED SLIP LOCK-UP CLUTCH IN 3RD (2)	THREE-SPEED WITH LOCK-UP CLUTCH IN 2ND-3RD (3)	WIDE-RANGE 3-SPEED ´4)	ADD FOURTH GEAR (5)	FOUR-SPEED WITH LOCK-UP CLUTCH IN 4TH (6)	FOUR-SPEED WITH LOCK-UP CLUTCH IN 2ND-3RD-4TH (7)
REAR AXLE	Effects stall speed & acceleration rate; has little effect on economy once ratio is established. Shift point & engine noise can be improved with small axle changes.			Axle adjusted to give equiv. 4-speed ratio spread	Adjusted for top speed economy & quiet operation; or maximize accel.	Permits lower ratio to improve high speed operation	Permits lower ratio to improve high speed operation
CARBURETOR CALIBRATION	Must be enriched to prevent stumble on take-off	More prone to stumble over low slip converter (1)	More torque required from engine carburetor throttle must be open further than (2)	Same as (3)	Improved carburation over production can be attained	Improved carburation over production can be attained	Same as (3)
TORSIONAL DAMPING	None required	None required	Probably require a vibration damper	Smoother than (2) and (3)	None required	None required	Same as (3)
SIZE AND WEIGHT	No change	Approximately 8-10# of rotating weight	Same as (2)	No change over conventional unit	Approximately 12-15# increase weight (integral design)	20-25# increased weight	Same as (6)

*Torque converter limited slip clutch permits less than 5% slip at any speed (when engaged)

3. DRIVELINE COMPONENTS

This section describes driveline components (transmissions and drive axles) that may be selected for use in automobiles. The objective is to familiarize the reader with the general mechanical configuration of the most significant types of components and to discuss their performance characteristics.

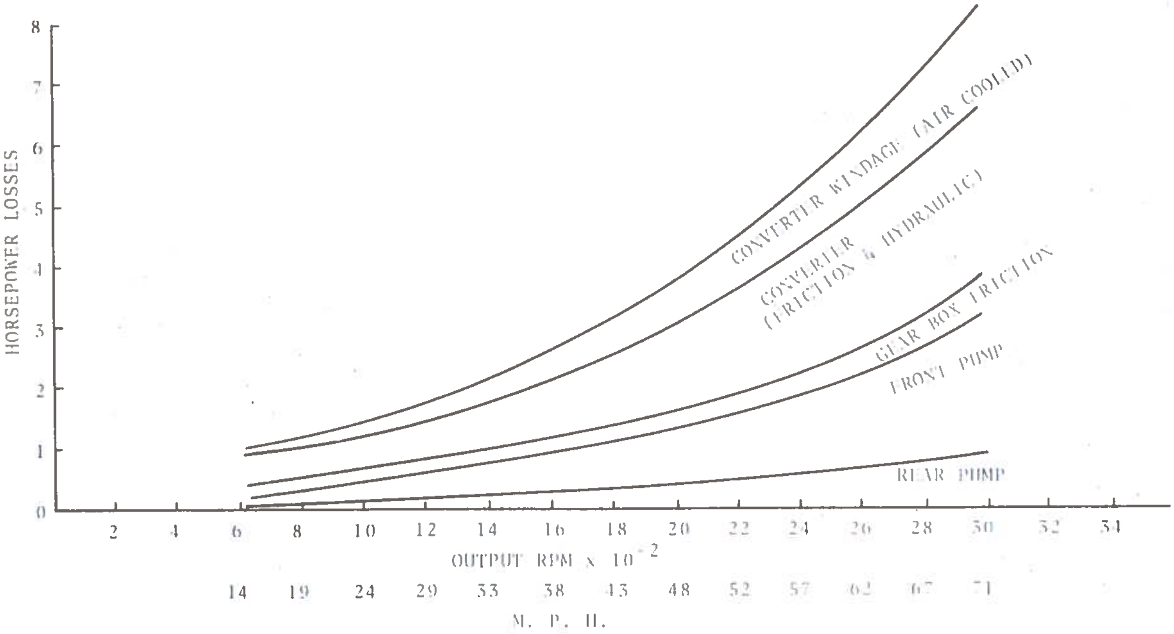
3.1 MANUAL TRANSMISSIONS

The modern manual transmission consists of a dry, friction clutch and fully synchronized gears. The manual transmission has a higher component efficiency than the production automatic. Component efficiency cannot be considered alone however. The production automatic transmission has torque multiplication, available from its torque converter, which the manual transmission does not. Thus, for a vehicle with a given acceleration and gradeability capability, selection of a manual transmission required a higher rear axle ratio (increasing the torque multiplication provided by the rear axle) than would be required if an automatic transmission with equivalent number of gear ratios were selected. The higher rear axle ratio reduces the fuel economy advantages of the higher efficiency manual transmission.

3.2 HYDRODYNAMIC AUTOMATIC TRANSMISSION

Modern American production passenger car automatic transmissions utilize a hydrodynamic drive unit to provide a smooth coupling between the engine and driveline, especially during start-up of the vehicle. The hydrodynamic drive transmits power solely by dynamic fluid action in a closed, recirculating path. Fluid coupling and torque converters are dynamic drive units. A planetary gear box is commonly employed with the hydrodynamic drive unit in order to provide forward speed ratio steps and a reverse. Significant power losses occur in the hydrodynamic automatic transmission. The order of magnitude and source of the losses can be seen by referring to Figure 3-1. Note that horsepower losses in an automatic transmission can be substantial and are predominantly due to torque converter and oil pump losses.

The particular transmission given in the example (Figure 3-1) shows the total loss at 55 mph to be about 5.1 horsepower. Torque converter inefficiencies (friction and hydraulic) account for a 1.8 horsepower loss, torque converter windage (air cooled torque converter) uses 1.1 horsepower, and front and rear oil pumps take 1.9 horsepower, while gear box friction accounts for only 0.3 horsepower.



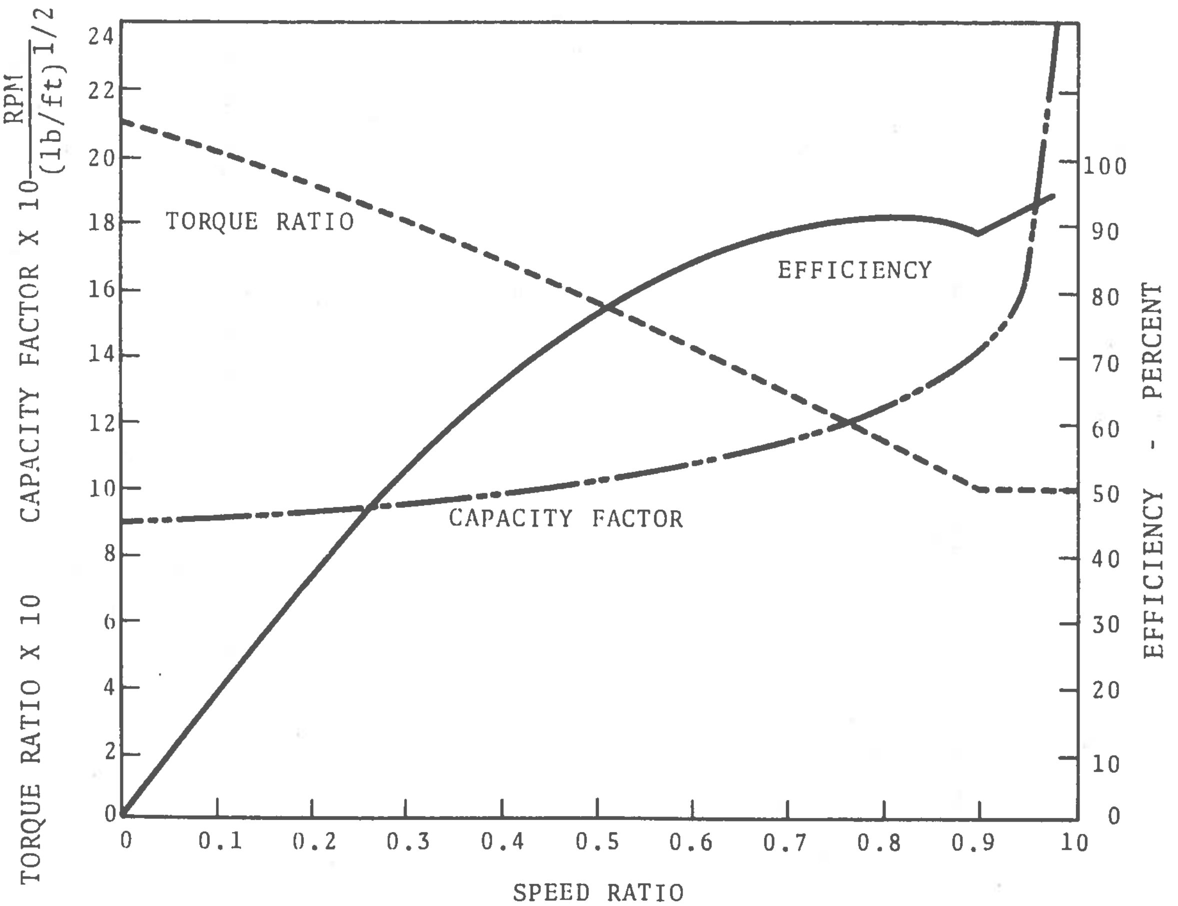
Source: Reference 7

Figure 3-1. Horsepower Losses in an Automatic Transmission

3.2.1 Torque Converter Characteristics

The hydrodynamic drive unit employed in current American production automatic transmissions is the torque converter. The torque converter possesses a number of desireable advantages. It is inherently a continuously variable transmission over its range of torque multiplication, which is a maximum at stall (commonly 2 to 3 for a three-element converter) and decreases continuously to a value of unity, which defines the coupling point. It is durable, provides a smooth fluid start-up, torsional damping and driveline shock protection, and requires no external controls for acceptable performance. The torque converter, however, accounts for the greatest power loss in the transmission over much of the automobile driving cycle. The loss shows up as heat in the transmission fluid.

Performance characteristics are illustrated in Figure 3-2 for a typical production torque converter. The torque converter shown achieves a maximum torque multiplication ratio of 2.1 at stall (speed ratio = 0). The coupling point is achieved at a speed ratio of 0.89. Over its torque multiplying speed ratio range (0 to 0.89)



Source: Reference 8

Figure 3-2. Relative Torque Converter Performance Characteristics its efficiency varies significantly, from 0 to 90%. The efficienc characteristic illustrates that the torque converter accounts for a significant power loss over those portions of the driving cycle when its torque multiplication feature is required. The capacity factor is a measure of the torque that can be transmitted at any given speed subsequently defined by Equation 3.

