Passenger Car Drive Axle Technology

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Introduction

A drive axle is an integral assembly containing mechanical components that are used to deliver power from the engine to the driving wheels of an automotive vehicle. This course will deal with the drive axles that are used in the rear of front engine vehicles and are also in the front of four-wheel drive front engine vehicles. (Drive axles are also used in front engine, front drive vehicles where they are combined with the transmission in what is called the “transaxle”.)

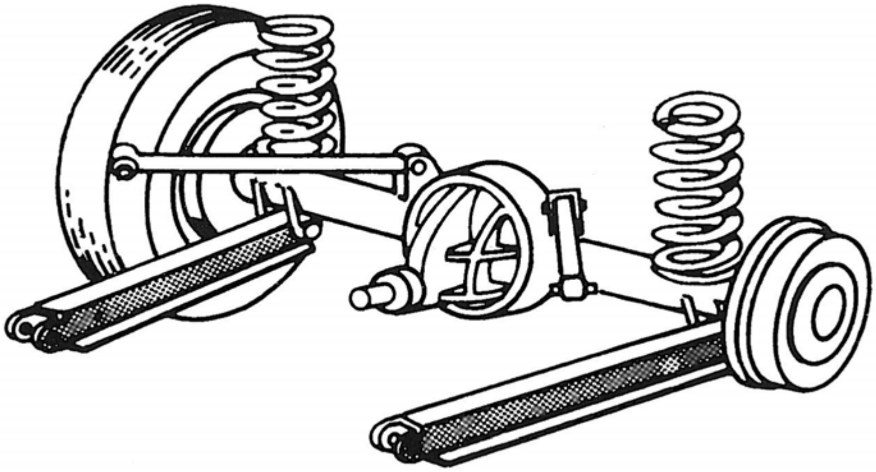
It can be seen on the top sketch of Figure 1 that the rear drive axle is mounted on trailing suspension arms and serves as a base for mounting the springs and shock absorbers. The track bar shown connects to the frame and serves as lateral support for the drive axle/rear suspension system. The lower sketch has a front drive axle with linkage attached to the left hand wheel mounting flange and a “tie rod” connecting both wheels to provide for vehicle steering.

The power transmitting components in drive axles are gears. Figure 2 shows four kinds of commonly used gears. The basic form is the “spur” gear. It has straight teeth around the periphery that engage with another spur gear on a parallel shaft. A version of a spur gear is called the “helical” gear. A helical gear has teeth like spur gears except they are curved. Helical gears deliver more power and run more quietly than spur gears but are less efficient. The third kind of gear is called a “bevel” gear. Bevel gears have teeth like spur gears except they are tapered. Bevel gear axes are not parallel like spur gears but mount at an angle such as 90^O as shown on Figure 2. An adaption of the bevel gear is the “spiral bevel gear”. It has curved teeth similar to what helical gears are to spur gears.

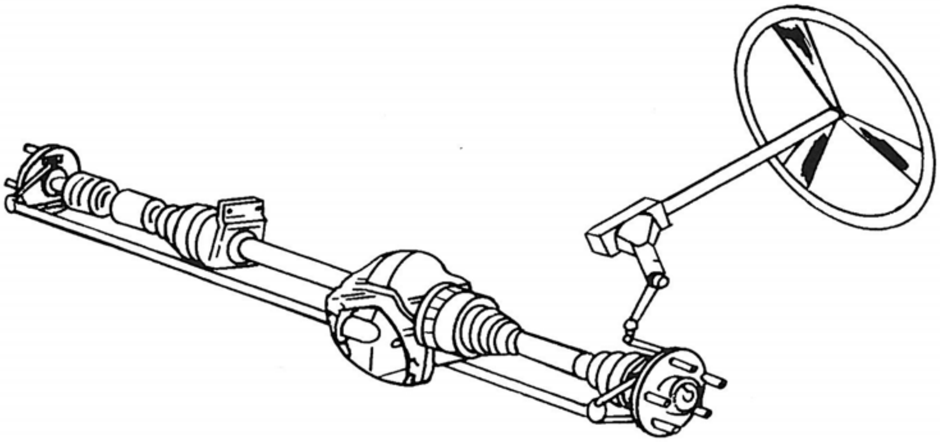
Figure 3 has sketches of a version of a spiral bevel type gear with the pinion (small gear) axis either below or above the ring (large gear) axis. When the axes of the two gears are not on the same vertical plane, spiral bevel gears are called “hypoid” gears. Straight bevel gears, spiral bevel gears, and hypoid gears are used in automotive drive axles as explained later in this course.

