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FUEL CONSUMPTION OF TRACTOR-TRAILER TRUCKS AS AFFECTED BY SPEED LIMIT AND PAYLOAD WEIGHT

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FINAL REPORT

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16. Abstract

The effect of speed limit and payload weight on fuel consumption was determined in tests of tractor-trailer rigs. Two virtually identical vehicles were used, one loaded with a 28,000 lb payload and the other carrying 42,000 lbs; each was driven over two different sets of terrain on the Massachusetts Turnpike at simulated speed limits of 50, 55 and 60 mph. Onboard TSC observers recorded data on tank-measured fuel consumption, trip average speed, etc. An analysis of the data led to the following conclusions: (1) Increased fuel consumption results from higher speed limits in the range of 50-60 mph; (2) Terrain is an important factor in determining the effect of speed limit on fuel consumption; (3) A payload increase from 28,000 lbs to 42,000 lbs is carried at no detectable increase in fuel consumption for the "hilly" route, and less than a 7 percent increase in fuel consumption for the route including a crossing of the Berkshire Mountains.

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PREFACE

This brief, intensive study was carried out as part of a larger, long-term project at the DOT Transportation Systems Center. The study was sponsored by the Office of the Secretary of Transportation under Project Plan Agreement OS414. This project, entitled "Automotive Energy Efficiency," is part of a program which includes highway-vehicle systems modeling, gathering of a highway-vehicle technical data base, evaluation of contemporary propulsion system modifications and advanced vehicle studies, all with the objective of reducing transportation-related fossil fuel demands and accelerating the incorporation of effective near-term payoff technology into industrial mass production.

We acknowledge with thanks the help and cooperation of the diverse group of people who made this study successful. We are especially grateful to members of the Energy Conservation Committee of the Massachusetts Motor Truck Association, the drivers Phil Chesbrough and Lowell Crouse, Service and Maintenance personnel of Holmes Transportation, Inc., who were gracious enough to permit the use of their facility as a staging area and the Massachusetts Turnpike Authority for making special provisions for these tests. Maurice Dumais, Arnold Spicer and Jacques Thompson acted as TSC observers during the study and Barbara Kolodziej performed the statistical analyses of the data reported herein; their cooperation and superior performance deserve special thanks.

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1. INTRODUCTION

This report presents the results of an experimental evaluation of the effect of speed limit on fuel consumption for long-haul tractor-trailer trucks. Two virtually identical trucks were used in the experiment, one having a payload of 28,000 lbs and the other carrying 42,000 lbs. The effect of payload weight on fuel consumption was also analyzed.

The experiment was conducted over two types of terrain on the Massachusetts Turnpike which included a route consisting of repeated short hills, of up to 3.5 percent grade and less than two miles long, and a longer route which covered the short route but added a long (7.5 mile) mountain crossing at 3.5 percent grade. Fuel consumption was determined by measuring tank mileage obtained by carefully filling the fuel tanks before and after each trip. (More sophisticated fuel meters were not available on short notice.)

A complete set of all relevant data obtained is presented, to allow others to perform analyses which might be pertinent to their needs. Our analysis of the data is restricted to determining the effects of speed and payload weight on fuel consumption.

2. DESCRIPTION OF TESTS

2.1 VEHICLES

The tests were conducted with two virtually identical long-haul tractor-trailer rigs rented from the Hertz Corporation. Each was driven by a veteran driver with extensive experience in hauling heavy loads over the specific test route. Vehicle specifications are given in Table 2-1. The "light" rig (vehicle 1) was loaded with two concrete blocks, each weighing approximately 14,000 lbs to simulate a payload of 28,000 lbs. The "heavy" rig (vehicle 2), was loaded with three concrete blocks of the same nominal weight. Though the tractor bodies were manufactured by different companies, their general lines and aerodynamic shapes were very similar. Since the vehicles were equipped with identical drive trains, the only significant difference between the two units was a 50 percent greater payload in the heavy vehicle.

2.2 ROUTES

The routes followed in these tests traversed the Massachusetts Turnpike (Interstate 90). The short ("hilly") route began at Natick, Massachusetts (Exit 13) and continued west to Westfield, Massachusetts (Exit 3) and return, a distance of 156 miles. The longer (hills plus mountain) route also began at Natick but extended furter west to West Stockbridge, Massachusetts (Exit 1) and return, a distance of 240 miles. The terrain on the short route, between Natick and Westfield can be described as very hilly, with constantly varying grades up to ± 3.5 percent but of lengths not exceeding about two miles. The long rouge includes the entire short route, but the added distance between West Stockbridge and Westfield consists of a long, steep crossing of the Berkshires which includes a 7.5 mile, 3.5 percent grade. Each of these routes was traveled nine times by each truck, for a total of 36 round trips, with one long trip and one short trip made each day (weather permitting).

TABLE 2-1. VEHICLE SPECIFICATIONS

Tractor	
GMC Cab over engine type, Astro 95 (Vehicle 1)	
Ford Cab over engine type, Ford 9000 (Vehicle 2)	
Fuller RT 9513 Transmission	
1st Gear	12.5:1
2	8.35:1
3	6.12:1
4	4.56:1
5	3.38:1
6	2.86:1
7	2.47:1
8	2.10:1
9	1.81:1
10	1.56:1
11	1.35:1
12	1.16:1
13	1.00:1
Rear Axle:	4.11:1 ratio, Eaton twin-screw SQHD
Engine:	Detroit Diesel 8V71N 318 HP model
Tires:	10.00-22, 504 rev/mile
Trailer:	Square corner, extension ribbed, 45' x 11.5' x 8'
Payload:	28,000 lbs (nominal), Vehicle 1
	42,000 lbs (nominal), Vehicle 2

2.3 TEST METHOD

The test was designed to obtain three values for vehicle fuel consumption at each of three speed limits (50, 55 and 60 mph) on each route, a total of 36 data points. (A mix-up in trip scheduling actually resulted in an unequal data sample at the three speeds.) Each truck had a TSC observer who gathered data during the course of each trip. The drivers were instructed to maintain a speed as close as possible to the (artificially imposed) speed limit, but were allowed to exceed the speed limit by up to 5 mph on downgrades.

In the absence of fuel-metering equipment, tank mileage was used to determine fuel consumption. At the beginning and end of each trip, the twin "saddle" tanks were carefully topped off with No. 2 Diesel Fuel (Winter Blend).