Various design techniques can be employed to minimize or entirely avoid the torque converter's low efficiency range, over selected portions of the driving cycle, while retaining its most significant advantages. Several combinations of these design features have been incorporated in past production automatic transmissions. Torque converter efficiency can, in general, be improve by specifying a tighter converter which has less slip. A second technique is to bypass the torque converter completely during portions of the driving cycle by means of a lock-up, friction clutch. (See Section 3.2.2.) Third, a split torque transmission can be designed, in which only a fraction of the torque is transmitted through the torque converter in high gears with the remaining fraction transmitted mechanically. (See Section 3.2.3.)

The terms "tight" or "stiff" and "loose" or "soft" are qualitatively descriptive terms commonly used in reference to torque converters. A parameter that is used to indicate tightness in a quantitative manner is the capacity factor, K

$$K = N/\sqrt{T} \qquad (1)$$

where

N = input or output speed, rpm

T = input or output torque, lb-ft.

(Either input or output conditions may be used as long as consistency is maintained.)

For the same input speed to the torque converter, the lower the capacity factor the tighter the converter.

A tighter torque converter transmits the horsepower required for a given vehicle speed with a higher speed ratio across the converter, n (output speed divided by input speed). Torque converter efficiency is determined by the following relationship:

$$E = (n \times t) \times 100 \qquad (2)$$

where

E = Efficiency (%)
t = torque ratio (output torque divided by input torque)

It can be seen from equation (2) that when the torque converter has reached the coupling condition ($t = 1.0$ by definition), which occurs at most automobile cruise conditions, the efficiency is directly proportional to the speed ratio. Thus, the higher speed ratio (lower slip) of the "tight" torque converter gives generally a higher operating efficiency than the lower speed ratio of a "loose" torque converter. The reduced slip of a tighter converter also lowers engine speed for a given automobile speed causing the engine to operate at a higher load, which is generally a higher efficiency condition for the engine.

The capacity factor for a given torque converter geometry and working fluid is inversely related to its size according to the following equation:

$$K = \sqrt{\frac{1}{CD^5}} \qquad (3)$$

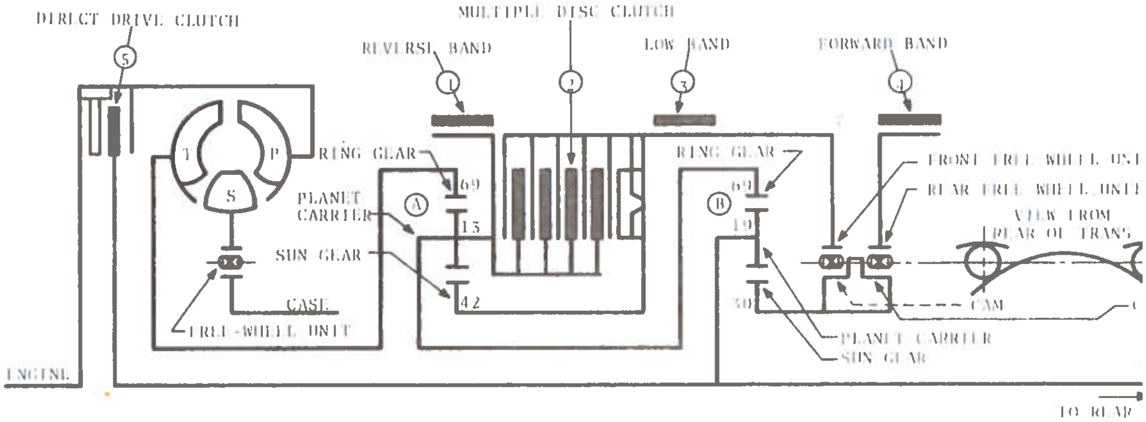
where

C = coefficient for a given design
D = impeller diameter.

It can be seen that the capacity factor is reduced and the converter made tighter as the impeller diameter is increased. The torque converter can also be designed tighter by appropriate selection of blade angles. Production torque converters have been designed with variable angle reactors to vary the capacity factor over the vehicle operating conditions. A two position reactor, for example, can provide high torque multiplication for vehicle start-up and low slip/high efficiency for cruise.

3.2.2 Torque Converter Lock-Up Clutches

Hydraulic slip between the input and output elements of a torque converter is a direct waste when no torque multiplication is required. Various clutch configurations can be used to lock-up or bypass the torque converter to eliminate the slip loss. Figure 3-3 is a schematic of a former U.S. production automatic transmission that uses a mechanical friction clutch in direct drive. The engine power is transmitted through the torque converter and planetary gears in low and intermediate gears. In direct drive, the mechanical friction clutch is applied. Engine power is then transmitted through the clutch directly to the drive shaft, while the torque converter and planetary gears free-wheel.

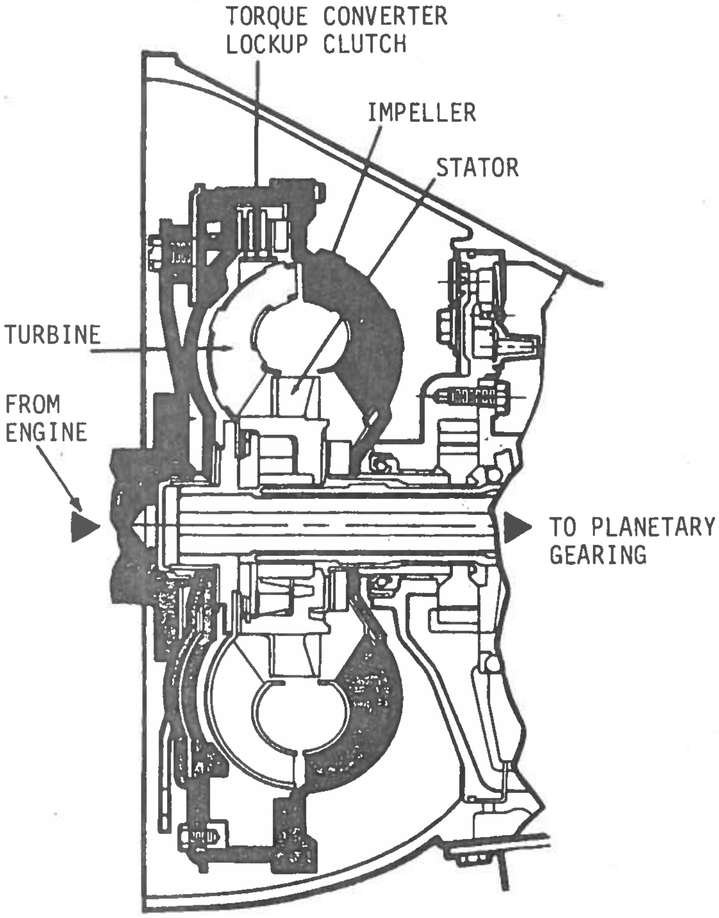


	ON	OFF	SPEED RATIO	TORQUE RATIO
FOR REVERSE	①	② ③ ④ ⑤	.498	2.009
FOR LOW	③ ④	① ② ⑤	.433	2.309
FOR INTERMEDIATE	② ④	① ③ ⑤	.697	1.435
FOR DIRECT	② ⑤ ④	① ③	1.000	1.000

Source: Reference 9

Figure 3-3. Automatic Transmission Schematic

Figure 3-4 is a cross section of a torque converter with lock-up clutch, that is currently under development. Note that the lock-up clutch locks the input (impeller) and output (turbine) elements of the torque converter together. Thus, torque converter lock-up can be accomplished on command by the hydraulic control system whenever driving conditions are favorable. This is in contrast to the configuration of Figure 3-3 which required that lock-up occur always and only in direct drive.



Source: Reference 10

Figure 3-4. Torque Converter with Lock-Up Clutch

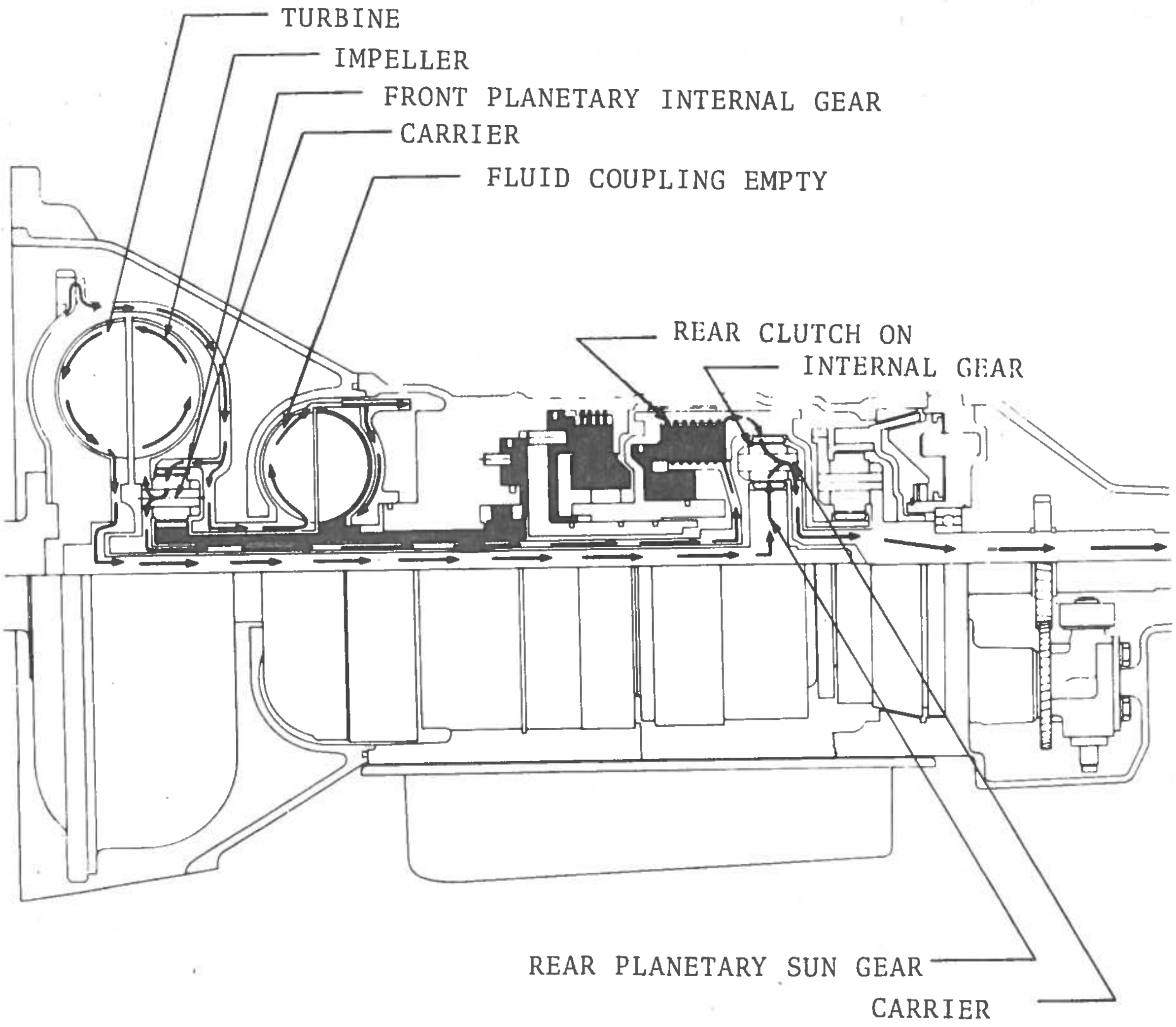
3.2.3 Split Torque Transmissions

Hydromatic split torque transmissions include two or more paths of power flow with a fluid coupling or torque converter transmitting the power in one of the paths.[11] Parallel power flow can be designed to occur in top gear, the top two gears, etc. A split torque transmission can be considered as a design compromise achieving performance advantages and disadvantages that lie somewhere between those of a current production automatic transmission and an automatic transmission employing a torque converter lock-up clutch. Split torque devices have been used by U.S. automotive manufacturers. In general, however, cost effectiveness and durability are not good with split-torque systems.[12]

