TRACTION AND STABILITY OF FRONT, REAR, AND FOUR-WHEEL DRIVE TRUCKS ON LAKE ICE, SERIES OF 1949

A. H. EASTON, *Director, Truck Research Project, University of Wisconsin*

SYNOPSIS

This report describes the behavior of vehicles on an ice tangent or curve with brakes or excess torque applied to the front, rear, and each of the four wheels Each condition is analyzed on the basis of the forces acting on the vehicle. The analyses are compared with the actual behavior of each vehicle on the ice, and the following conclusions are drawn

1. A stable vehicle may be defined as one which has zero moments acting on it in a horizontal plane when the driving wheels are locked or spinning. The front wheel drive vehicle is unstable in a clockwise direction when the vehicle is making a left hand curve; this characteristic causes the vehicle to hold its course on a straightaway, but when on a curved highway to go off the road
2. The rear drive vehicle is unstable in a counterclockwise direction when making a left hand curve. This characteristic causes it to go into a flat spin either on a curve or on a straightaway if subjected to even slight lateral forces
3. The four wheel drive vehicle for both braking and excess torque application has a relatively small net moment in the clockwise direction when making a left hand curve which causes it to hold its course on the straightaway, when on a curve, the moment is not so large as to throw the vehicle off the curve on a tangent

Following the analyses of each type of drive, data are presented on the drawbar pull of front, rear and four wheel drive vehicles on ice with various loads under static, spinning, and dynamic conditions. From these data the coefficients of traction are computed which are applied to the design of a vehicle for maximum drawbar pull The stability and traction of each type of drive may be summarized as follows·

1 Although the behavior of front wheel drive is good on the straightaway, it is undesirable on a curve. The traction provided by front wheel drive is a minimum for load distributions normally encountered in trucks
2 The rear wheel drive vehicle while superior to front wheel drive in traction, is apt to go into a flat spin when excess torque is applied to the driving wheels.
3. The four wheel drive vehicle with the torque and load distribution properly equalized provides the maximum traction, which in itself makes for a safer vehicle because the likelihood of the wheels losing traction is reduced. Further, with this type of drive, the vehicle is capable of holding its course on the straightaway and on a curve moves sideways if the wheels lose traction This is a definite advantage in regaining control
4. From the above conclusions and observations it follows that of the three types of drive, the four wheel drive offers a maximum of safety on an icy surface by providing a maximum of stability and traction.

As a part of the Truck Research Project established at the University of Wisconsin by grants from The Four Wheel Drive Auto Company of Clintonville, Wisconsin, tests were conducted on lake ice to determine the behavior and traction of trucks with various types of drive and to determine fundamental information relative to the tractive coefficients of friction on ice. These tests fall under the first two of the five phases of the Truck Research Project which are as follows: safety, engineering performance, fuel economy, special tests, and instruction and demonstration.

Because of the many inherent hazards involved in this type of testing on the highway, and even more important the traffic hazards created by attempting ice tests on the highway, it is almost imperative that such tests be conducted on lake ice. Figure 1 shows a one-quarter mile long course, 300 ft. wide prepared on Pine Lake near Clintonville by the Four Wheel Drive Auto Company. After the snow was removed, the ice was shaved and swept with a power broom which produced an ice surface free from sand and dirt and as smooth or smoother than road ice. The area cleared was large enough to permit loss of vehicle control without undue danger to personnel or equipment. The thickness of the ice was 16 to 20 in. during the tests.

FINDINGS AND CONCLUSIONS

The results of tests relative to safety and stability, although they were obtained with heavy duty trucks, nevertheless apply directly to all automotive vehicles supported by four wheels. The following findings are based on braking tests on an ice tangent:

1. Locking only the rear wheels produced an unstable condition resulting in partial or complete loss of control of the vehicle.

Figure 1. Aerial View of Test Course on Pine Lake Near Clintonville, Wisconsin

2. Locking only the front wheels produced a condition in which the vehicle traveled on a straight path, which coincided with the centerline of the vehicle frame. Under this condition there was almost complete loss of steering control.

3. Locking all four wheels produced a condition of near equilibrium. The vehicle traveled a path which coincided with the direction of motion of the center of gravity at the time the brakes were applied unless acted on by forces resulting from variation in the coefficient of friction at each of the wheels.

The following findings are based on travel on an ice tangent or curve:

1. When one or both of the rear wheels were caused to break traction (spin) by application of more torque than the coefficient of friction would support, the vehicle became unstable and eventually went out of control. This condition was aggravated by a high power to weight ratio.

2. When one or both of the front wheels were caused to break traction, the vehicle traveled a path which coincided with its longitudinal centerline.

3. When all four wheels were subjected to sufficient torque to break traction, the vehicle traveled in the direction of the instantaneous motion of the center of gravity.

Drawbar pull tests on lake ice revealed the following comparative information on the types of drive:

1. The greatest difference in drawbar pull on ice between a four-wheel drive and a rear-wheel drive was shown at no load where the load distribution to front and rear axles is nearly equal. The four-wheel drive truck with the center differential unlocked was able to exert as much as 82 percent more drawbar pull than the rear-wheel drive.

2. With a 24–76 load distribution (24 percent to the front axle and 76 percent to the rear axle) on the rear-wheel drive truck and a 39–61 distribution on the four-wheel drive truck (CDU)[1], the drawbar pull of each truck on ice for coefficients of friction below 0.1 was very nearly equal; above this value the rear-wheel drive exceeded the four-wheel drive in drawbar pull for this load.

3. With a 32–68 load distribution, which is in accord with the recent trend in the rear-wheel drive industry, and a 39–61 load distribution on the four-wheel drive truck (CDU), and a 50–50 torque distribution, the drawbar pull of the four-wheel drive truck was 15 percent more at a coefficient of friction of 0.1.

4. Using the four-wheel drive truck having a gross vehicle weight (G.V.W.) of 20,925 lb. and load distribution of 39–61 as a four-wheel drive with the center differential unlocked, the static drawbar pull was 2100 lb.; as a four-wheel drive center differential locked, 2600 lb.; as a rear-wheel drive, 1870 lb.; and as a front-wheel drive, 1180 lb.

Because there is reasonable agreement in most cases between the values of the coeffi-

[1] CDU—center differential unlocked. The torque distribution in this case was 50 percent to the front axle and 50 percent to the rear axle. This distribution places the four-wheel drive vehicle at a disadvantage.

cients of friction for each of the types of drive, it is possible then to compare the drawbar pull of any vehicle under any load if the coefficient of friction and the load on the driving wheels are known The following projected conclusions are based on this information and will be verified by future tests:

1. The optimum drawbar pull with any truck would be expected with all wheels driving and the torque distribution to the front and rear axle equal to the instantaneous load distribution.

2. The drawbar pull of a four-wheel drive truck with the center differential locked lies between the upper limit set by conditions in the preceding paragraph and the lower limit set with center differential unlocked If the wheels are spun, however, the maximum drawbar pull is obtained with the center differential locked, because as soon as this occurs the torque distribution automatically becomes equal to the load distribution.

3 By proper selection of the torque distribution to the front and rear axles relative to the load distribution, it would be possible to obtain a drawbar performance which would approach the theoretical maximum

4. The four-wheel drive truck has practical potential drawbar pull equal to 1 4 times that of the rear-drive truck and 3 3 times that of a front-wheel drive truck for the same load distributed in the same way (33 3–66 7)

5 With the proper torque distribution the gradeability of a four-wheel drive straight truck is expected to exceed that of a rear-wheel drive straight truck, each with the recommended load distribution and the same G V W., by 22 percent at a coefficient of friction of 0 1

6. With the proper torque distribution the gradeability of a four-wheel drive tractor and semi-trailer is expected to exceed that of a rear-wheel drive unit, each with the recommended fifth wheel location and the same G V W , by 23 percent at a coefficient of friction of 0 1

Summarizing with regard to the three types of drive, although the behavior of front-wheel drive is good on the straightaway, it is undesirable on a curve The traction provided by front-wheel drive is a minimum for load distributions normally encountered in trucks. The rear-wheel drive, while superior to front-wheel drive in traction, is apt to go into a flat spin when excess torque is applied to the driving wheels either on a straightaway or curve The four wheel drive vehicle with the torque and load distribution properly equalized provides the maximum traction, which in itself makes for a safer vehicle because the likelihood of the wheels losing traction is reduced Further, this type of drive is not only capable of holding its course on the straightaway, but also the vehicle moves sideways on a curve if the wheels lose traction This is a definite advantage in regaining control From the above conclusions and observations it follows that of the three types of drive, the four-wheel drive offers a maximum of safety on an icy surface by providing a maximum of stability and traction

The drawbar pull tests gave the following fundamental information which applies to safety in the operation of a motor vehicle on ice

1 The drawbar pull available below 32 F. with the drive wheels spinning was as little as 10 percent of that under static conditions

2 The dynamic coefficient of friction or that obtained with the vehicle in motion was 50 to 90 percent of the static coefficient

3 The static coefficient ranged from 0 10 to 0 41, the spinning coefficient ranged from 0 02 to 0 09 The dynamic coefficient varied from 0 13 to 0 30, however, the latter value was not measured under the most adverse conditions

4 As expected, the above data show that maximum traction on ice was achieved only when the wheels were not spinning

5 The static coefficient on ice where free water was present approached the value of the spinning coefficient. This emphasizes the need for extreme caution on wet ice.