2.4 DATA

Data collected during the experiment are summarized in Tables 2-2 through 2-8. This same data is summarized graphically in Figures 2-1 through 2-6.

2.5 STATISTICAL ANALYSIS

An analysis of variance was performed on the data and is summarized in Table 2-9. The analysis showed the following:

(1) There is a significant difference in the overall mean fuel economy between the two vehicles, and there is less than a 5 percent probability that this difference is due to chance.

(2) There is a significant effect of speed on fuel economy for the average of the two vehicles over the two routes, and there is less than a 1 percent probability that this difference is due to change.

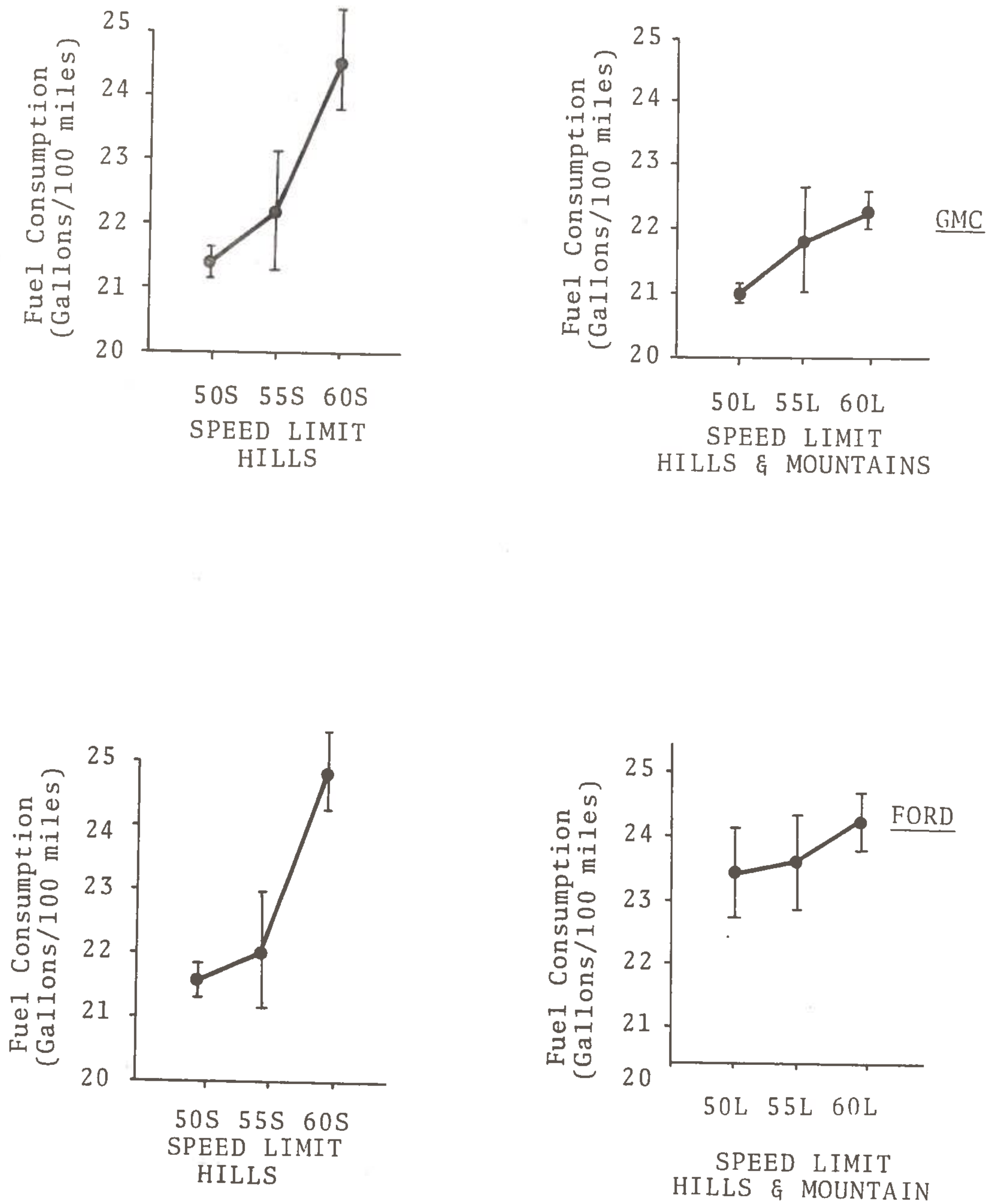


Figure 2-1. Fuel Consumption (Gals/100 Miles) vs. Speed Limit

TABLE 2-2. FUEL CONSUMPTION DATA

	Trip No.	Fuel Consumption (Gallons/100 miles) 50 mph Short Route	55S	60S	50 mph Long Route	55L	60L
Vehicle #1	1						22.96
	2	21.86					
	3		22.37				
	4				21.08		
	5	21.15					
	6					21.67	
	7			25.35			
	8					23.33	
	9		23.72				
	10						22.38
	11			23.72			
	12				20.92		
	13					20.50	
	14	20.84					
	15						21.84
	16		20.45				
	17	21.79					
	18						22.09
	Mean ± 1 std dev	21.41±0.5	22.18±1.64	24.54±1.15	21.00±0.11	21.83±1.42	22.32±0.48
	± 1 std error	±0.25	±0.95	±0.81	±0.08	±0.82	±0.24
Vehicle #2	1						25.13
	2	21.09					
	3		21.34				
	4				22.30		
	5	21.85					
	6					22.47	
	7			25.48			
	8					24.6	
	9		23.85				
	10						23.38
	11			24.23			
	12				23.67		
	13					22.38	
	14	21.22					
	15						23.45
	16		20.9				
	17	22.17					
	18						23.25
	Mean ± 1 std dev	21.58±0.51	22.03±1.59	24.86±0.88	22.99±0.97	23.15±1.26	23.80±0.89
	± 1 std error	±0.26	±0.92	±0.62	±0.69	±0.73	±0.45