Figure 3-5 illustrates the split torque principle as applied in a transmission power flow. The power flows from the engine to the internal gear of the front planetary gearset. The power splits at the carrier of the gearset. The carrier drives both the impeller of the fluid coupling (hydraulic path) and the intermediate shaft (mechanical path). Power flow through the hydraulic path goes through the oil-driven turbine, which drives the carrier of the rear planetary gearset through the sun gear. The carrier of the rear planetary gearset is part of the output shaft. The mechanical path is completed by the carrier of the front planetary gearset driving the carrier of the rear planetary gearset through the rear clutch and rear internal gear.

3.2.4 Transmission Oil Pumps

Pump losses can represent a signifcant power loss for automatic transmissions. The function of the transmission oil pump is to maintain fluid pressure in the torque converter or fluid coupling, to supply oil for lubrication of the transmission, to circulate oil through the transmission's oil cooler, to supply oil to the control system that regulates the various clutches and bands, and to provide oil pressure for activating the clutches and bands.



NOTE: Unit shown in third speed.

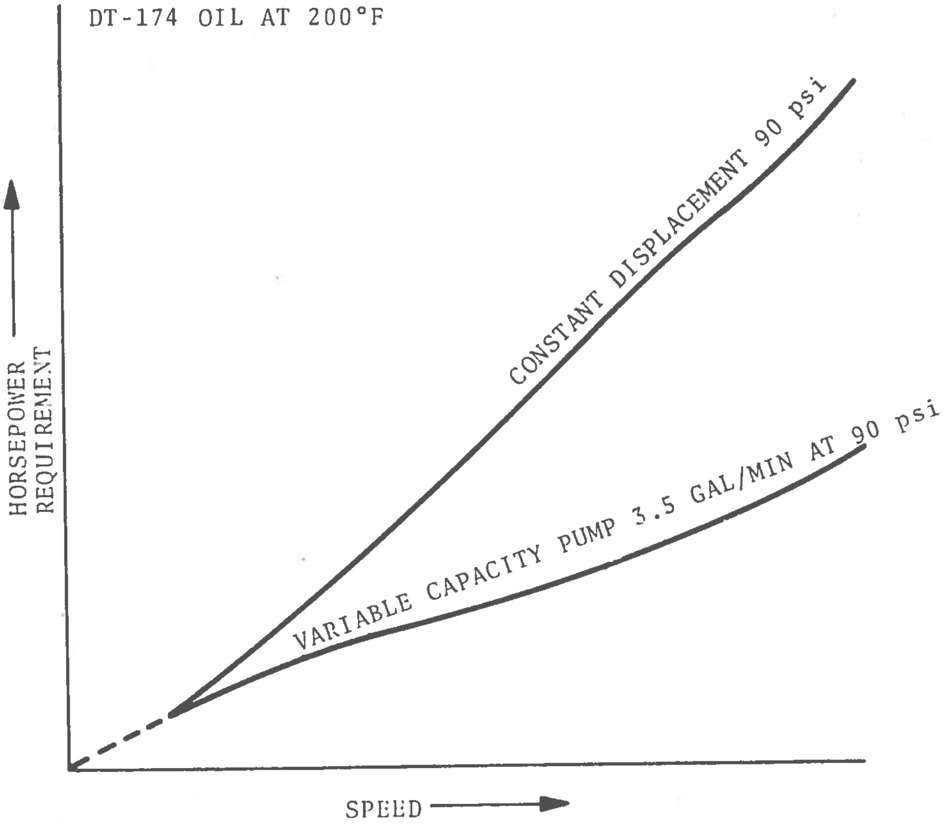
Figure 3-5. Split Torque Transmission Power Flow

Current automatic transmissions contain a constant displacement front pump and a pressure regulating valve. The pressure regulating valve maintains the maximum system pressure by short circuiting oil from the pump outlet to the pump inlet. The oil that is recirculated through the pump represents a direct waste of pumping power. Power required by a pump is directly proportional to flow rate of oil through the pump and pressure differential across the pump. The pressure difference parameter is effectively held constant by the pressure regulating valve. However, oil flow through a constant displacement pump is porportional to its speed. Pump oil flow rate should be matched to the needs of the hydraulic system and not to the pump speed in order to minimize the pump power requirement.

All hydrodynamic automatic transmissions have engine driven front pumps. Rear pumps, driven by the vehicle's drive shaft, are no longer used on American production transmissions,[13] but were once used to reduce the total oil pump power loss. The smaller rear pump takes over the pumping duties from the larger, constant displacement, front pump when a propeller shaft speed of about 1500 rpm is achieved. The front pump is then unloaded. Variable displacement pumps have been used to reduce oil pump power loss by controlling oil flow rate. Figure 3-6 indicates that a constant displacement pump can require more than twice the power of a variable capacity pump at high speeds.

3.3 CONTINUOUSLY VARIABLE RATIO TRANSMISSIONS

The continuously variable ratio transmission (CVRT) provides the ability to optimize fuel economy, emissions, and acceleration performance with any type of engine. CVRT's are not used in any current, production automobiles. However, CVRT's are used in aircraft, tractors, construction vehicles, machine tools, and most recently in special duty trucks. The CVRT, if successfully developed for production automobiles, is the best transmission for optimizing fuel economy.

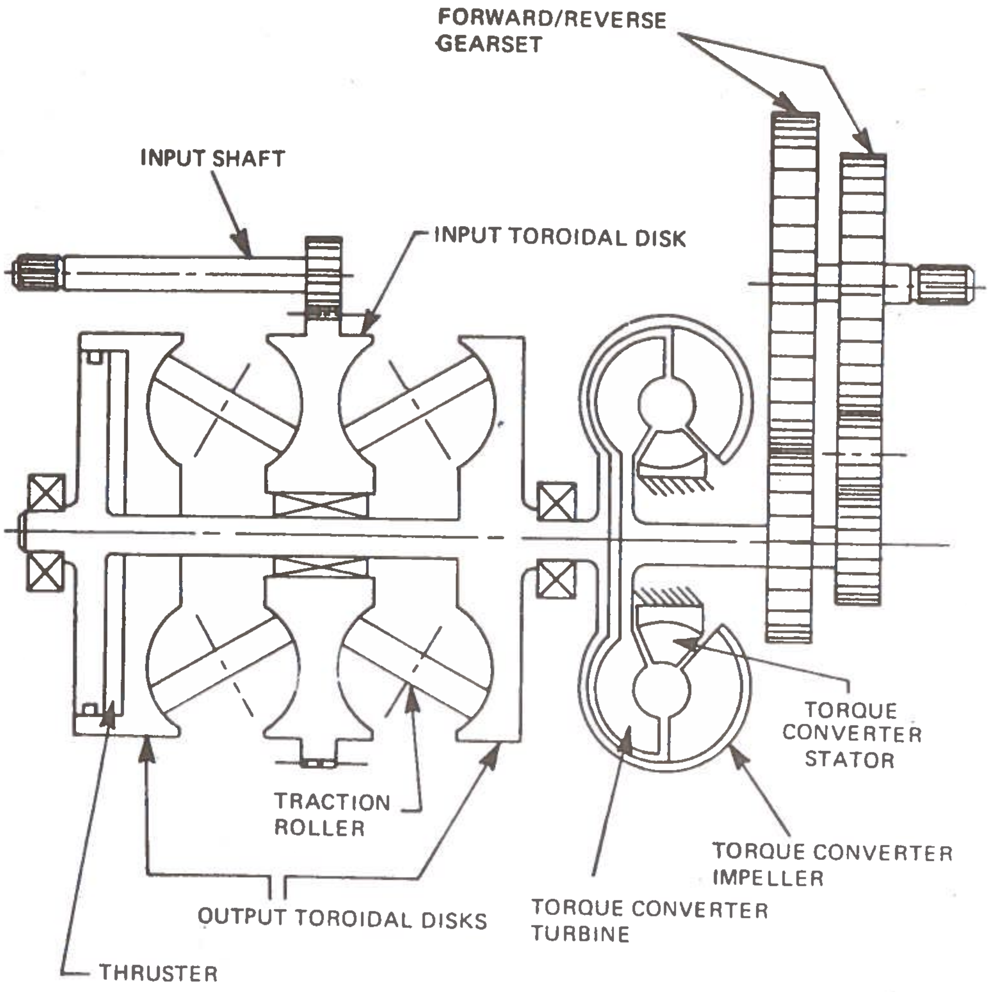


Source: Reference 14

Figure 3-6. Pump Horsepower Versus Speed

A recent transmission study sponsored by EPA[15] considers a number of continuously variable ratio transmissions and selects the hydromechanical and traction types as the best current candidates for automotive applications. Although the study is associated with gas turbine and steam engines, the conclusions pertaining to CVRT Types are generally applicable to any automobile heat energy.