6 With the driving wheels equipped with premium chains the outstanding differences as compared with bare tires were that the values of the static coefficient increased as much as 100 percent, and the spinning and dynamic values approached the value of the static coefficient

VEHICLES AND INSTRUMENTATION

The test vehicles used in this study were a representative commercial four-wheel drive truck, and a representative commercial rear-wheel drive truck They are as nearly alike in capacity, engine power, gear ratio, and tires as could be expected of two vehicles manufactured by different firms. The two trucks are shown in Figure 2, and the characteristics of each are given in Table 1.

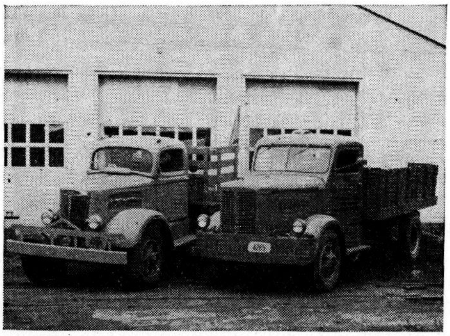

Figure 2. The Test Vehicles. Left, Rear-Wheel Drive. Right, Four-Wheel Drive

TABLE 1
VEHICLE CHARACTERISTICS

	Four-Wheel Drive	Rear-Wheel Drive
Gross Vehicle Weight, lb.	20,000	22,000
Dry Chassis Weight w/cab, lb.	8,000	8,019
Net Vehicle Weight, w/cab & body, lb.	9,445	9,380
Wheelbase, in.	144	160
C. A. Dimension, in.	$79\frac{1}{2}$	$84\frac{1}{4}$
Drive	4 × 4	4 × 2
Tire Size	9.00 x 20	9.00 x 20
Engine		
Type	L Head	L Head
Maximum bhp	129 at 2800 rpm.	125 at 2800 rpm.
Maximum torque, lb-ft.	290 at 1100 rpm.	285 at 1400 rpm.
Bore and stroke, in.	$4\frac{1}{2} \times 4\frac{3}{4}$	$3\frac{7}{8} \times 5\frac{1}{8}$
Number of cylinders	6	6
Displacement, cu. in.	404	362
Compression ratio	5.62:1	6.28:1
Clutch		
Type	Single plate, dry disc	Single plate, dry disc
Outside diameter of facing, in.	$13\frac{7}{8}$	$13\frac{7}{8}$
Transmission Ratios		
1st Gear	5.82:1	7.00:1
2nd Gear	3.13:1	3.97:1
3rd Gear	1.75:1	1.90:1
4th Gear	1.00:1	1.00:1
5th Gear	0.818:1	0.788:1
Reverse	6.07:1	7.00:1
Transfer Case Ratio	1.35:1	
Overall Gear Ratios		
1st Gear	41.45:1	49.98:1
2nd Gear	22.28:1	28.35:1
3rd Gear	12.47:1	13.56:1
4th Gear	7.12:1	7.14:1
5th Gear	5.83:1	5.63:1
Reverse	43.25:1	49.98:1
Brakes	Hyd. Vacuum	Hyd. Vacuum
Frame		
Size, in.	$9 \times 3 \times \frac{1}{4}$	$8\frac{1}{8} \times 3\frac{1}{16} \times \frac{5}{16}$
Section modulus of each side channel, in.^{3}	9.1	9.9

In addition to the characteristics given in the table it is noted that the four-wheel drive truck has a center differential between the front and rear axles. This differential allows relative motion between the front and rear drive shafts, thus preventing a build up of torque in the power train when operating on a surface with a high coefficient of friction. This vehicle may also be operated with the center differential locked (CDL), which prevents relative motion between the front and rear drive shafts. The lock is used when operating on a surface with a low coefficient of friction.

Figure 3 shows an interior view of a field dynamometer for measuring drawbar pull. The field dynamometer as a unit consists of a GMC $2\frac{1}{2}$-ton 6 by 6 chassis, an absorption unit, and a strain gage drawbar connected through an amplifier to a recording oscillograph. The absorption unit although not essential for ice tests is a Warner Electric retarder capable of absorbing up to 128 bhp. at 3000 rpm. It is connected to the power train of the truck by means of a heavy duty power take off fastened to the transmission. The power take off is in turn connected to the absorption unit by drive shaft and a 4-in. silent chain.

Figure 3. Inside View of Field Dynamometer Showing Recording Equipment

The strain gage drawbar, which is of the direct tension type, is fitted with two bonded strain gages and has a capacity of 20,000 lb. Two inactive strain gages form the other two legs of the electric strain gage bridge. The oscillator of the strain gage control unit imposes approximately one volt at 2000 cycles per second on the input of the strain gage bridge. The output of the bridge is then amplified in the control unit. This output when imposed on the terminals of a suitable galvanometer in the oscillograph produces a deflection of the "light spot" which may be viewed directly or recorded on photographic paper. In order that the deflection caused by a load may have a definite relation to the deflection of the "light spot," known loads are imposed on the drawbar in the laboratory After it is determined that the load against deflection curve is a straight line, it is possible to find the value of a calibrating resistance in terms of the load units By using a calibrating resistance of the proper value it is possible to use the same drawbar for several ranges of operation. For the tests on ice the value of the calibrating resistance was 2970 lb Thus, with a deflection of 80 mm. at this load and being able to read to the nearest 0.2 mm., it is possible to determine loads to the nearest $\left(\frac{2970}{80} \times 0\ 2\right)$ 7 lb.

DISCUSSION

From observation of previous tests conducted on lake ice and operation under icy highway conditions, it was noted that there were considerable differences between the stabilities of the various types of drive after skidding began. A demonstration of braking on a miniature automobile by Mr. T J Carmichael of General Motors Proving Ground also called attention to the probable differences.

To study the differences the rear-wheel drive truck was used for rear-wheel drive, and the four-wheel drive truck was arranged so that brakes and power could be applied to the front and rear axles separately and in combination. This vehicle was used to demonstrate front and four-wheel drive

Two types of demonstrations were employed to show relative stability, namely, the locking of the brakes on the straightaway and the application of excess torque, both on the straightaway and on a curve. It was found that if only the rear wheels were locked on a straightaway, this condition was unstable and soon resulted in loss of control characterized by rotation about a vertical axis. In the analysis of this action, and of all other actions in this category, it is well to remember that a rolling wheel is capable of resisting forces perpendicular to the plane of rotation, and a locked wheel is non-directional in its ability to resist forces.