Figure 1

Types of Drive Axles



Rear Drive Axle



Front (Steering) Drive Axle

Figure 2

Types of Gears

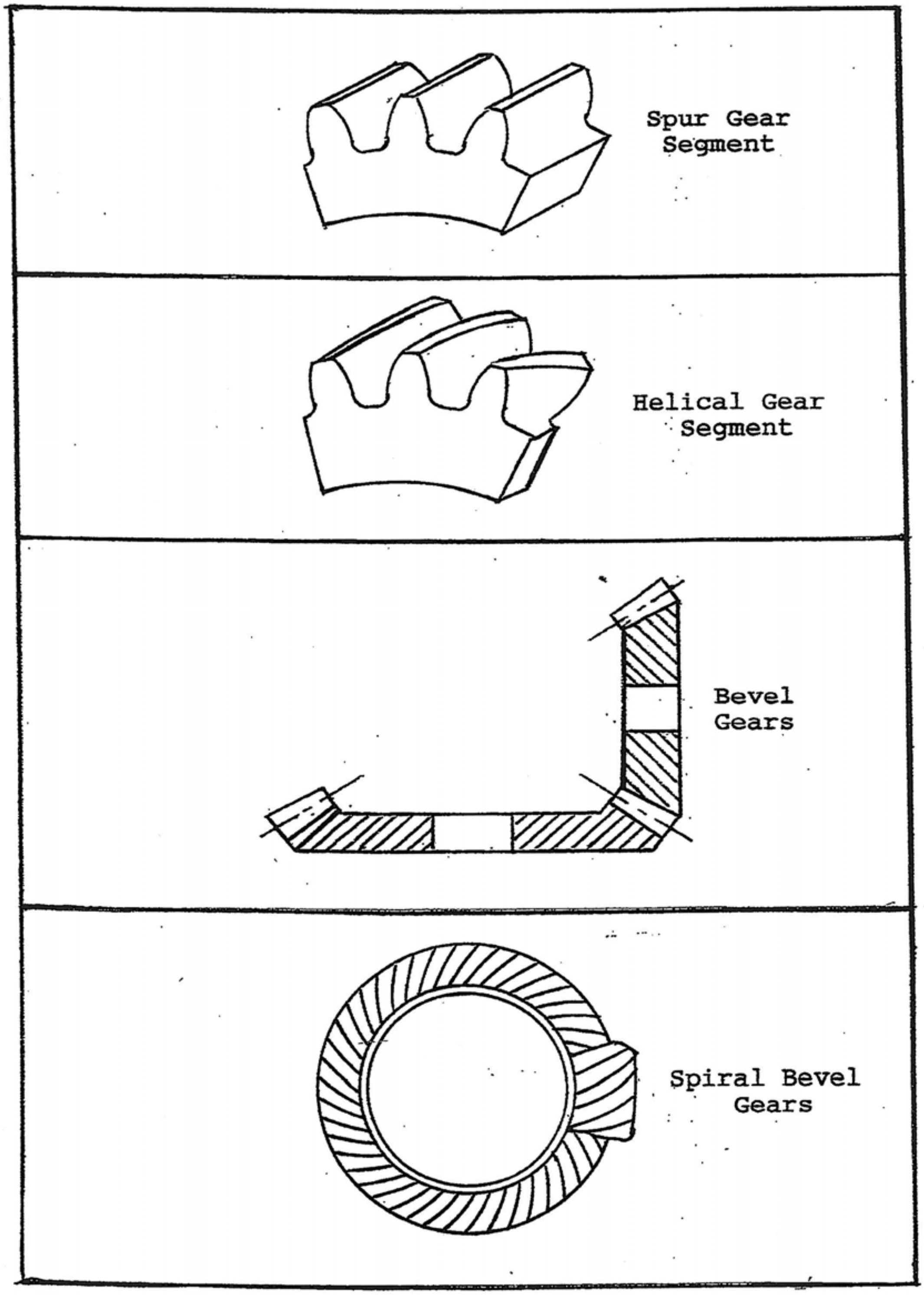
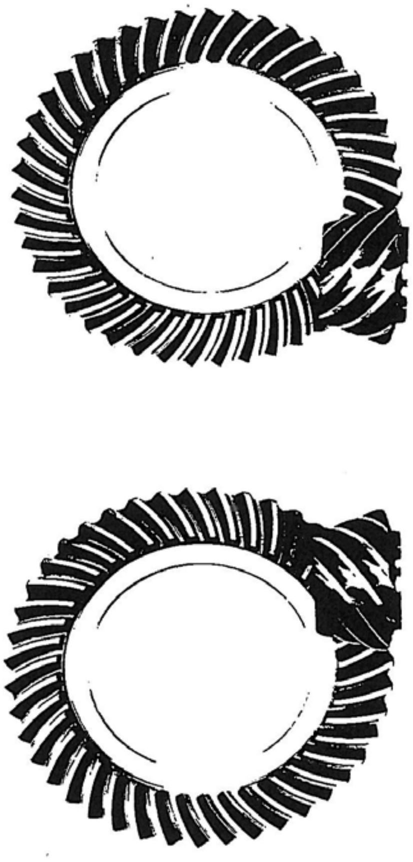