Traction transmissions transfer power through frictional contact. The toroidal type, shown in Figure 3-7, has emerged as the best design for highest power density, reasonable life, and good efficiency. The transmission input speed (speed of the input

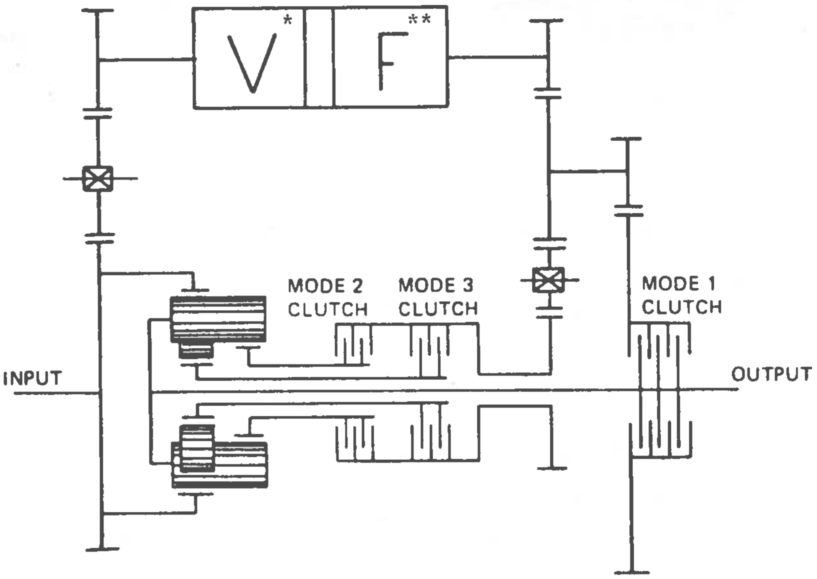


Source: Reference 15

Figure 3-7. Traction Drive - Torque Converter Transmission Schematic

toroidal disc) is proportional to engine speed. The speed of the output toroidal disks relative to the speed of the input toroidal disk is a function of the inclination of the traction rollers. The speed ratio across the traction drive is the same as the ratio of the radius of rolling contact on the output toroidal disk to the radius of rolling contact on the input toroidal disk with respect to the axis of the traction drive, less slip between the rollers and disks. Transmission ratio changes are affected by changing the tilt angle of the roller axis which varies the radius of the two points of contact with the toroids. The traction drive transmission, in this case, utlizes an output torque converter as a disengaging device to permit zero output speed when the engine is running.

The hydromechanical, continuously variable ratio transmission is commonly a split torque transmission that allows a varying fraction of the engine power to be transmitted through mechanical and hydraulic paths. The mechanical path consists of planetary gears. The hydraulic path typically includs a hydraulic pump and motor, at least one of the units being of variable displacement. Figure 3-8 is a schematic of a hydromechanical CVRT.



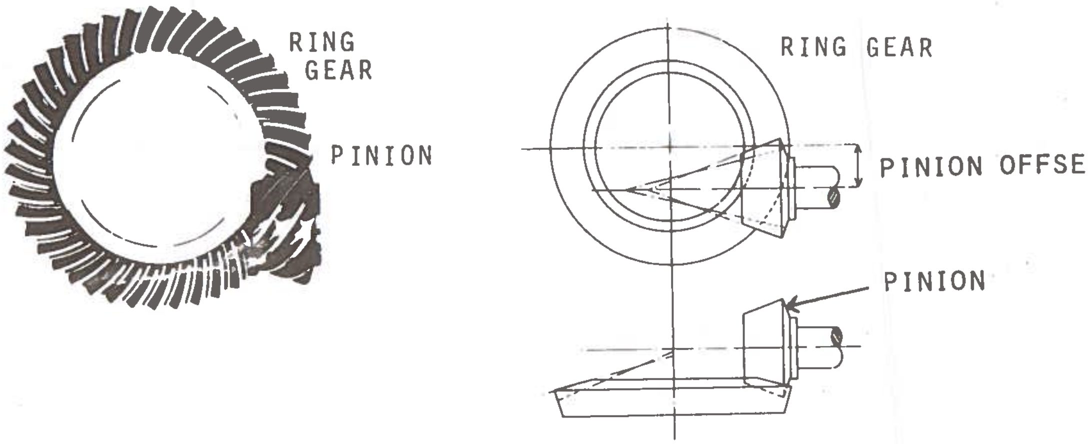
*V is variable displacemnt axial piston pump/motor.
**F is fixed displacement axial piston pump/motor.

Source: Reference 15

Figure 3-8. Hydromechanical Continuously Variable Ratio Transmission Schematic

3.4 DRIVE AXLE

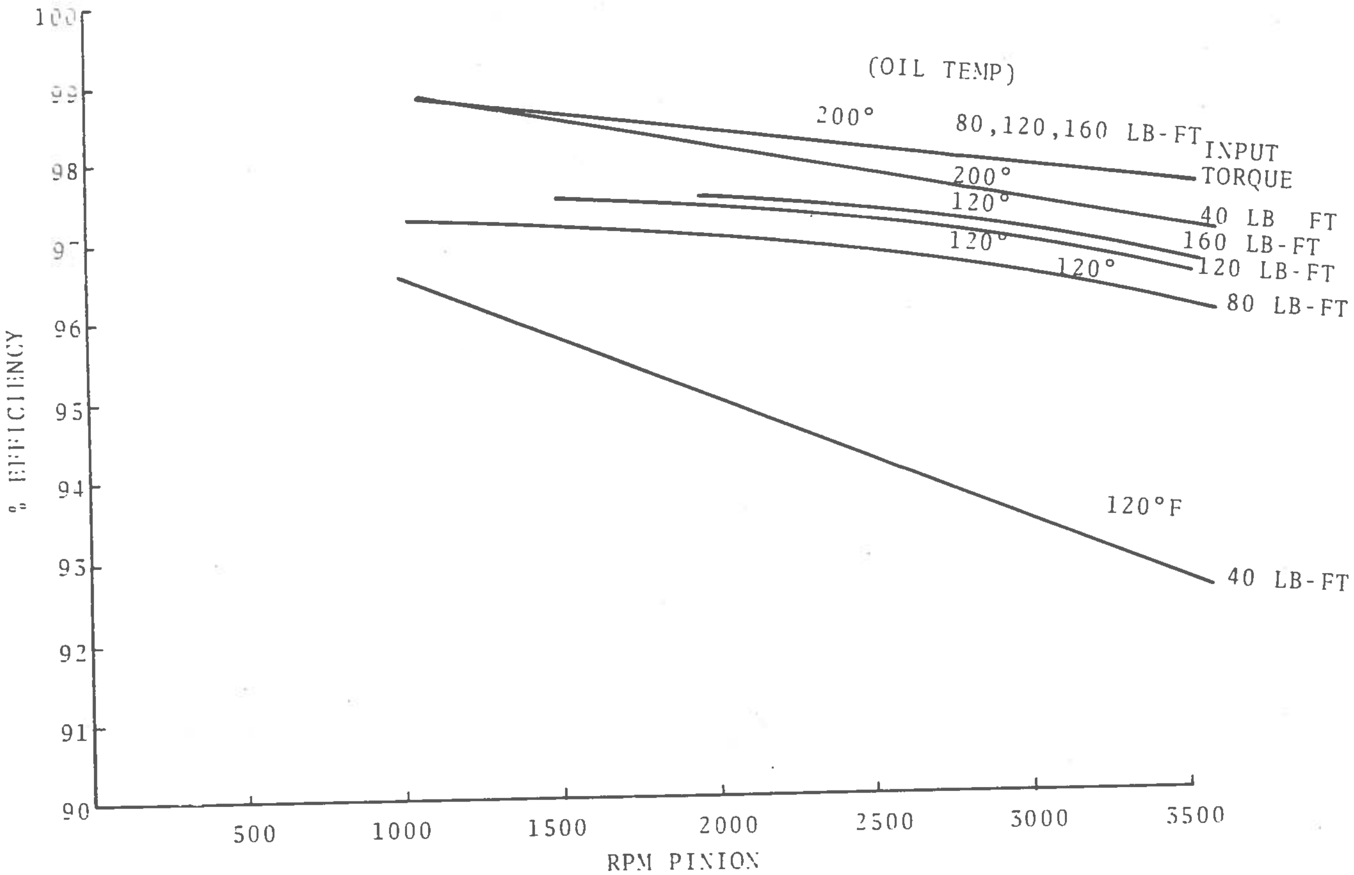
The automobile drive axle includes differential gearing which couples the propeller shaft to the axle, maintains differential action between the driving wheels, and provides a constant torque multiplication ratio. Modern automobiles with front engine/rear wheel drive utilize hypoid gears (Figure 3-9), in which the pinion is offset from the centerline of the ring gear. Hypoid gears maintain a low vehicle center of gravity and reduce the driveline hump in the passenger compartment. The low center of gravity is a significant safety item as it reduces the probability of vehicle overturning. Figure 3-10 is an illustration of the efficiency of a hypoid axle at various speed and torque conditions at 120°F and 200°F oil temperatures.



Source: Reference 16

Figure 3-9. Hypoid Gear and Pinion

The drive axle efficiency can be improved through use of a transaxle (combination transmission/axle). In a transaxle a spiral bevel gear may readily be substituted for the hypoid gearing. The spiral bevel gear has no offset between the centerlines of the ring gear and pinion. The spiral bevel gear axle offers higher efficiency than the hypoid axle through reduced gear tooth sliding.



Source: Reference 7

Figure 3-10. Hypoid Axle Efficiency

Fuel economy can be improved by lowering axle ratios at the sacrifice of acceleration capability. A lower axle ratio provides lower torque multiplication and lower engine speeds. The practical lower limit for hypoid axle ratios is reported to be 2.[11] For lower ratios the hypoid pinion diameter may become excessive, reducing road clearance and also creating manufacturing cost problems. In these cases, spiral bevel gears can be considered.