As the brakes are applied to the rear wheels and sliding takes place, the external forces acting on the vehicle are those shown in Figure 4 A. Under this condition the sum of the moments acting about the center of gravity is zero, and the vehicle will continue to travel on the tangent However, if the vehicle is given

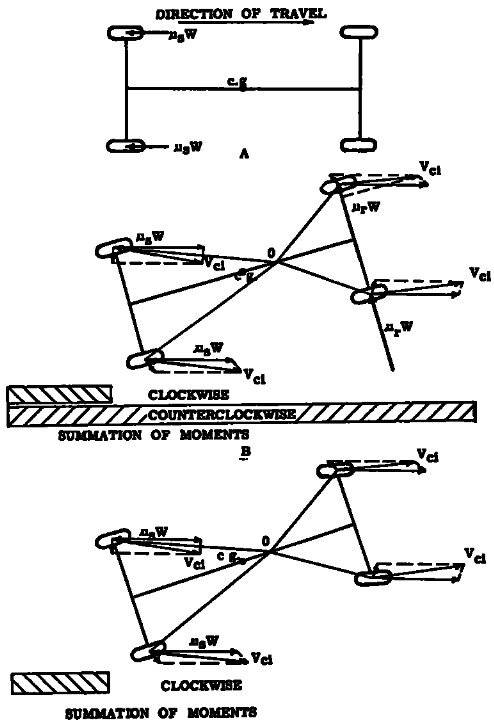

Figure 4. External Forces Acting on a Vehicle With The Rear Wheels Locked

a small angular velocity about some point 0 from a source such as superelevation or wind, regardless of how small, immediately forces begin to act to throw the vehicle out of control. Referring to Figure 4 B the analysis is made as follows· the instantaneous velocity of the center of each of the wheels, V_{cl}, is determined from the resultant of the velocity of translation and the angular velocity. Because the rear wheels are locked, the instantaneous velocity between each rear tire and the ice is equal to that of the center of the wheel. As a result the resisting forces at the rear wheels are opposite in direction to the resultant velocity at the center of each wheel and equal to μ_s W, where μ_s is the coefficient of sliding friction and W the normal weight on each wheel At the front wheels, because they are rolling, the instantaneous velocity between the tire and the ice in the plane of the wheel is zero However, the instantaneous velocity at the center of each front wheel does have a component perpendicular to the plane

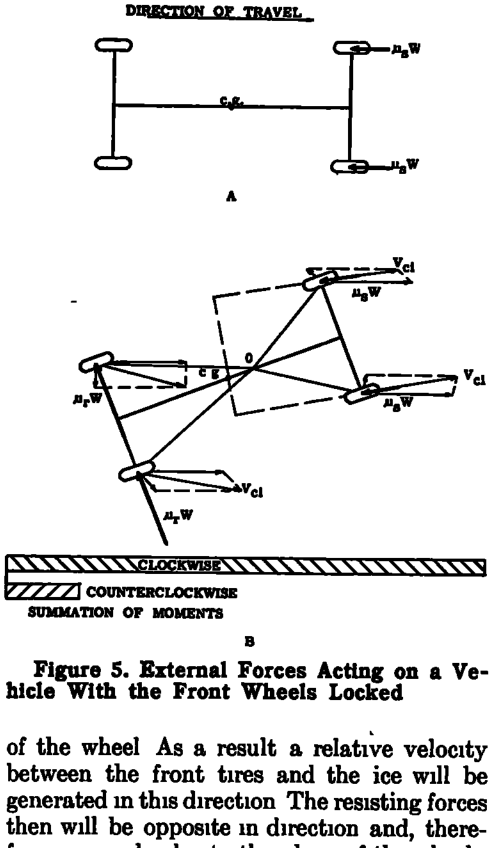

Figure 5. External Forces Acting on a Vehicle With the Front Wheels Locked

of the wheel As a result a relative velocity between the front tires and the ice will be generated in this direction The resisting forces then will be opposite in direction and, therefore, perpendicular to the plane of the wheels The magnitude of these forces will be equal to μ_r W, where μ_r is the coefficient of rolling friction. From experimental data on ice, μ_r is equal to at least twice μ_s Therefore, the forces acting at the front wheels will be at least twice those acting at the rear wheels Taking moments about the center of gravity, which is assumed to be at the geometric center for ease of calculation, the sum of the moments acting in a counterclockwise direction exceeds that in the clockwise direction As a result the vehicle goes into a flat spin about a vertical axis.

Considering Figure 4 C in which the front wheels are turned in the direction of the instantaneous velocity, V_{ci}, the forces μ_r W are no longer present, and the forces acting tend to turn the vehicle clockwise and restore it to its original direction of motion. It is difficult, however, for even the best drivers to maintain the front wheels in the plane of the instantaneous velocity. As soon as even a small angle exists between the plane of the front wheels and the instantaneous velocity, the full value of μ_r W begins to act. This accounts for the instability of a vehicle under these conditions.

Referring to Figure 5 A, which shows the forces acting when only the front wheels are locked, it is noted that the forces are in equilibrium. If it is assumed in this case as before that the vehicle has some angular velocity due to superelevation or wind, the forces acting are shown in Figure 5 B. In this case, for reasons advanced in the discussion of the rear wheels sliding, the forces acting at the front wheels will be equal to μ_s W and opposite in direction to the instantaneous velocity of the center of the wheels. Likewise the forces acting on the rear wheels will be perpendicular to the plane of the rear wheels Taking moments about the center of gravity and remembering that μ_r W is equal to or greater than 2 μ_s W, then by inspection the sum of the moments acting to turn the vehicle clockwise exceeds that acting to turn it counterclockwise As a result the vehicle instead of being thrown into a flat spin by the forces acting is turned so that the longitudinal axis is parallel to the instantaneous direction of motion of the center of gravity. Although under this condition there is complete loss of steering it can be regained as soon as the front wheels are allowed to roll.

If all four wheels are locked when the vehicle is traveling straight ahead, the forces are in equilibrium as shown in Figure 6 A If the vehicle attains a transverse velocity as shown in Figure 6 B, the forces acting are again in equilibrium If the vehicle attains an angular velocity, the moments of the forces acting to throw it out of control are exceeded by those tending to keep it in control This can be seen

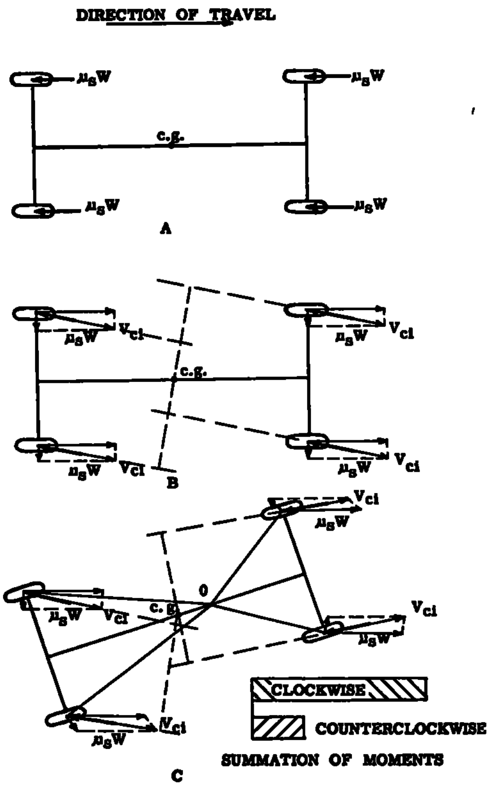

Figure 6. External Forces Acting on a Vehicle With Four Wheels Locked

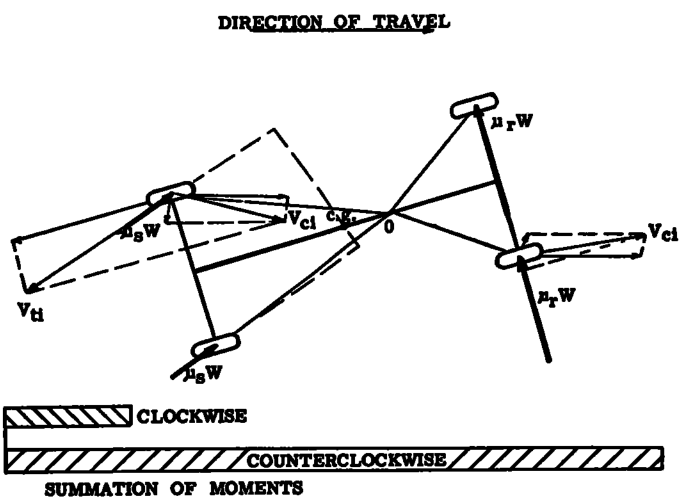

Figure 7. External Forces Acting on a Vehicle With the Rear Wheels Spinning

in Figure 6 C. The action of a vehicle on ice with all four wheels locked is not in accord with this last statement Actually the vehicle may go into a slow flat spin This is because, if all things are equal, the vehicle is in equilibrium; however, if the coefficient of friction is slightly different at any one of the wheels, this would put the vehicle into a slow flat spin.