Figure 3

Hypoid Gears



Drive Axle Description

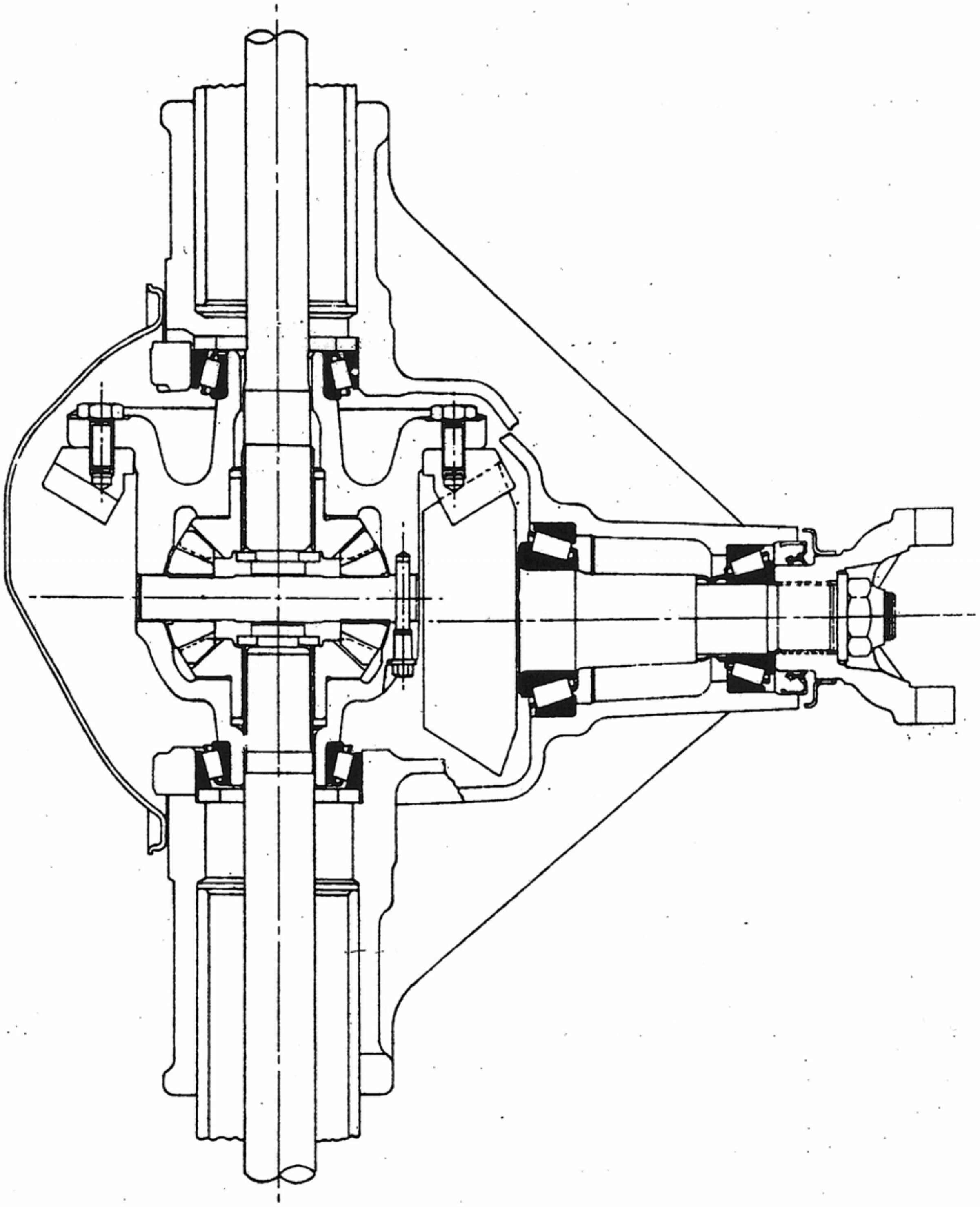
In rear drive vehicles, engine power is delivered from the front mounted engine/transmission module to a drive shaft which transmits it back to the drive axle assembly located along the centerline of the rear wheels. In rear drive vehicles with four-wheel drive capability, in addition to power being delivered to the rear wheels, engine power is also delivered by a shaft to a drive axle located along the centerline of the front wheels.