4. DRIVELINE ASSESSMENTS

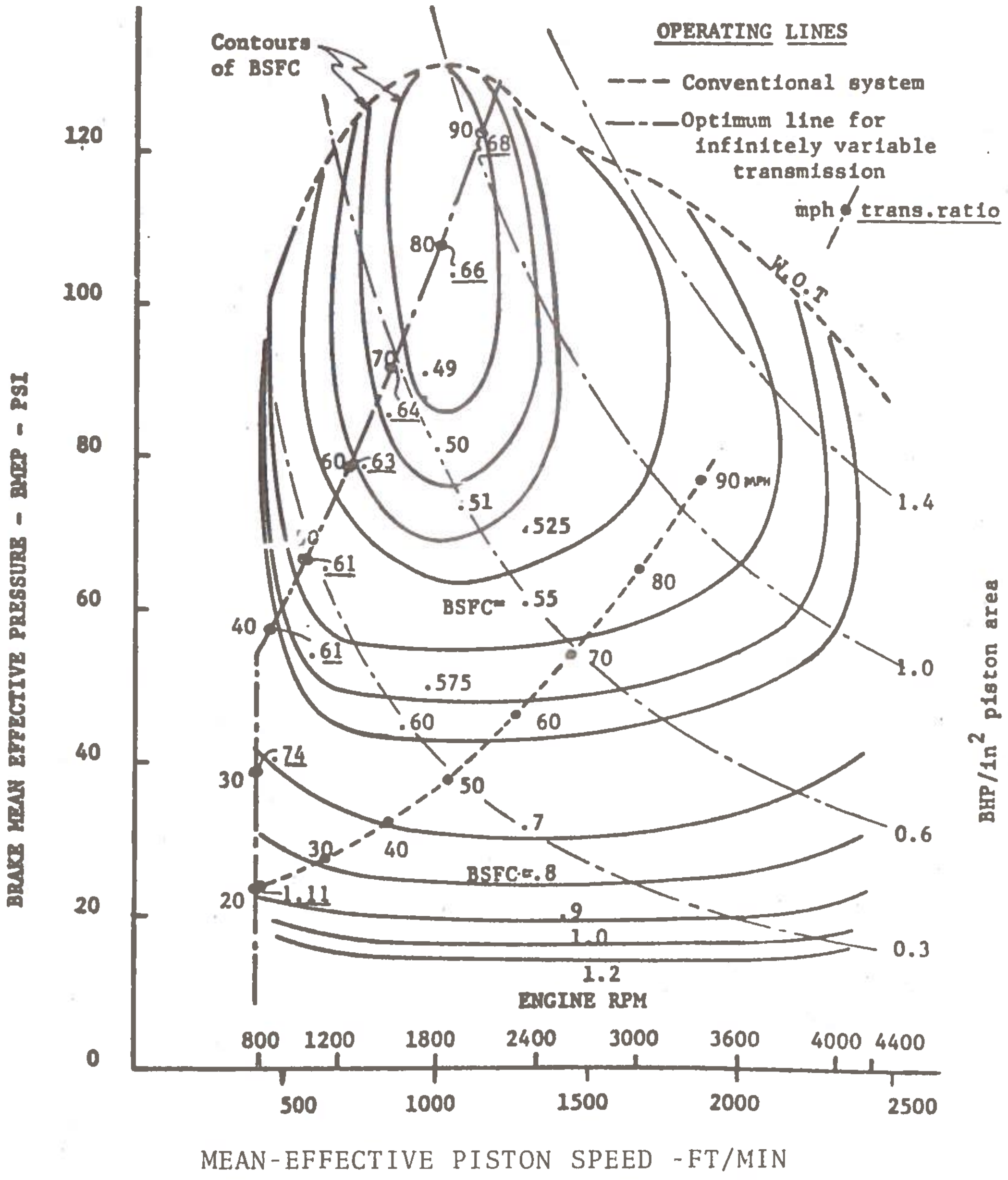
This section describes the driveline's role in determining fuel consumption, exhaust emissions, acceleration, and driveability. Individual driveline components and driveline variations are assessed.

4.1 MATCHING A VEHICLE'S DRIVELINE TO ITS ENGINE

The engine provides the power to operate the vehicle and its many accessories. How well this power is applied to drive the vehicle is a function of the driveline. The matching of driveline performance characteristics to those of the engine determines the overall performance characteristics of any given vehicle. Driveline component speed ratios affect fuel consumption by determining the engine speed at which the engine will produce the power required by the entire vehicle system. Driveline component efficiencies affect fuel consumption since driveline power loss must be added to all other vehicle power requirements.

Engine fuel consumption is commonly represented by a brake specific fuel consumption, BSFC, map. BSFC is the mass fuel consumption rate in pounds per hour, lb_m/hr, divided by engine brake horsepower. A typical map for a 300 cubic inch displacement, V8, spark ignition, gasoline engine is given in Figure 4-1. The abscissa is mean effective piston speed which is directly proportional to engine speed (rpm) and the ordinate is brake mean effective pressure which is directly proportional to engine torque. Engine brake horsepower is also indicated by lines of constant brake horsepower divided by piston area ($bhp/in.^2$).

Superimposed on the engine map are two operating lines, which indicate the engine operating points at steady-state speeds for the same automobile but with two different drivelines. It can be seen that the operating line for the "conventional system," which is a three-speed automatic transmission with a torque converter, passes through contours of higher brake specific fuel consumption



Source: Reference 17 NOTE: 300 in^3 V8 Engine

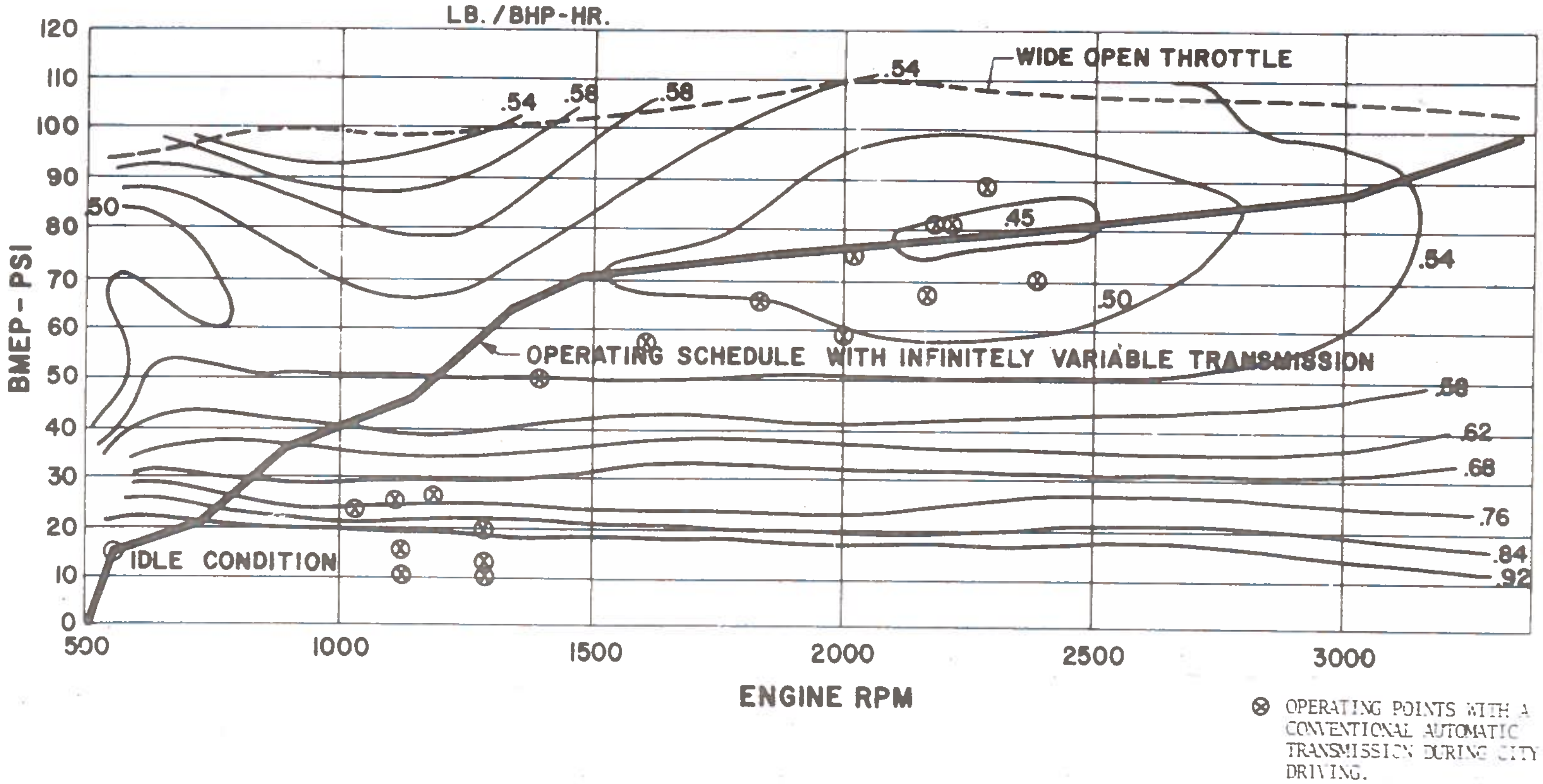
Figure 4-1. Performance Map Typical Gasoline Engine

(BSFC) than the operating line labelled, "optimum line for continuously variable transmission." Thus, for the example given in Figure 4-1, the fuel consumption will be greater for the engine/driveline combination of the conventional system.

Fuel economy cannot be considered alone however since engine/driveline matching also affects exhaust emissions, acceleration, gradeability, and driveability. Illustrating the engine/driveline matching affects on exhaust emissions, an engine BSFC map (Figure 4-2) is presented along with the corresponding exhaust emissions maps (Figures 4-3 through 4-5) for a 300 CID V8 engine. Two operating schedules are superimposed on the maps for two different drivelines installed in the same automobile. One driveline includes a conventional three-speed automatic transmission, while the other includes a hydromechanical infinitely variable ratio transmission. Although many types of transmission hardware can be used to effect different operating schedules, this discussion is concerned solely with the effect of engine/driveline matching. Thus the hydromechanical infinitely variable ratio transmission and the conventional three-speed automatic transmission were chosen to illustrate matching only.

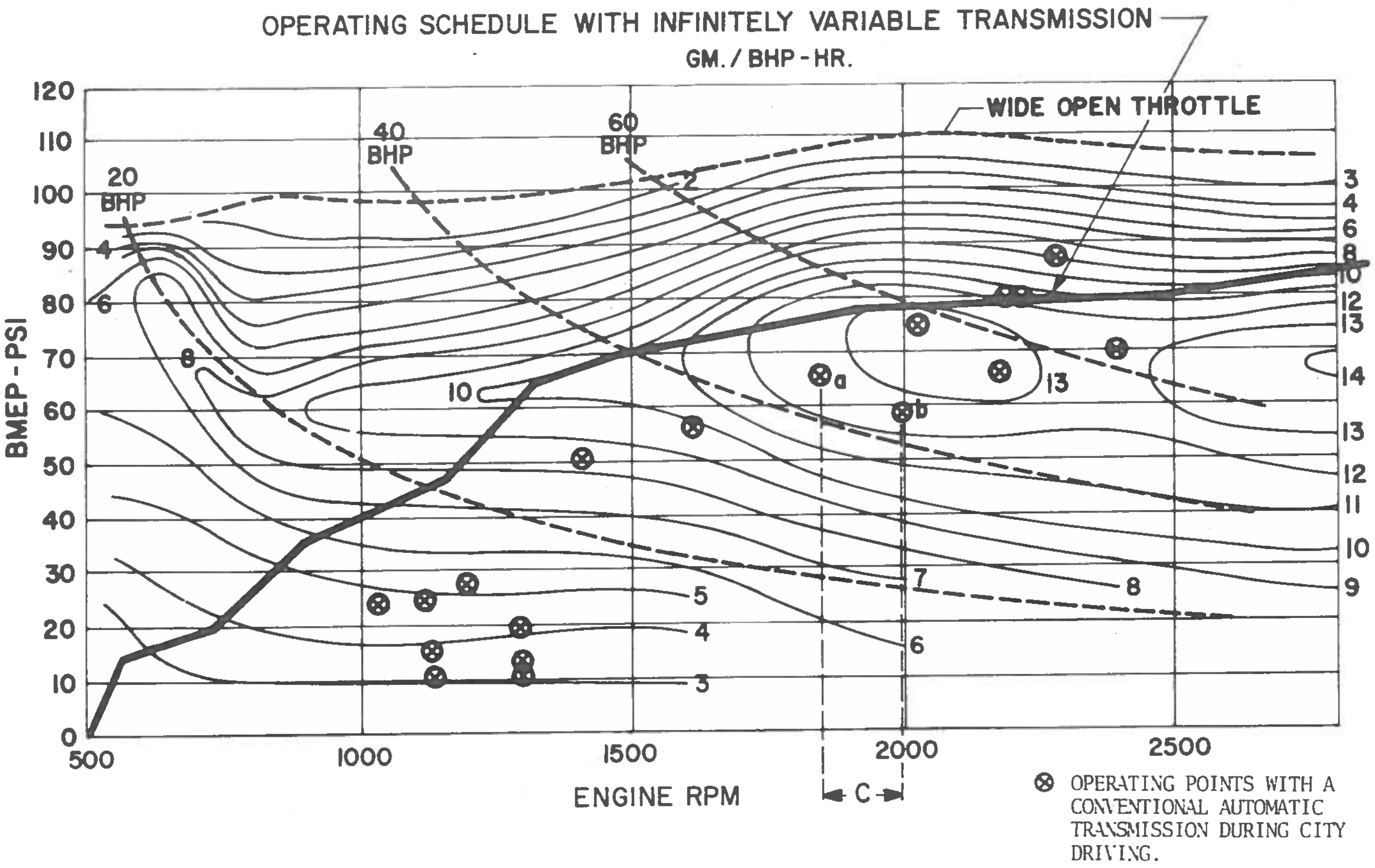
In this case, the infinitely variable ratio transmission has been matched so that the engine operates more highly loaded, especially at low engine speeds. The operating schedules have been integrated by computer simulation over a city and a suburban driving cycle. It can be seen from table 4-1 that the higher-loaded operating schedule gives a 17.1% fuel economy improvement for the city cycle and a 21.0% improvement for the suburban cycle. Furthermore, in this case, the infinitely variable transmission has been matched for reduced exhaust emissions. The changes in emissions are also summarized in table 4-1.