Consider now the second type of demonstration on a straightaway, i e the application of excess torque to the driving wheels or causing the driving wheels to spin As long as the longitudinal axis of a rear drive vehicle is parallel to the direction of travel, the vehicle is in equilibrium, but as soon as the vehicle attains a small angular velocity, then it is unstable as shown in Figure 7. The instantaneous velocity between the tire and the ice, V_{tl}, is the resultant of the peripheral velocity of the wheel and the components of the velocity of translation and the angular velocity parallel to the axis of the rotation of the wheel V_{tl} determines the direction of the force μ_s W The sum of the moments about the center of gravity is again greatest in the counterclockwise direction so that the vehicle will go into a flat spin. As before, turning the front wheels exactly into the plane of the instantaneous velocity, V_{cl}, removes the forces which throw the vehicle out of control On the ice, maintaining the front wheels in the plane of the instantaneous velocity was difficult, hence, "fishtailing" occurred with the application of excess power on the rear wheels caused by overcorrection with the steering wheels.

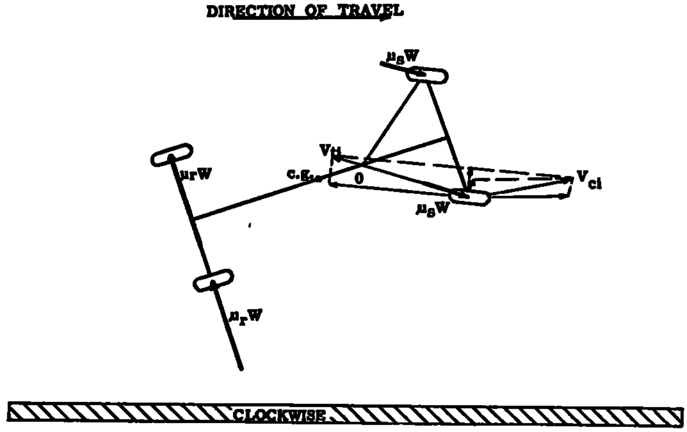

Figure 8. External Forces Acting on a Vehicle With the Front Wheels Spinning

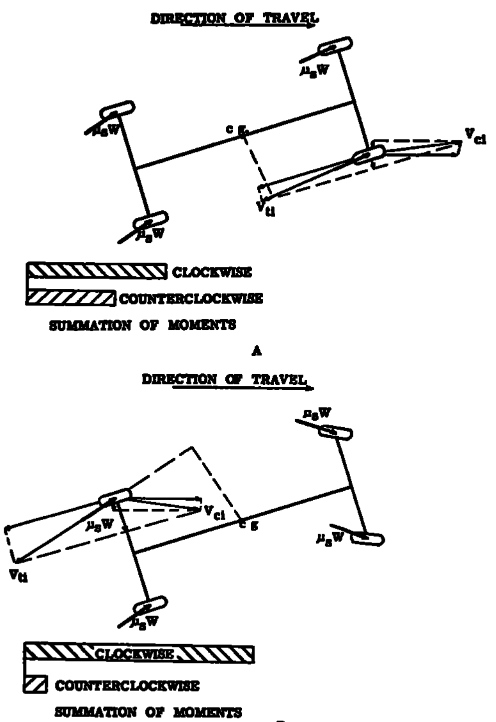

Figure 9. External Forces Acting on a Vehicle With Four Wheels Spinning

If excess power is applied to the front wheels only, they can be used to add to the restoring moment provided by the rear wheels in case the vehicle attains an angular velocity. This is shown in Figure 8. On the ice a front-wheel drive vehicle recovered quickly when deliberately thrown into a flat spin With the front wheels spinning and incapable of taking side forces, there was a loss of steering control, but it is not as complete as with the front wheels sliding.

Excess power applied to the wheels of a four-wheel drive vehicle produces forces at the four wheels, the direction of which are determined by the direction of V_{t1}. Their value will be μ_s W. Under the condition shown in Figure 9 A the vehicle is very nearly in equilibrium. There is a net moment tending to prevent rotation in a horizontal plane if the front wheels are in the straight ahead position. On the ice a four-wheel drive truck showed no tendency to "fishtail" when excessive torque was applied to the wheels. If subjected to a superelevation the entire vehicle moves parallel to itself down the grade. If such a vehicle is deliberately thrown into a skid, recovery is rapid because of the ease in regaining traction. Also it is possible, as shown in Figure 9 B to utilize the forces acting at the front wheel to aid in recovery.

In addition to the consideration of braking and application of excess torque on the straightaway a third and equally important condition is now analyzed It is the negotiation of a turn by each type of drive during which excess torque is applied to the driving wheels Referring to Figure 10 the front wheels provide forces for acceleration of the vehicle toward the center of the turn in a plane perpendicular to the plane of rotation. The maximum value of these forces will be μ_r W. At the rear these forces are acting also until the rear wheels begin to spin At the instant the inside rear wheel begins to spin the direction of the resultant force is nearly in the plane of the wheel. When the inside wheel breaks traction, because of the added load, the outside wheel begins to slide. Then the value of the forces acting at the rear decreases from μ_r W to μ_s W, and the moment arms about the center of gravity also are reduced so that the summation of the moments tending to turn the vehicle counterclockwise exceed those acting in the clockwise direction. As a result the vehicle goes into a skid on the turn As this

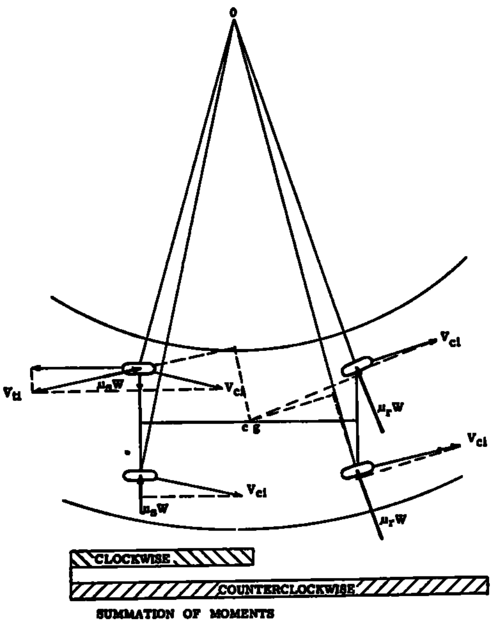

Figure 10. External Forces Acting on a Rear-Wheel Drive Vehicle Negotiating a Turn With Excess Torque on the Driving Wheels

happens the moment arms of the forces at the rear wheels lengthen, but their value remains equal to μ_s W, which is not more than half of μ_r W acting at the front wheels so the skid continues. This corresponds to the actual behavior of a rear-wheel drive truck on lake ice under these conditions. It was easily thrown into a flat spin by the application of excess torque on the driving wheels while negotiating a turn.

With a front-wheel drive vehicle on the same turn the clockwise moments exceed those in the counterclockwise direction so that the front wheels leave the curved path The forces acting are shown in Figure 11 The forces at the rear wheels act to maintain the longitudinal axis of the vehicle in line with the instantaneous direction of travel of the center of gravity of the vehicle. Thus, the vehicle leaves the curve on a tangent to its original path. This was found to be true with the front-wheel drive truck. There was loss of steering control but no tendency to go into a flat spin

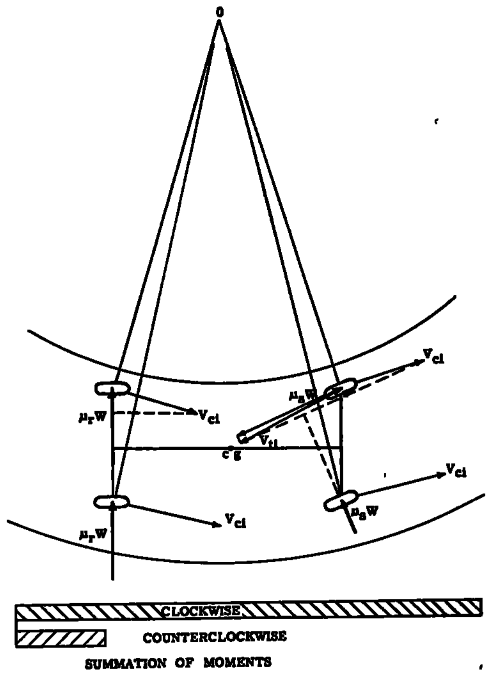

Figure 11. External Forces Acting on a Front-Wheel Drive Vehicle Negotiating a Turn With Excess Torque on the Driving Wheels

Referring to Figure 12 in which all four wheels are driving, just before the wheels begin to spin the forces producing acceleration of the vehicle toward the center of the turn are acting perpendicular to the plane of the wheels as in the other two cases considered. At the instant the wheels begin to spin these forces decrease from μ_r W to μ_s W, the direction of their action is dependent on the relative motion of the tire to the surface, V_{ti} However, the summation of moments about the center of gravity is more nearly equal to zero than in the other two cases As a result the vehicle will move parallel to itself in a direction which is the resultant of the tangential and radial velocity of the center of gravity. This will continue until the curvature of the vehicle path is reduced. On the ice with a locked center differential, which forced the wheels on each axle to spin simultaneously, it was difficult to throw a truck driven on all four wheels into a flat spin.