TABLE 2-3. GEAR SHIFTING TEST DATA

	Trip No.	Number of Shifts (Both Up and Down)					
		50 mph Short Route	55S	60S	50L	55L	6ØL
Vehicle #1	1						186
	2	134					
	3		128				
	4				129		
	5	104					
	6					241	
	7			172			
	8					240	
	9		197				
	10						261
	11			225			
	12				197		
	13					239	
	14	129					
	15						213
	16		147				
	17	110					
	18						217
	Mean ±1 std dev ±1 std error	119.25±14.5 ±0.73	157.33±35.64 ±20.57	198.50±37.48 ±26.50	163.00±48.08 ±34.0	240.0±1.0 ±0.58	219.25±31.05 ±15.53
Vehicle #2	1						
	2	238					
	3		213				
	4				263		
	5	190					
	6					311	
	7			178			
	8					304	
	9		234				
	10						342
	11			257			
	12				355		
	13					355	
	14	224					
	15						302
	16		244				
	17	219					
	18						286
	Mean ± 1 std dev ± 1 std error	217.75±20.17 ±10.09	230.33±15.82 ±17.91	217.50±55.86 ±39.49	309.0±65.05 ±46.0	323.33±27.65 ±15.96	283.75±57.54 ±28.77

TABLE 2-4. TIME IN ELEVENTH GEAR TEST DATA

GMC Trip No.	Time In 11th Gear (minutes) 50S	55S	60S	50L	55L	60L
1						29.08
2	42.95					
3		30.78				
4				56.18		
5	31.88					
6					31.42	
7			25.42			
8					40.53	
9		24.67				
10						30.83
11			26.80			
12				48.38		
13					28.50	
14	50.60					
15						35.08
16		26.03				
17	34.42					
18						39.07
Mean ± 1 std dev	39.96±8.53	27.16±3.21	26.11±0.98	52.28±5.52	33.48±6.27	33.52±4.48
± 1 std error	±4.27	±1.73	±0.69	±3.90	±3.62	±2.24
Ford Trip No.						
1						41.57
2	34.08					
3		30.92				
4				48.60		
5	35.22					
6					34.32	
7			28.50			
8					65.22	
9		32.45				
10						35.25
11			26.38			
12				45.28		
13					35.23	
14	31.12					
15						39.95
16		29.20				
17	33.30					
18						35.50
Mean ± 1 std dev	33.43±1.73	30.86±1.63	27.44±1.50	46.94±2.35	44.92±17.58	38.07±3.18
± 1 std error	±0.87	±0.94	±1.06	±1.66	±10.15	±1.59

TABLE 2-5. TIME IN TWELFTH GEAR TEST DATA

GMC Trip No.	Time in 12th Gear (minutes)					
	50S	55S	60S	50L	55L	60L
1						52.22
2	129.03					
3		56.75				
4				210.85		
5	154.30					
6					54.52	
7			54.58			
8					70.57	
9		43.57				
10						60.77
11			110.33			
12				205.68		
13					65.07	
14	144.32					
15						59.73
16		45.33				
17	144.67					
18						47.48
Mean ± 1 std dev	143.08±10.45	48.55±7.16	82.46±39.42	208.27±3.66	63.39±8.16	55.05±6.32
± 1 std error	±5.23	±4.13	±27.87	±2.59	±4.71	±3.16
Ford Trip No.						
1						57.53
2	101.62					
3		42.92				
4				173.38		
5	120.83					
6					83.58	
7			42.70			
8					65.47	
9		40.07				
10						48.33
11			38.35			
12				161.12		
13					66.33	
14	107.32					
15						43.77
16		36.63				
17	109.70					
18						46.98
Mean ± 1 std dev	109.87±8.06	39.87±3.15	40.53±3.08	167.25±8.67	71.79±10.22	49.15±5.90
± 1 std error	±4.03	±1.82	±2.18	±6.13	±5.90	±2.95

TABLE 2-6. TIME IN THIRTEENTH GEAR TEST DATA

GMC Trip No.	Time in 13th Gear (minutes) 50S	55S	60S	50L	55L	60L
1						138.63
2	6.35					
3		80.75				
4				8		
5	-0					
6					167.92	
7			97.13			
8					149.02	
9		106.83				
10						150.55
11			166.92			
12				10.83		
13					169.97	
14	4.33					
15						164.93
16		104.37				
17	3.92					
18						163.80
Mean ± 1 std dev ± 1 std error	3.65±2.66 ±1.33	97.32±14.4 ±8.31	132.03±49.35 ±34.90	9.42±2.00 ±1.414	162.30±11.55 ±6.67	154.48±12.42 ±6.21
Ford Trip No.						
1						140.25
2	28.48					
3		91.95				
4				24.33		
5	13.42					
6					120.47	
7			94.42			
8					135.67	
9		90.85				
10						139.57
11			91.90			
12				27.65		
13					129.67	
14	26.20					
15						145.68
16		98.38				
17	14.93					
18						84.03
Mean ± 1 std dev ± 1 std error	20.76±7.68 ±3.84	93.73±4.07 ±2.35	93.16±1.78 ±1.26	25.99±2.35 ±1.66	128.60±7.66 ±4.42	127.38±29.03 ±14.52

TABLE 2-7. MEDIAN TEMPERATURE TEST DATA

Both Vehicles are the same Trip No.	50S	55S	60S	50L	55L	60L
1						-10
2	-2.5					
3		0				
4				+3		
5	+3					
6					+1	
7			-11			
8					-12	
9		-15				
10						-9
11			0			
12				+2.5		
13					+6	
14	+7					
15						+8
16		+12				
17	+4					
18				+8		

TABLE 2-8. AVERAGE SPEED TEST DATA

GMC Trip No.	Trip Avg. Speed (MPH) 50S	55S	60S	50L	55L	60L
1						48.81
2	44.78					
3		48.50				
4				45.00		
5	44.57					
6					46.91	
7			50.92			
8					48.32	
9		48.50				
10						48.28
11			50.60			
12				44.18		
13					48.00	
14	45.86					
15						51.18
16		49.26				
17	46.57					
18						51.18
Mean ± 1 std dev	45.45±0.94	48.75±0.44	50.76±0.23	44.59±0.58	47.74±0.74	49.86±1.54
± 1 std error	±0.47	±0.25	±0.16	±0.41	±0.43	±0.77
Ford Trip No.						
1						44.86
2	44.83					
3		45.73				
4				45.18		
5	43.81					
6					46.56	
7			49.58			
8					44.81	
9		45.66				
10						48.81
11			49.26			
12				43.64		
13					45.28	
14	43.74					
15						48.41
16		45.22				
17	44.86					
18						49.03
Mean ± 1 std dev	44.31±0.62	45.54±0.28	49.42±0.23	44.41±1.09	45.55±0.91	47.78±1.96
± 1 std error	±0.31	±0.16	±0.16	±0.77	±0.53	±0.98