Choosing the driveline for increased engine loadings will, in general, improve fuel economy. Emissions will also change, but the trend of the changes are a function of the particular operating schedules considered. Engine life will tend to be reduced if loading is increased by more than about 30%, and heavier duty engines may be necessary. Highly loaded regions of the engine map



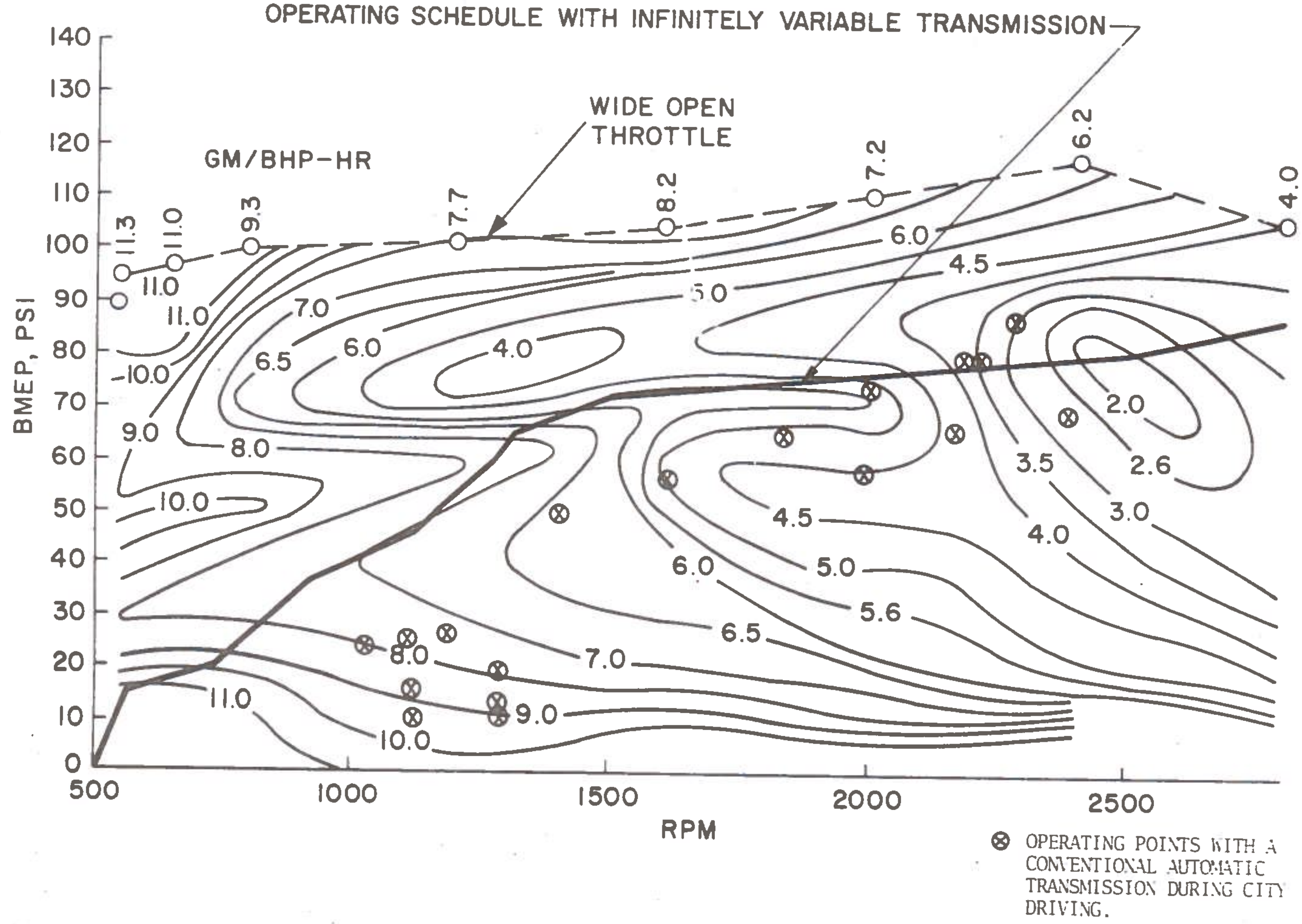
Source: Reference 4

Figure 4-2. Specific Fuel Consumption Map



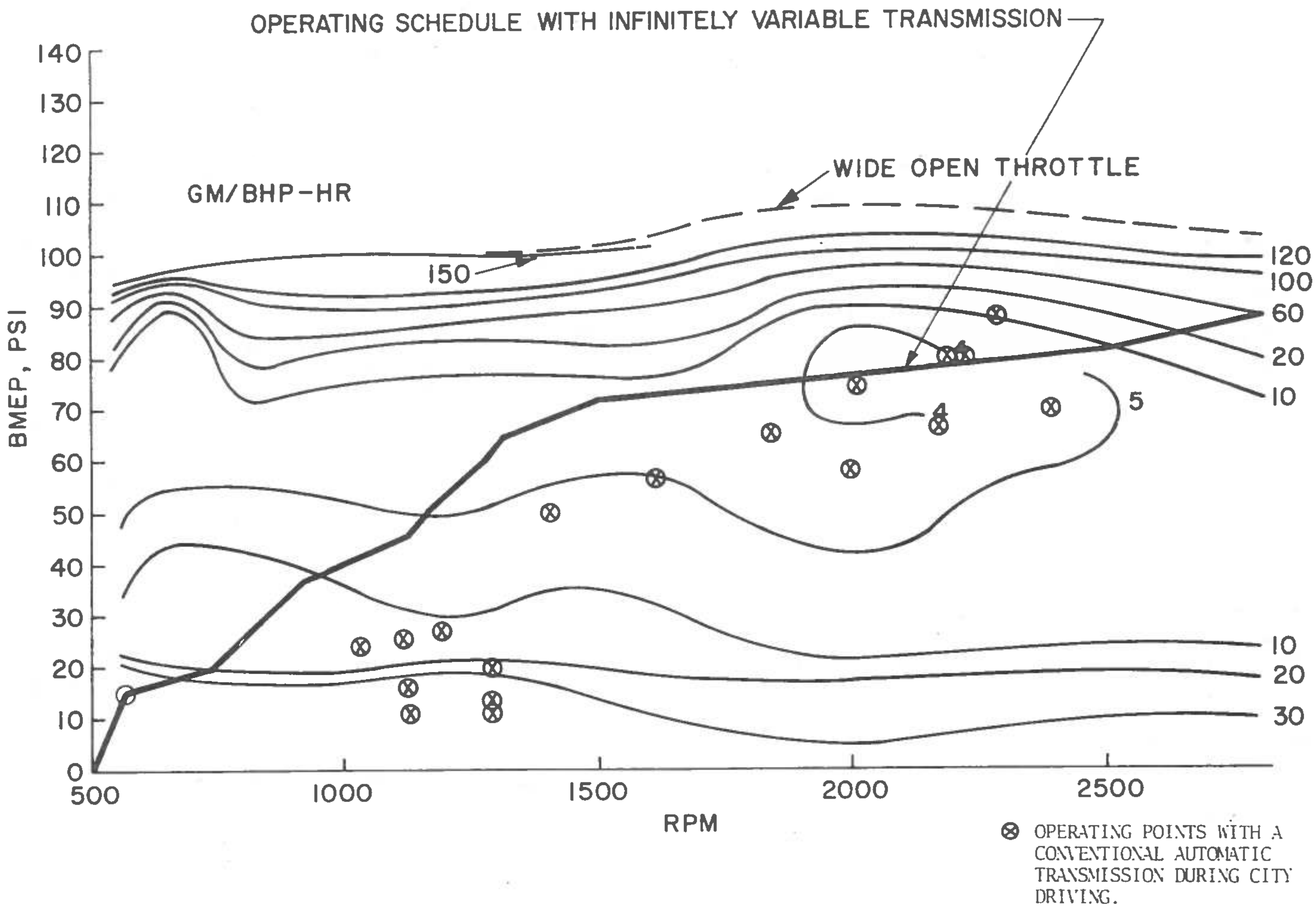
Source: Reference 4

Figure 4-3. NO_x Emission Rate



Source: Reference 18 Reproduced with permission of Mr. P. Huntley, Orshansky Transmission Corp.

Figure 4-4. Emission Rate of Unburned Hydrocarbons from a V-8 Engine



Source: Reference 18 Reproduced with Permission of Mr. P. Huntley, Orshansky Transmission Corp.

Figure 4-5. Emission Rate of Carbon Monoxide from a V-8 Engine

TABLE 4-1. SIMULATED DRIVES COMPARISON

Vehicle Weight	Conventional Automatic 4433	Hydromechanical Transmission 4463	Change, %
City driving			
mpg	10.63	12.45	+17.1
NO_x, g/mile	6.23	5.40	-13.3
HC, g/mile	0.548	0.567	+ 3.5
CO, g/mile	25.7	20.5	-20.2
Suburban driving			
mpg	17.41	21.07	+21.0
NO_x, g/mile	4.40	4.63	+ 5.2
HC, g/mile	0.304	0.327	+ 7.6
CO, g/mile	10.5	4.53	-57.0

NOTE: Hydromechanical continuously variable transmission compared with conventional automatic transmission, both vehicles having same 300 cubic inch engine.