From a practical standpoint, especially on curves, it is desirable to have the sum of the moments of the forces acting on the vehicle

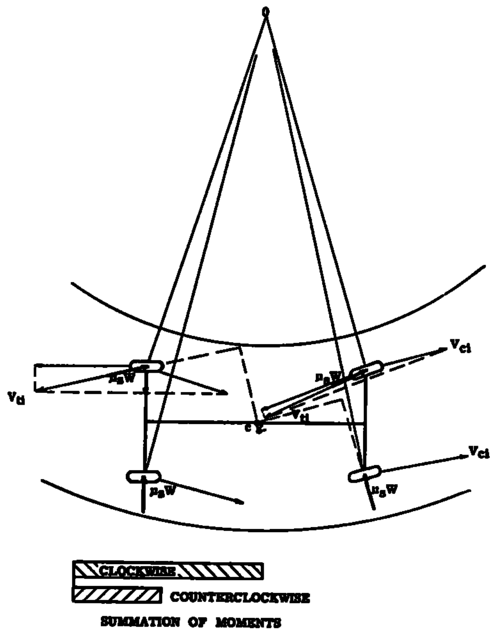

Figure 12. External Forces Acting on a Four-Wheel Drive Vehicle Negotiating a Turn With Excess Torque on the Driving Wheels

as low as possible. A comparison of the moments acting on the vehicle under the several conditions is shown in Figure 13 If a stable vehicle is defined as that vehicle which has zero moments acting on it in a horizontal plane, then the front-wheel drive is unstable in a clockwise direction which causes it to hold its course on a straightaway but to go off a curve on a tangent to that curve The rear drive is unstable in a counterclockwise direction causing it to go into a flat spin either on the straightaway, or on a curve. The four-wheel drive in each case has a relatively small net moment in the clockwise direction which causes it to hold its course on the straightaway, but is not so large as to throw it off a curve on a tangent to that curve.

Thus far in the discussion of stability little has been said of load distribution Within reasonable limits it enters into these considerations only as it affects the ability of the vehicle power plant to spin the driving wheels. For example, of two identical rear drive vehicles, the vehicle that has the greater percentage of the load on the driving wheels is least

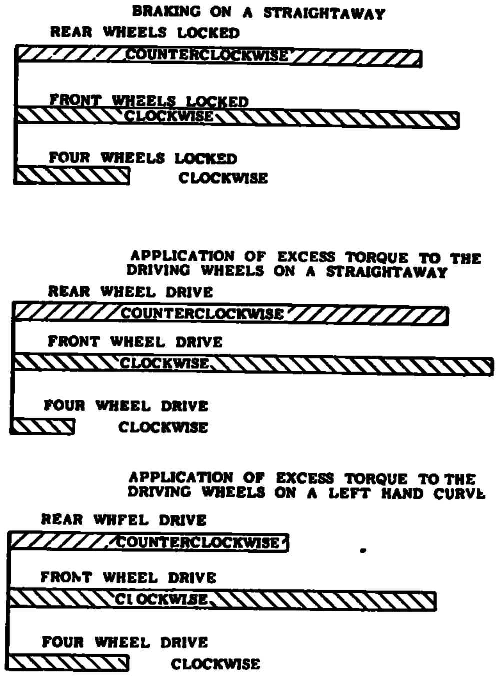

Figure 13. Net Moment Acting on a Vehicle About the Center of Gravity Under Each of Three Conditions

likely to skid on an icy surface If the center of gravity is moved, say to the rear, the normal forces at the rear wheels are increased, but the moment arms about the center of gravity are decreased a corresponding amount so that the net moment remains very nearly the same.

Since the majority of the vehicles are manufactured and operated as rear-wheel drive vehicles, the following suggestions are made as an aid to winter driving·

1. Treat the accelerator pedal as carefully as you do the brake pedal. Sudden release of the accelerator pedal may be as disastrous as sudden application of power.

2. When driving on an icy highway, drive at a speed which is well below the maximum attainable under the conditions.

3 If the road is crowned, rough, or there is a side wind be careful not to apply excess power.

4. If the rear wheels do begin a skid, release the accelerator pedal, but not too suddenly, until the wheels regain traction.

5 Turning the front wheels in the direction of the skid will also aid in regaining control unless, of course, the skid has gone too far.

were conducted first, to obtain fundamental information on the coefficient of friction on ice relative to traction, and secondly, to determine the relative drawbar ability of the rear-wheel drive and the four-wheel drive truck on ice. Drawbar pull tests for each vehicle were conducted under the following conditions:

Four-Wheel Drive

No payload
  Center differential locked
    With and without V-bar chains

TABLE 2
DRAWBAR PULL TESTS ON LAKE ICE
Comparison of Four-Wheel and Rear-Wheel Drive Trucks
Payload—None

	Four-Wheel Drive								Rear-Wheel Drive			
			lb.			*percent*			*lb.*		*percent*	
Static weight on front axle			5355			55			4395		46	
Static weight on rear axle			4360			45			5095		54	
Total weight			9715[a]						9490			
	DBP[b] CDL-S[b]	Tract. Eff	DBP CDU[b]	Tract. Eff	Coef of Fric	DBP CDL	Tract Eff	Temp	DBP	Tract Eff	Coef of Fric	Temp
	lb	%	*lb*	%		*lb*	%	*deg F*	*lb*	%		*deg F.*
WITH BARE TIRES												
January 27, 1949												
At Stall			2600	27	28	3070	32	21	1690	18	31	21
Spinning, 0 MPH			390	4	04	390	4	21	123	1	02	21
January 29, 1949												
At Stall[c]			1870	19	19	1610	17	—5	895	10	17	—5
Spinning, 0 MPH			510	5	06	515	5	—5	315	3	06	—5
January 31, 1949												
At Stall[c]	1490	15	1530	16	16	2060	21	12	900	10	17	12
Spinning, 0 MPH	460	5	350	4	04	465	5	12	185	2	.04	12
Dynamic												
1000 rpm 1st Gear	1290	13	1260	13	13	1270	13	12	830	9	15	12
1500 rpm 1st Gear	1388	14	1220	13	13	1170	12	12	675	7	13	12
WITH V-BAR CHAINS												
At Stall			4670	48	56	4410	45	10	2720	29	47	10
Spinning, 0 MPH			3535	36	40	3790	39	10	1975	21	35	10
Dynamic												
1000 rpm 1st Gear			3360	35	37	3030	31	10	2390	25	42	10

[a] Includes 400 lb of test equipment
[b] DBP—drawbar pull, CDL-S—center differential locked, single tires, CDU—center differential unlocked
[c] Driving tires coated with ice on both vehicles

6. If your car shows a tendency to fishtail upon acceleration, a safe measure would be to apply chains, preferably of the premium type

7. Once a vehicle is in a bad skid or flat spin, there is little that can be done to recover even by an expert test driver.