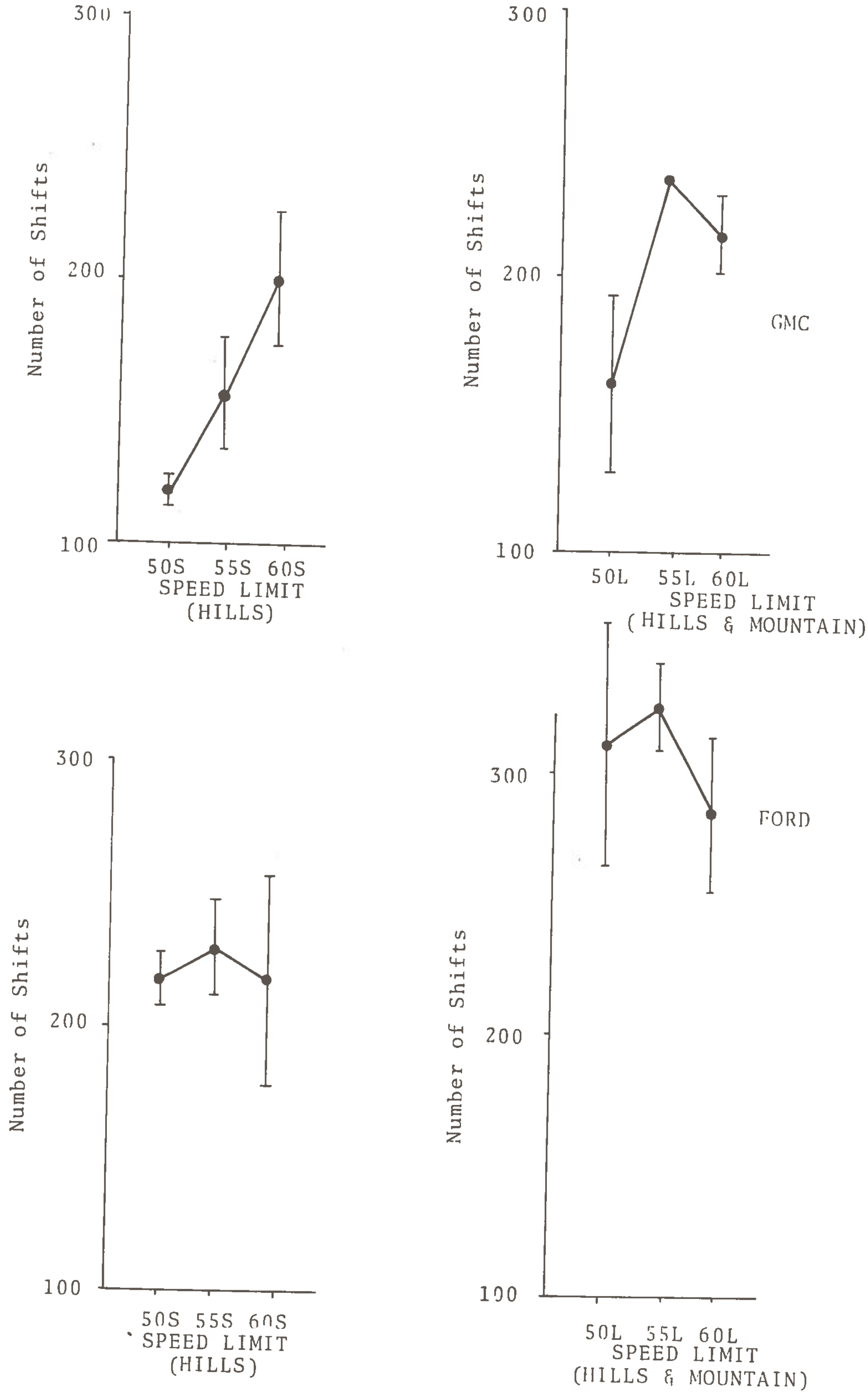


Figure 2-2. Number of Shift vs. Speed Limit

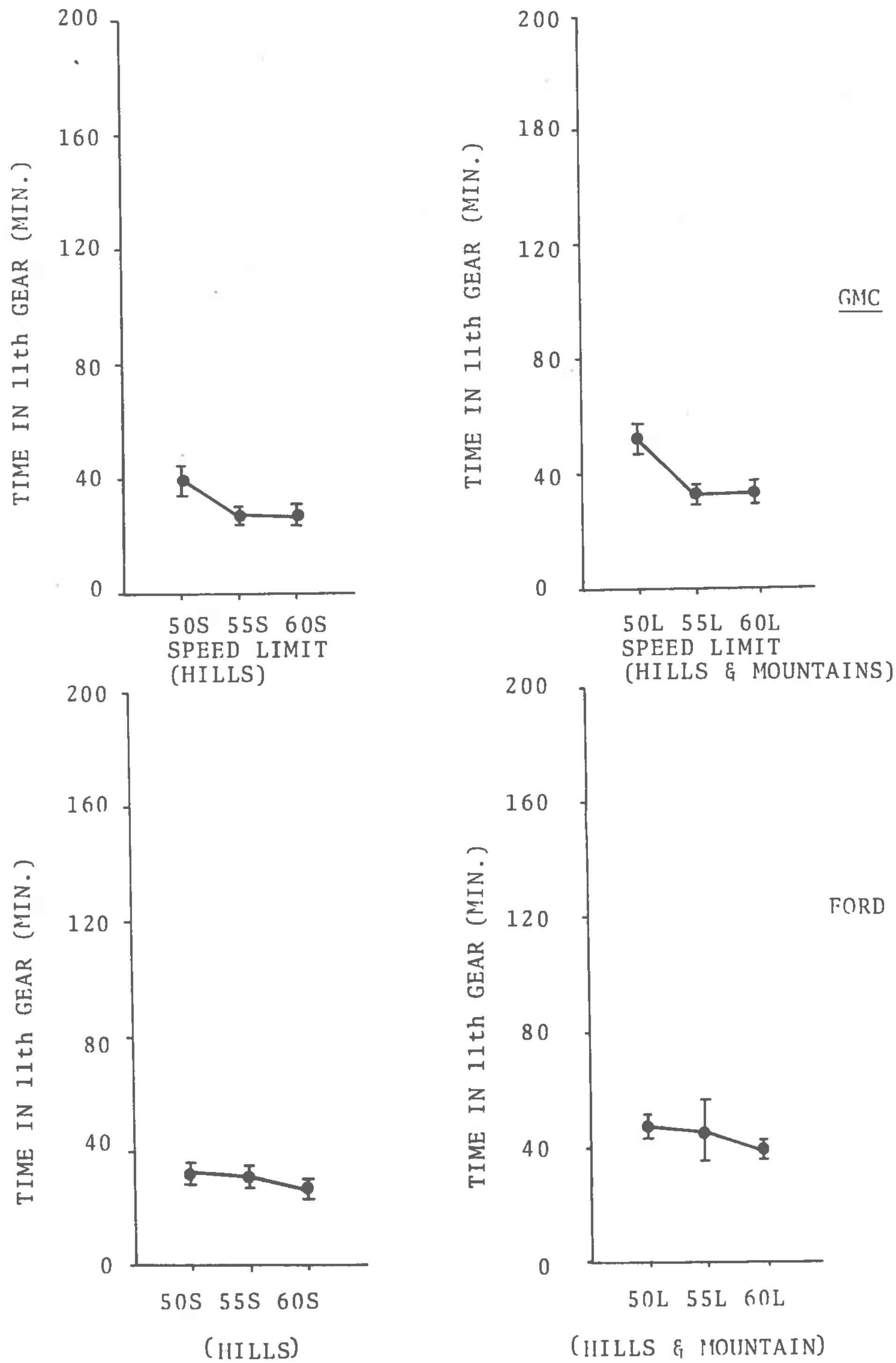


Figure 2-3. Time in 11th Gear (Min.) vs. Speed Limit

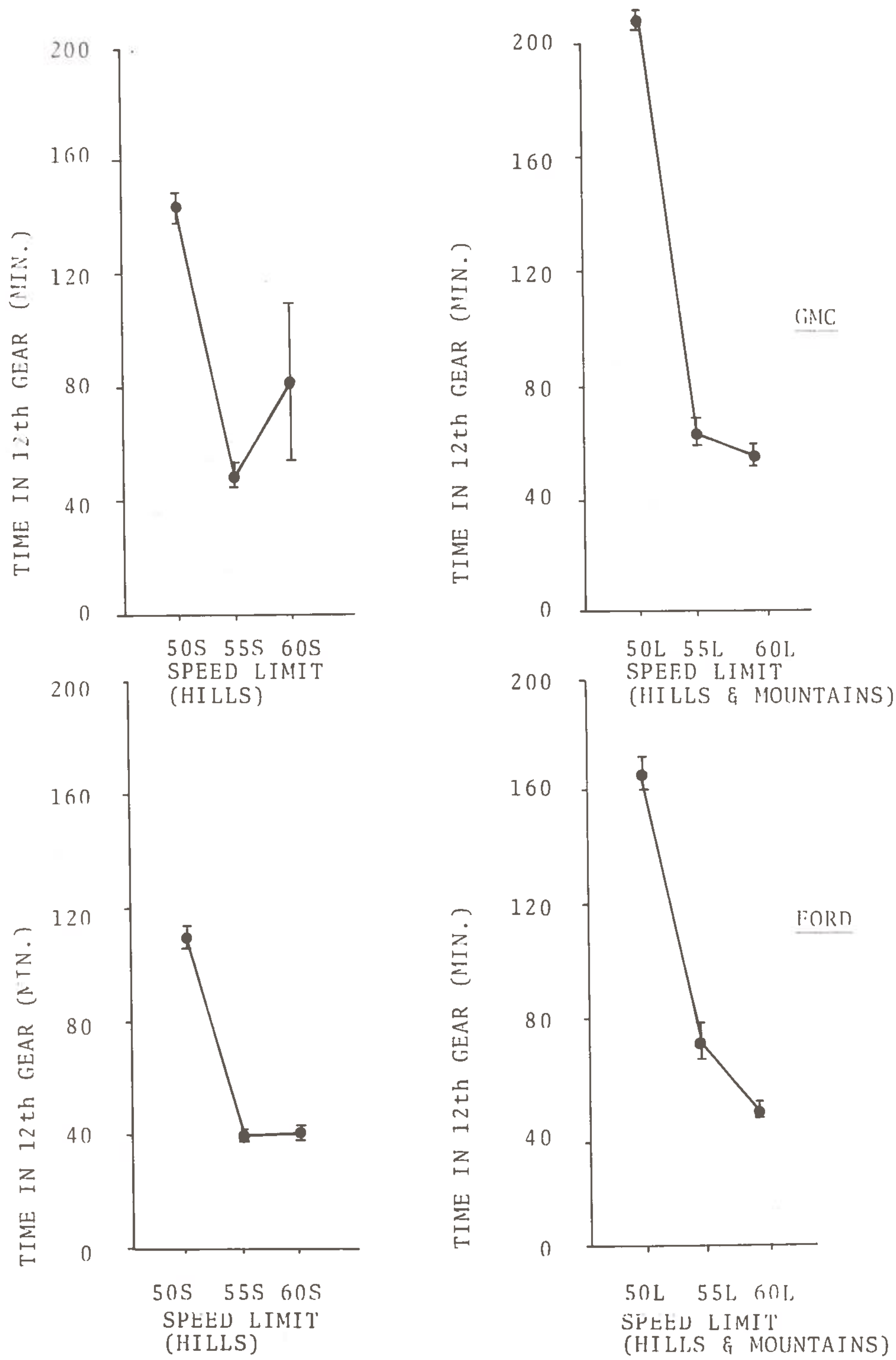


Figure 2-4. Time in 12th Gear (Min.) vs. Speed Limit

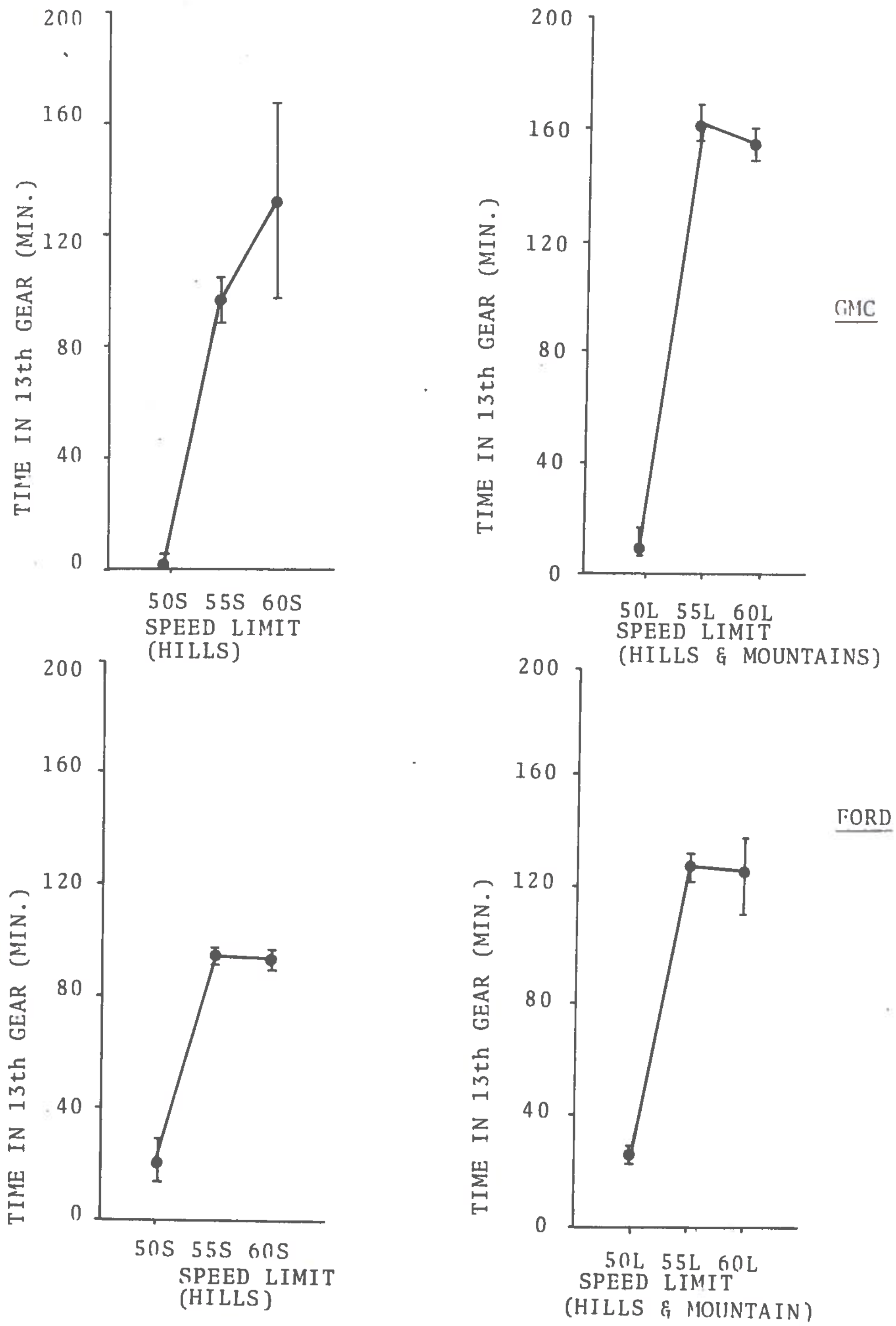


Figure 2-5. Time in 13^{th} Gear (Min.) vs. Speed Limit

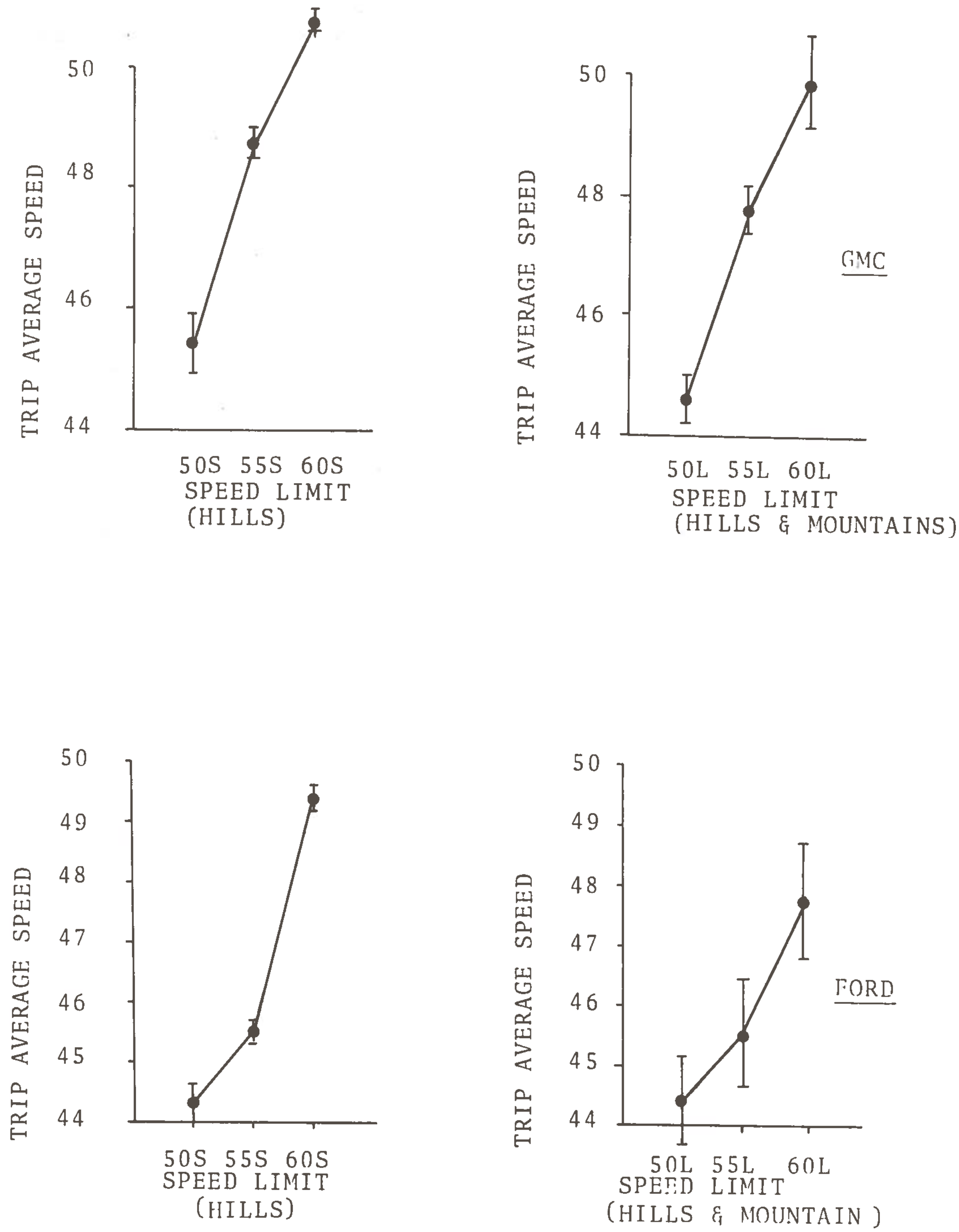


Figure 2-6. Trip Average Speed (MPH) vs. Speed Limit

TABLE 2-9. ANALYSIS OF VARIANCE SUMMARY

Source	SS	df	MS	F	p
Trucks	6.09476	1	6.09476	5.78	<.05
Speed	27.24720	2	13.62360	12.91	<.01
Route	0.52414	1	0.52414	0.50	--
Trucks x Speed	0.35061	2	0.17531	0.17	--
Trucks x Route	4.57557	1	4.57557	4.34	<.05
Speed x Route	8.00768	2	4.00384	3.79	<.05
Trucks x Speed x Route	0.14592	2	0.07296	0.07	--
Error	25.32597	24	1.05525	--	--

SS = Sum/Squares

df = Degrees of Freedom

MS = Mean Square

F = F-Ratio

p = Significance Level

TABLE 2-10. SIMPLE MAIN EFFECTS, VEHICLES X ROUTES

Source	SS	df	MS	F	p
Vehicles on Short Trip	.054349	1	.054349	.5	
Vehicles on Long Trip	10.61599	1	10.61599	10.06	<.01
Trip at Vehicle 1	4.09850118	1	4.09850118	3.88	<.10
Trip at Vehicle 2	1.00121978	1	1.00121978	.95	
Within Cell	25.32597	24	1.05525		

TABLE 2-11. SIMPLE MAIN EFFECTS, SPEED X ROUTES

Source	SS	df	MS	F	p
Speed on Short Route	32.11	2	16.06	15.22	<.01