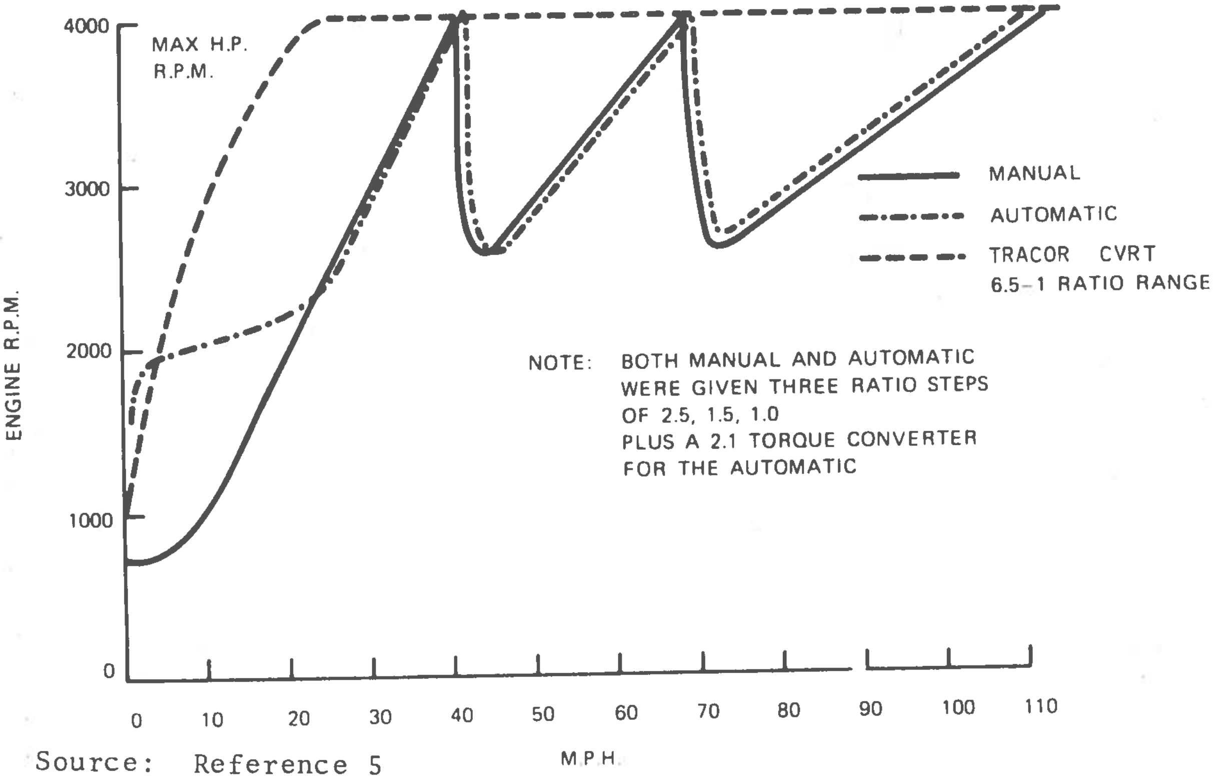
Source: Reference 4

are regions where engines are more prone to roughness, stall and stumble, and driveability may suffer. Horsepower margin for acceleration is reduced and more shifting is necessary for rapid acceleration.

4.2 CONTINUOUSLY VARIABLE RATIO TRANSMISSIONS

The continuously variable ratio transmission (CVRT) provides considerable improvement over conventional transmissions in the ability to properly match engine to vehicle. The CVRT, for example, allows the engine to operate along a path that can be optimized for fuel economy or along a path that provides a balance between improved fuel economy and improved exhaust emissions.

A CVRT equipped automobile can use a smaller engine than a vehicle equipped with a conventional manual or automatic transmission with no loss in acceleration performance. Figure 4-6 shows the acceleration characteristics for an automobile equipped with a traction drive CVRT compared with those of conventional three-



Source: Reference 5

Figure 4-6. Maximum-Acceleration Engine Speed for Different Transmissions

speed manual and automatic transmissions. Maximum engine power is attained and maintained in the CVRT vehicle shortly after acceleration begins. The conventional transmissions allow maximum engine power to be achieved only momentarily during maximum engine speed in each gear. For the example given, the CVRT equipped vehicle with a 140 horsepower engine gives better acceleration performance than the same size vehicle equipped with conventional transmissions and a 170 horsepower engine (Table 4-2). Furthermore, the CVRT equipped automobile is predicted to give a 33 to 41% improvement in fuel economy.

The CVRT has been under development for the modern automobile for many years. Toroidal type, traction transmissions and split torque, hydromechanical transmissions have emerged as the best CVRT candidates (see Section 3.3 for descriptions). A number of problems must be solved before the CVRT is viable for production

TABLE 4-2. PERFORMANCE COMPARISON OF TRANSMISSIONS

TRANSMISSION TYPE	STD-4 SPD MANUAL	SPD AUTOMATIC	TRACOR 6.5-1 CVRT
4300 lb. Reference Automobile	'73 Mid-Size Car	'73 Mid-Size Car	'73 Mid-Size Car
Engine Horsepower	170	170	140
Acceleration			
0-30 MPH/sec	4.2	4.4	3.2
0-60 MPH/sec	11.3	11.5	10.3
Top speed MPH	114	110	105
Miles per gallon			
Urban Driving cycle	12.1	11.5	16.2
80 MPH	13.5	13.3	19

Source: Reference 5

passenger car use. These problems include: improving efficiency, decreasing weight, decreasing noise (hydromechanical type only), improving durability and decreasing cost.

4.3 MANUAL TRANSMISSIONS

In order to assess the effect of the manual transmission's efficiency on fuel consumption, the DOT/TSC automobile simulation study[3] includes an investigation of nine 1973 production automobiles in which the three-speed automatic is replaced by a three-speed manual transmission, for the same rear axle ratio. The results show that average improvement in computed fuel economy with a manual transmission is 3.9% for EPA Urban Driving Cycle, 2.8% for the EPA Highway Cycle, and 3.5% over a national average mileage composite of the two.

The cost of a three-speed manual transmission is about $210 to $300 less than a three-speed automatic with torque converter.[19] This, combined with the probability of decreased fuel consumption, means the manual transmission must be considered more cost effective than the automatic. With respect to safety, the most significant aspect of driveline design involves the automobile's ability to accelerate for safe passing at road speeds. Drivelines designed for improved fuel economy reduce the engine power margin available for acceleration. The automobile must be downshifted when high acceleration is demanded to avoid an unsafe passing situation. The automatic must be considered generally safer in this respect, since it does not require manual intervention.

A qualitative assessment of emissions[19] indicates that use of the manual transmission results in higher carbon monoxide (CO) and hydrocarbon (HC) emissions than the automatic. More engine speed transients occur with the manual transmission due to the difficulty in coordinating the operation of clutch, throttle, and shift lever. These speed transients affect fuel-air ratio and the residual fraction in the combustion chamber leading to the higher CO and HC emissions. If an oxidizing catalyst is installed as part of the engine system however, the increase in CO and HC emissions can be insignificant.

Manual transmissions currently exist as standard (or optional) on a number of production automobiles. However, the strong bias in sales towards the automatic transission indicates that customer acceptance of the manual transmission exists with only a small percentage of American automobile buyers.

4.4 TORQUE CONVERTERS

Improvement in automobile fuel economy through the use of tighter torque converters was investigated in the DOT/TSC vehicle simulation study.[3] If a baseline production automobile was equipped with a relatively soft torque converter, a tighter one was substituted in the simulation. The converse was also investigated. The results show that the average improvement in fuel economy substituting current production torque converters that are tight is 2.2% over the EPA Urban Driving Cycle, 1.3% over the EPA Highway Driving Cycle, and 1.9% over a national average mileage composite of the two. Substituting current production torque converters that are soft decreased fuel economy by 3.9% for the EPA Urban, 1.6% for the EPA Highway, and 3.2% for the composite driving cycle. These results are a gross indication of the sensitivity of fuel economy to torque converter tightness. The range of tight to soft torque converters represents existing 1973 production converters; a range perhaps not specifically selected to optimize fuel economy.

Emissions will tend to increase with tighter torque converters, since the lower slip will tend to cause the engine to run more heavily loaded. Customer acceptance may be affected since the automobile will be less smooth during shifting. If an engine is prone to stumble or stall, a stiffer torque converter will aggravate the problem.

4.5 TORQUE CONVERTER LOCK-UP CLUTCHES

Various applications of torque converter lock-up clutches were considered in the vehicle simulation studies conducted by DOT/TSC.[3] Nine 1973 production automobiles with three-speed automatic transmissions (no lock-up) formed the baseline fleet for this portion of the Study. The average percentage improvement in fuel economy with the various lock-up combinations, compared with the no-lock-up baseline automobiles, are shown in Table 4-3. A standard deviation indicating the spread of the results for all the vehicles is also given.

The first three entries of Table 4-3 deal with three-speed automatic transmissions. Three lock-up possibilities were investigated: lock-up in top gear, in the top two gears, and lock-up for torque converter speed ratios greater than 0.85 (in all gears). For highway driving, all of the lock-up possibilities gave a 4.2 to 4.5 percent improvement in fuel economy compared with the baseline three-speed automatic transmissions. For urban driving, lock-up in the top two gears gave the greatest improvement in fuel economy, 4.9%, and lock-up at torque converter speed ratios greater than 0.85 gave the smallest improvement, 2.0%. All of the three speed automatics investigated had gear ratios of 2.5, 1.5, and 1.0.

The four speed transmission had an overdrive gear ratio of 0.7. The simulation study results with the four speed automatic transmission without lock-up are given in Table 4-3, Entry 4. The overdrive ratio gave a 10.5% improvement in fuel economy for highway driving and a 1.3% improvement for urban driving.