8 Driving practice for the various types of automatic transmissions is not treated here. This information may be obtained from the National Safety Council

Drawbar pull tests were conducted on ice in January and February of 1949. These tests

  Center differential unlocked
    With and without V-bar chains
  Center differential locked—single tires on rear
      Reference: Table 2
Nominal payload—5500 lb.—load distribution $\frac{1}{4}$ on front axle and $\frac{3}{4}$ on rear axle
  Center differential unlocked
    With and without V-bar chains
  Center differential locked
    With and without V-bar chains
    Reference: Table 3

TABLE 3

DRAWBAR PULL TESTS ON LAKE ICE

Comparison of Four-Wheel and Rear-Wheel Drive Trucks

Nominal Payload—5500 lb
Nominal Distribution—⅓-⅔

	Four-Wheel Drive		Rear-Wheel Drive	
	lb	*percent*	*lb*	*percent*
Static weight on front axle	5,330	35	5,270	35
Static weight on rear axle	10,030	65	9,790	65
Total weight	15,360[a]		15,060	

	DBP[b] CDU[b]	Tract Eff	Coef of Fric	DBP CDL[b]	Tract Eff	Temp	DBP	Tract Eff	Coef of Fric.	Temp.
	lb	%		*lb*	%	*deg F*	*lb*	%		*deg F*
WITH BARE TIRES										
February 1, 1949										
At Stall[c]	2400	16	.25	3400	22	9	2640	18	25	11
Spinning, 0 MPH	425	3	05	840	6	8	360	2	04	11
Dynamic										
1000 rpm 1st Gear							2065	14	20	11
1500 rpm 1st Gear	2770	18	30	3230	21	8	2860	19	27	11
WITH V-BAR CHAINS										
At Stall	4200	27	49	6500	42	8	4650	31	43	11
Spinning, 0 MPH	3480	23	39	5530	36	8	3805	25	36	11
Dynamic										
1000 rpm 1st Gear	5080	33	62	6180	40	8	4800	32	45	10
1500 rpm 1st Gear	5160	34	63	5270	34	8	5025	33	46	10

[a] Includes 400 pounds of test equipment
[b] DBP—drawbar pull, CDU—center differential unlocked, CDL—center differential locked
[c] Driving tires on both vehicles coated with ice

TABLE 4

DRAWBAR PULL TESTS ON LAKE ICE

Comparison of Four-Wheel and Rear-Wheel Drive Trucks

Nominal Payload—5500 lb
Nominal Distribution—40-60 and 25-75

	Four-Wheel Drive		Rear-Wheel Drive	
	lb	*percent*	*lb*	*percent*
Static weight on front axle	6,245	40	3,910	26
Static weight on rear axle	9,265	60	10,995	74
Total weight	15,510[a]		14,905	

	DBP[b] CDL-S[b]	Tract Eff	DBP CDU[b]	Tract Eff	Coef of Fric	DBP CDL	Tract Eff	Temp	DBP	Tract Eff	Coef of Fric	Temp
	lb	%	*lb*	%		*lb*	%	*deg F*	*lb*	%		*deg F*
February 2, 1949												
Bare Tires												
At Stall[c]	2540	16	2180	14	19	2450	16	7	2180	15	19	5
Spinning, 0 MPH	710	5	510	3	04	690	4	7	380	3	03	5
Dynamic												
1000 rpm 1st Gear	1890	12	2010	13	18	2360	15	7	1490	10	13	5
1500 rpm 1st Gear	2235	14	1700	11	15	2665	17	7	1780	12	15	5
1000 rpm 2nd Gear	2340	15	2980	19	27	2600	17	7	2240	15	20	5
February 3, 1949												
Chains												
At stall[d]									5460	37	.45	20
Spinning, 0 MPH									4200	28	.35	20
Dynamic												
1000 rpm 1st Gear									6340	43	51	20
1500 rpm 1st Gear									5740	39	47	20

[a] Includes 400 lb of test equipment
[b] DBP—drawbar pull, CDL-S—center differential locked, single tires, CDU—center differential unlocked.
[c] Driving tires on both vehicles coated with ice
[d] Runs were not made on the FWD with chains at this load

Nominal payload—5500 lb.—load distribution
40 percent on front axle
and 60 percent on rear axle

Center differential locked
With dual and single tires
Center differential unlocked
Reference· Table 4

TABLE 5
DRAWBAR PULL TESTS ON LAKE ICE
Comparison of Four-Wheel and Rear-Wheel Drive Trucks
Payload—11,200 lb
Nominal Distribution—⅓-⅔

	Four-Wheel Drive		Rear-Wheel Drive	
	lo	percent	lb	percent
Static weight on front axle	6,860	32	6,680	32
Static weight on rear axle	14,240	68	14,020	68
Total weight	21,100[a]		20,700	

	DBP[b] CDU[b]	Tract Eff	Coef of Fric	DBP[b] CDL[b]	Tract Eff	Temp	DBP	Tract Eff	Coef of Fric	Temp
	lb	%		lb	%	deg F.	lb	%		deg F.
February 15, 1949										
At Stall	4800	23	41			29	3160	15	22	31
Spinning, 1000 rpm										
1st Gear, 0 6 MPH	405	2	03			29	480	2	03	31
Dynamic										
1000 rpm 1st Gear	3100	15	25			28	2180	10	15	30
1500 rpm 1st Gear	2610	12	21			28	2610	12	.18	30
1000 rpm 2nd Gear	3625	17	30			28	2410	11	17	30
February 16, 1949[c]										
At Stall	3600	17	30	5320	25	24	3170	15	22	24
Spinning, 1200 rpm										
1st Gear, 0 MPH	309	2	02	417	2	24	210	1	02	24
Dynamic										
1000 rpm 1st Gear	2140	10	17	3340	16	24	2055	10	14	24
1500 rpm 1st Gear	2610	12	21	3455	17	24	2840	13	19	24
1000 rpm 2nd Gear	2645	13	21	3210	15	24	3255	15	22	24

[a] Includes 400 pounds of test equipment
[b] DBP—drawbar pull, CDU—center differential unlocked, CDL—center differential locked
[c] Driving tires on both vehicles slightly iced

TABLE 6
DRAWBAR PULL TESTS ON LAKE ICE
Comparison of Four-Wheel and Rear-Wheel Drive Trucks
Payload—11,200 lb
Nominal Distribution—40-60 and 25-75

	Four-Wheel Drive		Rear-Wheel Drive	
	lb	percent	lb.	percent
Static weight on front axle	8,200	39	4,970	24
Static weight on rear axle	12,725	61	15,800	76
Total weight	20,925[a]		20,770	

	DBP[b] CDU[b]	Tract Eff	Coef of Fric	DBP CDL[b]	Tract Eff	Temp	DBP	Tract Eff	Coef of Fric	Temp
	lb	%		lb	%	deg F	lb	%		deg F
February 17, 1949[c]										
At Stall	3760	18	25	4470	21	18	4620	22	28	15
Spinning, 0 MPH	335	2	02	495	2	18	260	1	02	15
Dynamic										
1000 rpm 1st Gear	3130	15	21	3790	18	18	2315	11	14	15
1500 rpm 1st Gear	3210	15	21	3745	18	18	2905	14	18	15
1000 rpm 2nd Gear	2920	14	19	3250	16	18	2435	12	15	15
1500 rpm 2nd Gear	3300	16	22	2910	14	18				
February 18, 1949[d]										
At Stall	690	3	04	890	4	40	1050	5	.07	39
Spinning, 0 MPH	330	2	02	325	2	40	250	1	02	39
March 2, 1949[e]										
At Stall	2100	10	14	2600	12	38	1650	8	.10	38
Spinning, 0 MPH	1360	7	.09	1740	8	38	1210	6	08	38

[a] Includes 400 pounds of test equipment
[b] DBP—drawbar pull, CDU—center differential unlocked, CDL—center differential locked
[c] Tires on both vehicles slightly iced
[d] Tires excessively wet on both vehicles
[e] Ice soft as a result of 12 hours of above freezing temperatures

Nominal payload—11,200 lb.—load distribution ⅓–⅔ and 40–60

Center differential locked and unlocked

Reference: Tables 5 and 6

With various loads as a front, rear and four wheel drive

Reference: Table 7

measurements are known as the static, spinning and dynamic coefficients respectively. Each of the three types of measurements was made with the field dynamometer using the 20,000-lb drawbar and the oscillograph Because of the variability of the values of drawbar pull at stall, the average of at least ten or more values was taken. For the most part the spinning and dynamic values given in Tables 2 to 7 are the average of two or more trials. Examples of oscillograms taken under each of the three conditions are shown in Figures 14 and 15.