Speed on Long Route	3.17	2	1.59	1.51	<.25
Long Route at 50 mph	.70	1	.70	.66	
Long Route at 55 mph	.42	1	.42	.40	
Long Route at 60 mph	7.42	1	7.42	7.03	<.05
Within Cell	25.32597	24	1.05525		

(3) There is a significant difference in the behavior of the fuel economy of the individual vehicles as averaged over all speeds, on the two different types of terrain, and there is less than a 5 percent probability that the observed difference is due to chance.

(4) There is significant difference in the fuel economy vs. speed characteristics of vehicles on the two different types of terrain, and there is less than a 5 percent probability that this difference is due to chance.

The analysis of variance was then carried further to more precisely pinpoint the nature of the significance of these variables. Tables 2-10 and 2-11 are tabulations of determinations of simple main effects for the vehicle x trip interaction (3, above) and the speed x trip interaction (4, above). Tables 2-12 and 2-13 are summaries of the Newman-Keuls tests performed to determine the level of significance of the differences among fuel economies achieved on the short (hilly) route and the significance of differences in averaged fuel economies at different speeds.

From these tests, it is evident that speed was the primary variable in determining fuel consumption. Further, fuel consumption did not vary significantly with speed limit on the route which included hills and mountains, but speed was significant on the short, hilly route. The two vehicles had nearly identical fuel-consumption vs. speed characteristics on the short route, but vehicle no. 2 had significantly higher fuel consumption than vehicle no. 1 over the longer route. This last interaction led to a significantly higher overall fuel consumption for vehicle no. 2.

TABLE 2-12. NEWMAN-KEULS TEST, SPEED ON SHORT TRIP

Order	1	2	3
$\bar{X}$	21.50	22.11	24.60
Truncated range	2	3	
q. 95 (v, 24)	2.92	3.53	
q. 99 (v, 24)	3.96	4.54	
q. 95 (v, 24) $\sqrt{\frac{MS\ error}{\bar{n}_n}}$	1.81	2.19	
q. 99 (v, 24) $\sqrt{\frac{MS\ error}{\bar{n}_n}}$	2.46	2.81	

$$\sqrt{\frac{MS\ error}{\bar{n}_n}} = .62$$

MPH	MPH 50	MPH 55	MPH 60
50	-	.61	3.10
55		-	2.49
60			.

MPH	MPH 50	MPH 55	MPH 60
50	-	NS	$p<.01$
55		-	$p<.01$

TABLE 2-13. NEWMAN-KEULS TEST, SPEED

Order	1	2	3
$\bar{X}$	21.7	22.3	23.9
v	2	3	
$q_{.95}(v, 24)\sqrt{MS\ error/\bar{n}_n}$	1.81	2.19	
$q_{.99}(v, 24)\sqrt{MS\ error/\bar{n}_n}$	2.46	2.81	

MPH	MPH 50	MPH 55	MPH 60
50	-	.60	2.20
55		-	1.60
60			-

MPH	MPH 50	MPH 55	MPH 60
50	-	NS	p<.05
55		-	NS
			-

3. DISCUSSION OF RESULTS

These tests clearly demonstrate the increased fuel consumption associated with higher speed for long-haul tractor-trailer rigs. When terrain similar to the longer route (including a steep mountain crossing) is encountered, there is a weaker relationship between speed limit and fuel consumption, since the vehicles are slowed by the long grade. On the shorter route, however, which covers smaller hills, the average of the two trucks shows a fuel savings of about 2 percent per mile per hour slowdown between 60 and 55 mph. Understandably, only an additional 0.6 percent per mile per hour showdown from 55 to 50 mph can be expected. The difference between the fuel consumption values at 50 and 55 mph has been shown to be statistically insignificant. The differences in reported fuel consumption between 50 and 60 mph, and 55 and 60 mph are significant, though, with less than a 1 percent probability that these differences are due to chance.

Since the only real difference between the two vehicles was payload weight, it is of interest to examine the effect of increased weight on fuel consumption. Assuming that weight was the only significant difference, and no other effects went undetected, a 50 percent greater payload produced no significant effect on fuel economy over the short ("hilly") route. Averaged over all speeds on the long route (which included a mountain crossing), the 50 percent increase in payload was carried at the expense of less than a 7 percent increase in fuel consumption.