TABLE 4-3. COMPARATIVE FUEL ECONOMIES

ENTRY	NUMBER OF GEARS	TORQUE CONVERTER LOCKED IN GEAR NO.	FUEL ECONOMY % DIFFERENCE FROM BASELINE			
			EPA URBAN	EPA HIGHWAY	EPA COMPOSITE	SAE COMPOSITE (55 MPH)
1	3	3	2.9 ±1.1	4.3 ±1.7	3.4 ±1.0	3.7 ±1.0
2	3	2 & 3	4.9 ±1.7	4.5 ±1.9	4.7 ±1.3	4.7 ±1.1
3	3	SR > .85	2.0 ±0.9	4.2 ±1.7	2.7 ± 0.9	3.6 ±0.8
4	4	NONE	1.3 ±0.6	10.7 ±5.4	4.5 ±2.3	–5.1 ±2.4
5	4	4	2.9 ±0.7	21.1 ±8.1	8.7 ±3.0	10.3 ±3.2
6	4	3 & 4	5.1 ±1.4	21.7 ±8.3	10.4 ±2.7	11.9 ±3.3
7	4	2,3 & 4	6.9 ±1.6	21.9 ±8.2	11.8 ±2.9	13.3 ±3.4
8	4	SR > .85	3.4 ±1.0	19.3 ±7.3	8.6 ±2.2	10.0 ±2.6

NOTE: Fuel economy percent difference from baseline three-speed automatic transmission with no lock-up due to three & four speed automatic transmission with various lock-up schemes averaged over baseline fleet (1973 production automobiles).

Four torque converter lock-up possibilities were investigated in combination with the four-speed automatic transmission: lock-up in top gear, in the top two gears, the top three gears, and lock-up for torque converter speed ratios greater than 0.85 in all gears. All torque converter lock-up possibilities combined with four speed transmission gave further, significant improvements in fuel economy, beyond the improvement obtained from adding the overdrive fourth gear to the transmission alone. For highway driving, lock-up doubled improvements in fuel economy with the additional fourth gear, giving total improvements of 19.3 to 21.9%. During urban operation, the gains of adding a lock-up clutch to overdrive were two to five times as great as with an overdrive gear ratio alone, giving total improvements ranging from 6.9% with lock-up in the top three gears to 2.9% with lock-up in fourth gear only.

Overdrive provides improved fuel economy by reducing engine speed at a given vehicle speed, thereby loading up the engine and forcing it to operate at conditions of lower specific fuel consumption. The torque converter must transmit the same horsepower at a lower speed and thus at a proportionately higher torque. Thus, the torque converter will operate at a lower capacity factor for a given power output, which is generally a condition of greater slip and lower efficiency. The lower torque converter efficiency gives an increased transmission power loss. Furthermore, the increased torque converter slip reduces the effectiveness of the overdrive ratio in lowering engine speeds. Full advantage cannot be taken of increased engine loading and lower specific fuel consumption. Therefore, a torque converter lock-up clutch is an effective addition to a torque converter driveline with an overdrive gear ratio.

The torque converter lock-up clutch has been developed by U.S. automotive manufacturers so that technological risk is not a major issue. Application of the lock-up clutch does affect, to some degree, exhaust emissions, driveability, and acceleration as well as cost and engine life. The emissions, driveability, acceleration and engine life problems should be no more severe with torque converter lock-up in an automatic transmission than with the lock-up friction clutch of a manual transmission. The cost of the additional lock-up mechanism and automatic controls will increase the cost of an automatic transmission.

4.6 REAR AXLE RATIO CHANGES

The automobile driving axle includes differential gearing which couples the propeller shaft to the driving axle, maintains differential action between the driving wheels, and provides a constant torque multiplication ratio. Engine/driveline matching can be varied by changing the axle ratio. Reduction in axle torque ratio causes the engine to operate at a lower speed for a given power output, thus improving fuel economy. Variations in driving axle ratio of ±10% for the ten-car baseline fleet were investigated in the DOT/TSC vehicle simulation study.[3] The average fuel economy improvement with driving axle ratio reduced by 10% was 1.2% for the EPA Urban Driving Cycle, 4.6% for the EPA Highway cycle, and 2.5% for the composite of the EPA driving cycles.

Torque converter lock-up (discussed in Section 4.5) in combination with reduced axle ratios should further enhance the fuel economy improvements given above. Reduction in axle ratio is similar to adding an overdrive ratio to the transmission. The discussion in Section 4.5 concerning combining overdrive with torque converter lock-up is applicable here.

Technological risk, manufacturability, lead time, noise, and safety are not significant issues in lower axle ratio considerations. However, emissions will be affected due to increased engine loading. Lower rear axle ratios are worthwhile because increased fuel economy should be obtained with no increase in hardware costs. The detriments to customer acceptance are driveability penalties including reduced acceleration capability, more downshifting and an increased tendency to engine roughness and stumble.

4.7 OVERDRIVE

Fuel economy can be improved at higher automobile speeds by using an overdrive gear. It was shown in Section 4.5 that the overdrive ratio can be included as a fourth gear ratio in the transmission. The overdrive gear ratio can also be provided as an add-on feature. Adding an integral fourth gear to the transmission would be less costly, amounting to at most $30 to $40 as initial cost to the first buyer.[17] An add-on overdrive unit would cost about $100 to $150 additional cost to the first buyer.

The DOT/TSC simulation study fuel economy results, given in Table 4-3, Entry 4, show that adding an overdrive ratio of 0.7 to a three-speed automatic transmission with torque converter gives a 10.7% improvement for EPA Highway Driving Cycle and only a 1.3% improvement for the EPA Urban Driving Cycle. The fuel economy improvement for the composite of the EPA cycles is 4.5%. As is further discussed in Section 4.5, the fuel economy benefits can be enhanced for automatic transmissions by providing torque converter lock-up. With lock-up and the 0.7 overdrive ratio, the fuel economy improvements are 2.9% for the EPA Urban Driving Cycle, 21.1% for the EPA Highway cycle, and 8.7% for the composite cycle.

4.8 INCREASED TRANSMISSION RATIO RANGE

It has been shown in Section 4.6 that fuel economy can be improved by reducing the driving axle ratio. Wide ratio three-speed transmissions have been proposed[6] to be used in combination with a reduced axle ratio. The wide ratio three-speed transmission includes an increased low speed ratio, thus maintaining vehicle start-up torque while obtaining the fuel economy advantage of the lowered axle ratio at higher speeds. This technique is within existing production restrictions and can be considered a practical aproach. A study has been conducted using the DOT/TSC vehicle simulation program[3] with the wide-ratio transmission and rear axle ratios described in Section 2.2. The fuel economy results are tabulated in Table 2-2.

Alternately, an additional gear ratio can be added to the three-speed transmission to increase the transmission ratio range. The fuel economy results with this technique are also tabulated in Table 2-2 for the four-speed transmission.

4.9 CHANGES IN SHIFT LOGIC

Altering the shift logic of an automatic transmission is a means by which engine/driveline matching can be changed. Early shifting to high gears results in lower engine speeds, thus increasing engine loading and improving fuel economy. However, early shifting also causes the torque converter to run at a lower capacity factor, thus increasing torque converter slip and lowering efficiency, which reduces fuel economy. If early shifting is combined with a torque converter lock-up clutch, improved fuel economy will result. If the torque converter is not by-passed by means of a lock-up clutch fuel, economy may or may not improve depending on the specific engine/torque converter combination installed in the automobile.

The DOT/TSC vehicle simulation study[3] includes investigation of shift logic variations for nine 1973 production automobiles with three-speed automatic transmissions. Torque converter lock-up is not included in the study. The procedure employed is that if a baseline car has a shift logic with relatively delayed shifts, then a shift logic with earlier shifts is investigated. The converse is also applied. In addition tighter and softer torque converters are studied in combination with shift logic changes. No significant change in fuel consumption occurs with any of the shift logic variations that have been considered.

Arthur D. Little, Inc. performed a similar vehicle simulation study using one reference vehicle with torque converter lock-up operating over an EPA Urban Driving Cycle. The results show that earlier shifts reduce fuel consumption by 4.1% for an automobile equipped with torque converter lock-up.

Early shifts will tend to reduce acceleration performance and to increase emissions. Changes in shift logic are cost-effective if used with a driveline that already includes torque converter lock-up since early shifts improve fuel economy with no increase in first cost.

REFERENCES

1. Carl E. Burke et al., "Where Does All the Power Go?" SAE Transaction, Vol. 65, 1957, pp. 713-738.
2. E. W. Upton, "Application of Hydrodynamic Drive Units to Passenger Car Automatic Transmissions," SAE Design Practices, Passenger Car Automatic Transmissions, Vol. 5, 1973.
3. U.S. Dept. of Transportation/TSC, "Analysis of 1973 Automobile and Integration of Automobile Components Relevant to Fuel Consumption," September 1974. Available from Power and Propulsion Branch, TSC (mailing address).
4. E. Orshansky, P. Huntley, and W.E. Weselok, "Automobile Fuel Economy with Hydromechanical Transmission by Simulation Studies," SAE Paper No. 740308, March 1974.
5. Milton H. Scheiter, "Economy Oriented Improvements for Production Automatic Transmission," Presentation to Arthur D. Little, Inc., August 1974.
6. Herbert McAninch, "Automobile Drivetrains," Presentation to U.S. Dept. of Transportation/TSC, December 1974.
7. John W. Greer and George W. Schulz, "A New Ford 3-Speed Automatic Transmission," SAE Paper No. 660075, January 1966.
8. H.E. Churchill, "Studebaker's Automatic Transmission," SAE Journal, March 1950.
9. "On the Way: More Efficient More Versatile Transmissions," Popular Science, January 1975.
10. P. Bloch and R.C. Schneider, "Hydrodynamic Split Torque Transmissions," SAE Transactions, Vol. 68, 1960, pp. 257-273.
11. Milton H. Scheiter, "Automobile Drivetrains," Presentation to U.S. Dept. of Transportation/TSC, December 1974
12. J.R. Doidge, "Oil Pumps-Introduction," SAE Design Practices, Passenger Car Automatic Transmissions, Vol. 5, 1973, p. 145.

13. R.W. Stapleton, "Variable-Capacity Transmission Pump," SAE Design Practices, Passenger Car Automatic Transmissions, Vol 5, 1973, pp. 158-161.

14. Sunstrand Corp., "Transmission Study for Turbine and Rankine Cycle Engines," U.S. Environmental Protection Agency, (Contract No. 68-04-0034), December 1972.

15. Donald A. Hertz et al., "A Study of Technological Improvements in Automobile Fuel Consumption," 3 Vols., U.S. Dept. of Transportation Office of the Secretary/U.S. Environmental Protection Agency, December 1974, DOT-TSC-OST-74-40. I-III.

16. Orshansky Transmission Corp., "Hydromechanical Passenger Car Transmission," Report No. 404, San Diego CA, May 1974.

17. C.W. Coon et al., "Technological Improvements to Automobile Fuel Consumption," 2 Vols., U.S. Dept. of Transportation Office of the Secretary/U.S. Environmental Protection Agency, December 1974, DOT-TSC-OST-74-39: I-II.

130 Copies

U. S. DEPARTMENT OF TRANSPORTATION
TRANSPORTATION SYSTEMS CENTER
KENDALL SQUARE, CAMBRIDGE, MA. 02142

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

U.S. MAIL

POSTAGE AND FEES PAID
U. S. DEPARTMENT OF TRANSPORTATION
518