TABLE 7

DRAWBAR PULL TESTS ON LAKE ICE

Comparison of Front, Rear and Four Wheel Drive on a Four-Wheel Drive Truck

	DBP[a] CDU[a]	Tract Eff.	Coef. of Fric	DBP CDL[a]	Tract Eff.	Temp	DBP RW-D[a]	Tract Eff.	Coef of Fric.	DBP FrW-D[a]	Tract Eff	Coef of Fric	Temp
February 4, 1949													
Static load on front axle							6,245 lb				40 percent		
Static load on rear axle							9,265 lb				60 percent		
Total weight							15,510 lb						
	lb.	*%*		*lb.*	*%*	*deg F*	*lb*	*%*		*lb*	*%*		*deg F*
At Stall[b]				3440	22	17	2320	15	.24	1990	13	35	17
Spinning, 0 MPH				490	3	17	302	2	03	146	1	02	17
Dynamic													
1000 rpm 1st Gear				2015	13	17	1415	9	15	1100	7	18	17
1500 rpm 1st Gear				2340	15	17	1110	7	12	925	6	15	17
February 16, 1949													
Static load on front axle				6,860 lb							32 percent		
Static load on rear axle				14,240 lb							68 percent		
Total weight				21,100 lb									
At Stall				5320	25	24	3780	18	25	2130	10	34	18
Spinning, 0 MPH				417	2	24	520	3	04	0	0	00	18
Dynamic													
1000 rpm 1st Gear				3340	16	24	2335	11	16	1100	5	17	18
1500 rpm 1st Gear				3455	16	24	3235	15	22	1105	5	17	18
1000 rpm 2nd Gear				3210	15	24	2265	11	15	1430	7	23	18
March 2, 1949[c]													
Static load on front axle				8,200 lb							39 percent		
Static load on rear axle				12,725 lb							61 percent		
Total weight				20,925 lb									
At Stall	2100	10	.14	2600	12	38	1870	9	14	1180	6	15	38
Spinning, 0 MPH	1360	7	09	1740	8	38	1052	5	08	620	3	08	38

[a] DBP—drawbar pull, CDU—center differential unlocked, CDL—center differential locked, RWD—rear wheel drive, FrWD—front wheel drive

[b] Driving tires slightly iced under each of the three conditions

[c] Ice soft as a result of 12 hours of above freezing temperatures

Rear-Wheel Drive

No payload

With and without V-bar chains

Reference: Table 2

Nominal payload—5500 lb.—load distribution of ⅓–⅔ and 25–75

With and without V-bar chains

Reference: Tables 3 and 4

Nominal payload—11,200 lb.—load distributions of ⅓–⅔ and 25–75

With and without V-bar chains

Reference: Tables 5 and 6

The drawbar pull for the various conditions stated above was measured in three ways; namely; at stall, with the drive wheels spinning, and with the drive wheels rolling The coefficients of friction corresponding to these

Also found in the tables for drawbar pull on ice are the computed values of tractive efficiency and tractive coefficient of friction. Tractive efficiency is a measure of the ability of a vehicle to pull in accordance with its weight or tractive efficiency = $DBP \times 100/G.V.W.$ For values below 15 percent this value is very nearly equal to the gradeability at that load. In general the tractive coefficient of friction (μ) is equal to the drawbar divided by the weight on the driving wheels. For a rear wheel drive the equation is:

$$\mu = \frac{DBP + R_{rf}}{W_r + \frac{H}{WB} DBP}$$

where DBP = drawbar pull
W_r = static weight on rear axle
H = height of towing hook, inches
WB = wheelbase, inches
R_{rf} = rolling resistance of the front wheels

For a four-wheel drive with the center differential unlocked and the weight distribution

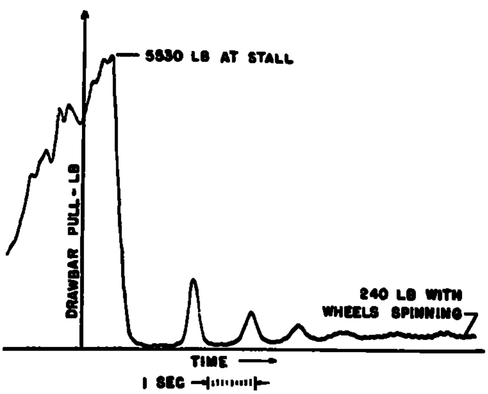

Figure 14. Oscillogram of Drawbar Pull on Lake Ice Under Static and Spinning Conditions

Vehicle—Rear-Wheel Drive

	lb.	percent
Static weight on front axle	**4,970**	**24**
Static weight on rear axle	**15,800**	**76**
Gross vehicle weight	**20,770**	

Ambient—15 F.

This oscillogram shows the drawbar pull increasing as the clutch is gradually engaged until the wheels start to spin. Then the drawbar pull decreases rapidly and stabilizes at a relatively small value with the wheels spinning.

such that the front wheels slip first, the equation becomes:

$$\mu = \frac{DBP}{2\left(W_f - \frac{H}{WB} DBP\right)}$$

W_f = static weight on front axle

If the rear wheels slip first:

$$\mu = \frac{DBP}{2\left(W_r + \frac{H}{WB} DBP\right)}$$

All of the values shown in the tables for coefficient of friction were computed by means of these equations. There is reasonable agreement in most cases between the values for four and rear-wheel drive trucks given in Tables 2 to 7 This fact makes it possible to compare the drawbar pull of any vehicle under any load if the coefficient is known. Figure 16 presents graphically the drawbar

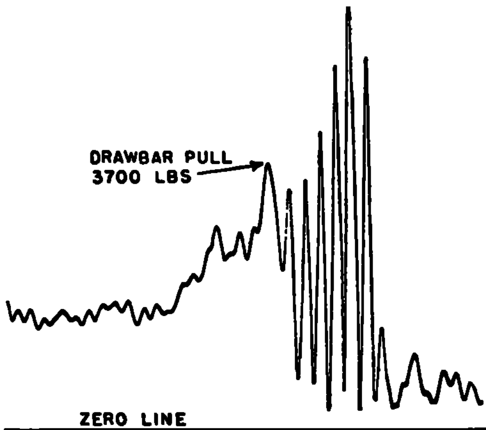

Figure 15. Oscillogram of Drawbar Pull on Lake Ice Under Dynamic Conditions

Vehicle—Four-Wheel Drive

	lb.	percent
Static weight on front axle	**6,860**	**33**
Static weight on rear axle	**14,240**	**67**
Gross vehicle weight	**21,100**	

Ambient—29 F.
Center differential unlocked
Engine speed 1000 rpm
1st Gear

This oscillogram shows the increase in drawbar pull as the towed load is increased, and the throttle is gradually opened to hold the engine speed constant at 1000 rpm. The drawbar pull increases until the wheels spin, then stabilizes at a small value with the wheels spinning.

pull of the two trucks as tested, plotted against the coefficient of friction under several conditions. It is noted that no attempt is made to calculate the coefficient of friction when the center differential is locked because the torque distribution is not known unless the wheels are spinning.

Figures 17 and 18 are projected results based on the behavior of the vehicles as tested. It was planned to install a torque proportioning cen-

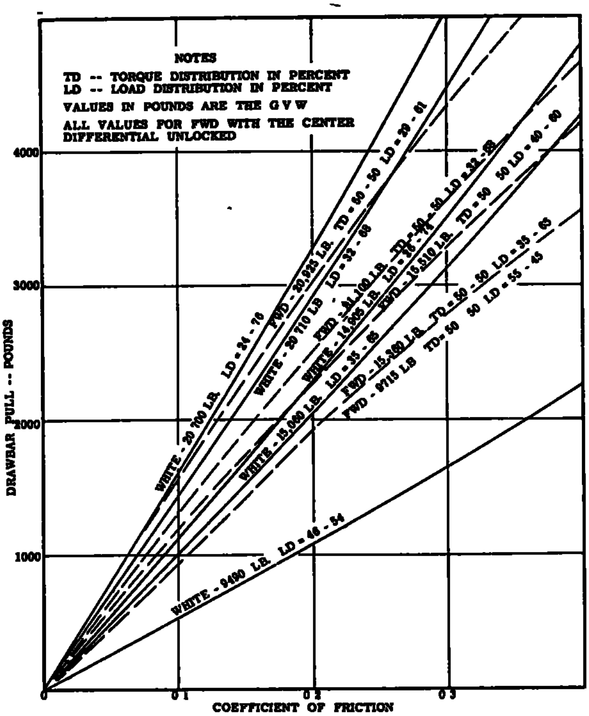

Figure 16. Variation of Drawbar Pull With Coefficient of Friction for the FWD and White Trucks as Tested