Though these tests were not conducted over flat terrain, it is reasonable to expect that the observed differences in fuel consumption would follow the same general trends as were observed in going from a route including hills and a mountain crossing to one with only hills. Thus, we would expect significant fuel savings if speed limits were lowered from 60 mph to 55 mph, but less significant savings for a speed limit of 50 mph on flat terrain. In regard to payload weight, we would not expect to be able to detect any significant difference in fuel consumption between a 28,000 lb payload and a 42,000 lb payload of a similar test were conducted on level terrain. This is not to say that there is no increased fuel consumption due to extra payload, only that this difference would fall within experimental errors.

4. CONCLUSIONS

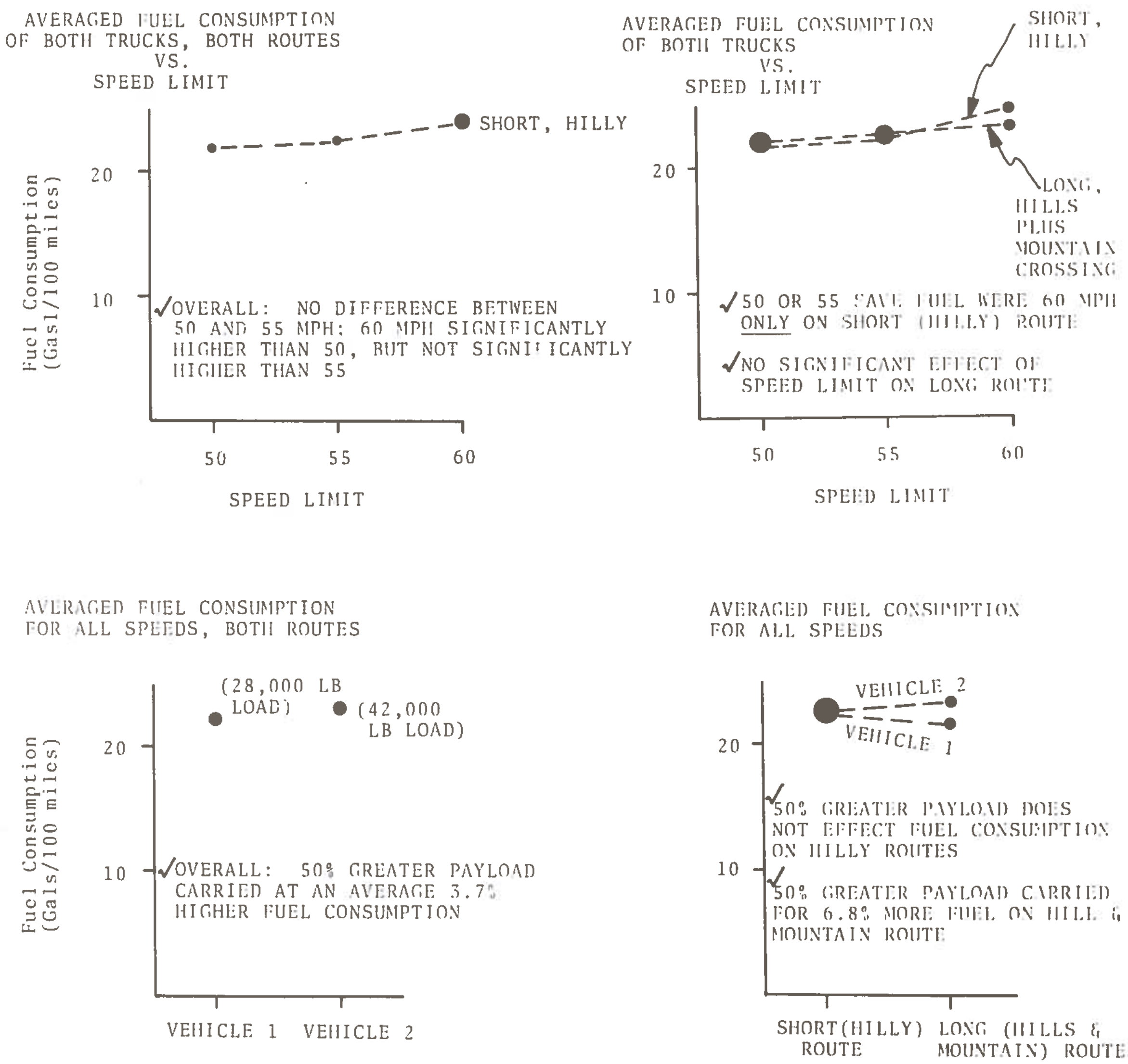
Increased fuel consumption results from higher speed limits in the range to 50 - 60 mph. Lowering the speed limit from 60 to 55 mph on hilly terrain (typical of the eastern half of the Massachusetts Turnpike) would result in a savings of over 10 percent in fuel for these vehicles; further reduction to 50 mph would add less than 3 percent to that saving.

Terrain is an important factor in determining the effect of speed limit on fuel consumption. There is a much weaker correlation between speed limit and fuel consumption for tractor-trailers on routes similar to the western half of the Massachusetts Turnpike, which includes a mountain crossing.

A payload increase from 28,000 lbs to 42,000 lbs is carried at no detectable increase in fuel consumption for the "hilly" route, and less than a 7 percent increase in fuel consumption for the route including a crossing of the Berkshires.

5. SUMMARY

The effect of speed limit and payload weight on fuel consumption was determined in tests of tractor-trailer rigs. Two virtually identical vehicles were used, one loaded with a 28,000 lb payload and the other carrying 42,000 lbs; each was driven over two different sets of terrain on the Massachusetts Turnpike at simulated speed limits of 50, 55 and 60 mph. Onboard TSC observers recorded data on tank-measured fuel consumption, trip average speed, etc. An analysis of the data, summarized in Figure 5-1, led to the following conclusions: (1) Increased fuel consumption results from higher speed limits in the range of 50 - 60 mph. (2) Terrain is an important factor in determining the effect of speed limit on fuel consumption. (3) A payload increase from 28,000 lbs to 42,000 lbs is carried at no detectable increase in fuel consumption for the "hilly" route, and less than a 7 percent increase in fuel consumption for the route including a crossing of the Berkshires.



WIDTH OF DATA POINTS INCLUDES ± 1 STD. ERROR OF MEAN

SUMMARY OF DATA

Figure 5-1. Data Summary - Fuel Consumption vs. Speed and Route