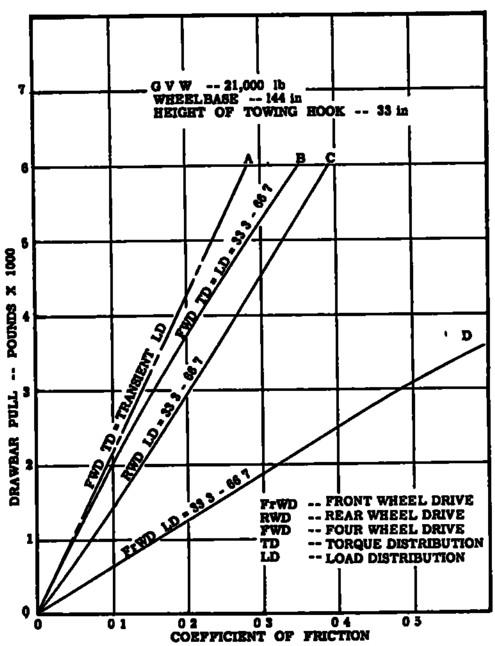

Figure 17. Variation of Drawbar Pull With the Coefficient of Friction for Each of Three Types of Drive on the Same Vehicle

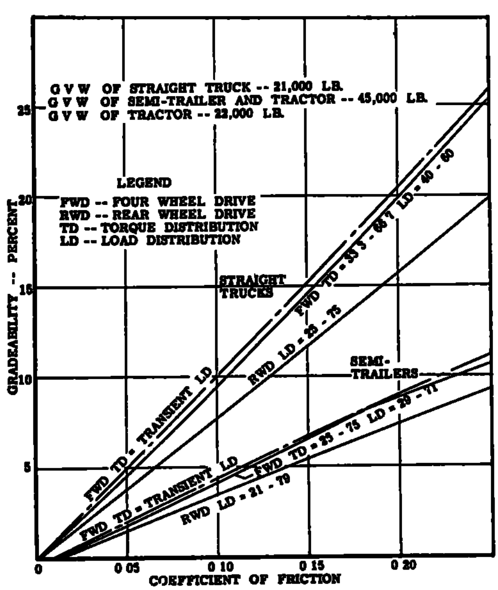

Figure 18. Variation of Gradeability With the Coefficient of Friction for Four Types of Vehicles

ter differential in the four-wheel drive truck for the tests in January, 1950, in order that the results given for the four-wheel drive truck in Figures 17 and 18 may be proved by actual tests. In each of these figures, the curves labeled "FWD TD = Transient LD" represent the maximum that could be obtained with a four-wheel drive truck if it were possible to adjust the torque distribution to the front and rear axle equal to the load distribution at the time of a given drawbar pull. This is Curve A in Figure 17. Curve B in the same figure shows the drawbar pull of a four-wheel drive truck with a torque distribution equal to the static load distribution. Curve C is the drawbar pull of a rear-wheel drive truck also for any coefficient of friction up to 0 6, and Curve D is that of a front-wheel drive truck. The computations for these curves were based on the same G.V W , 21,000 lb ; the same load distribution, 33.3–66.7; the same wheelbase, 144 in.; and the same tow hook height, 33 in. At a coefficient of friction of 0 1 the drawbar pull which it is practicable to obtain with the four-wheel drive truck (Curve B) is 1 4 times that of the rear-wheel drive truck and 3.3 times that of the front-wheel drive truck.

If the height of the center of gravity and the coefficient of friction are known, it is possible to compute the gradeability of a vehicle. Figure 18 shows the variation of gradeability with the coefficient of friction for two classifications of trucks using the rear and four-wheel drive principles. The values chosen for the computations represent those in actual practice. They are as follows:

	4-Wheel Drive	*Rear-Wheel Drive*
G V.W of straight truck, lb.	21,000	21,000
Net weight of tractor, lb	8,410	8,420
G.V W of semi-trailer, lb	36,590	36,580
G.V.W of tractor, lb.	22,000	22,000
Gross weight on semi-trailer wheels, lb	23,000	23,000
G.V.W. of semi-trailer and tractor, lb	45,000	45,000
Straight truck wheelbase, in	144	160
Tractor wheelbase, in	132	136
Distance from fifth wheel to rear axle of semi-trailer, in	236	236
Location of fifth wheel ahead of tractor rear axle, in.	12	4
Height of center of gravity of tractor, in. ..	33	30
Height of center of gravity of semi-trailer, in	60	60
Height of center of gravity of straight-truck, in	46	44
Rolling resistance of non-driving axles, lb per ton	15	15

As an example the coefficient of friction required for the four-wheel drive to pull the semi-trailer up a four percent grade will be computed. Inasmuch as there is 29 percent (6400 lb.) on the front wheels and 71 percent (15,600 lb.) on the rear wheels, a torque distribution of 25 percent on the front axle and 75 percent on the rear axle is selected thus allowing the rear wheels to slip first. The force to be supplied by the driving wheels is equal to the grade resistance plus the rolling resistance of the trailer wheels

$$45{,}000 \sin \arctan \ 04 + \frac{23{,}000}{2000} 15$$
$$\text{or } 1800 + 172 = 1972 \text{ lb}$$

Of this force 75 percent or 1480 lb must be supplied by the rear wheels If x is the grade in terms of degrees, the normal weight on the rear wheels (W_{rn}) will be equal to the static weight on the rear wheels times the cos x, plus the shift of weight to rear wheels of the tractor due to grade on the tractor alone, plus the shift of weight due to the grade resistance of the trailer, plus the shift of weight caused by the rolling resistance of the rear wheels of the trailer, minus the shift of weight on the trailer due to grade. In terms of actual values

$$\begin{aligned} W_{rn} &= 15{,}600 \cos x + 8410 \sin x \frac{33}{132} \\ &\qquad + 36{,}590 \sin x \frac{38}{132} \\ &\quad + \frac{23{,}000}{2000} 15 \frac{38}{132} - 36{,}590 \sin x \frac{60}{236} \\ &= 15{,}600 + 84 + 420 + 50 - 374 \\ &= 15{,}780 \end{aligned}$$

The coefficient of friction required will be·

$$\mu = \frac{\text{force to be supplied by rear wheels}}{\text{weight on rear wheels}}$$
$$= \frac{1480}{15{,}780} = 0\ 0937$$

The gradeability of the straight trucks and of the rear-wheel drive semi-trailer truck are computed in the same manner except that the rolling resistance of the front wheels must also be supplied by the driving wheels in the case of rear-wheel drive vehicles The optimum curve for the straight and semi-trailer trucks are based on a torque distribution to the front and rear axles equal to the load distribution caused by the grade or that all of the weight on the driving wheels is utilized for traction. It is interesting to note that before a vehicle of the semi-trailer type could be moved on a level surface, a coefficient of friction of 0.0082 must be available for the four-wheel drive and 0.0119 for the rear-wheel drive.

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ACCIDENT ANALYSES FOR PROGRAM PLANNING

ROY E. JORGENSEN, *Deputy Commissioner and Chief Engineer* AND ROBERT G MITCHELL, *Assistant Highway Engineer, Connecticut State Highway Department*

SYNOPSIS

Accident rates for a 4-yr. period (1945–48) have been established for all control sections on Connecticut's State highways Control sections, averaging a little over a mile in length, set off the road system in units with uniform surface type, width, age and traffic volumes

Accident rates have been developed for standard-meeting highways in different traffic volume groups. These roads are recently-constructed highways that conform to design standards now being used by the Connecticut Highway Department Comparison of the accident rates on the substandard highways in different traffic volume groups, with the accident values developed for the group of modern highways, shows that a great reduction in accidents would be made possible by reconstruction of the State highway system to these standards

The Highway Department will use this type of analysis to support highway improvement programs In annual programming the number of lives, injuries and the property damage costs that will be saved by each year's construction program will be shown It will be possible, also, to develop total accident reductions obtainable by improvement of any particular group of roads in accordance with design standards

Development of the accident rate on all control sections has enabled the Department to rank all sections in order of their relative hazard. This is of great value in determining the sections most needing improvement The accident values are used with other evaluations of roadway characteristics to produce sufficiency ratings for the entire State highway system.

The Connecticut Highway Department is making many allied uses of the data that are carried on its new accident punch card The relationships of accidents to width and type of pavement by traffic volume groups has been developed Many other accident analyses with respect to the roadway characteristics are possible.

With the accident rates by control sections, the Department can answer all letters and complaints calling attention to hazardous locations with factual information regarding the accident experience at the location, and can determine how that location compares in safety with other sections of the highway system