Drive axles consist of a center housing containing three sets of 90^O bevel type gears. (See Figure 4.) The first set, commonly called the drive gears are either spiral bevel or hypoid gears. They receive power from the vehicle drive shaft and deliver it to the “carrier” which houses the “differential”. The differential consists of two sets of 90^O straight bevel gears which receive power from the drive gears and transmit it to two axle shafts, one on each side of the center section. The axle shafts are contained in tubes connected to the center section and deliver power to the vehicle drive wheels. The differential is an ingenious device which allows power to be delivered simultaneously to each of the two axle shafts even though one may be rotating faster than the other such as when a vehicle is rounding a corner. (The differential was invented by German engineer Karl Benz in 1885 and hasn’t had any significant changes since.)

The drive gears can be either a “spiral bevel” gearset or a “hypoid” gearset. As mentioned, spiral gearsets have the pinion gear axis on the same vertical plain as the larger ring gear axis. On a hypoid gearset, the axis of the pinion is either below or above the axis of the ring gear. When the axis of the pinion gear is below the axis of the ring gear, the vehicle drive shaft is lowered allowing vehicle designers to add more space to the passenger compartment. When the axis of the pinion gear is above the axis of the ring gear, the vehicle driveshaft is raised allowing more drive shaft ground clearance. This right angle drive gearset is a speed reducing device since engine rpm is higher than wheel rpm. It can be seen on Figure 4 that the ring (larger) gear is attached to the carrier containing the differential which is comprised of two sets of straight bevel gears whose ring gears are splined to the axle shafts leading to the vehicle wheels.

Figure 4

Drive Axle Center Section



Drive Axle Types

The upper sketch on Figure 5 is a drive axle with rigidly mounted wheels while the lower sketch has a drive axle with independently suspended wheels.

1) Rigid Drive Axles: This type contains a center housing having fixed attaching tubes enclosing the axle shafts that deliver engine power from the center section gearing to the wheels. Advantages of this type of axle are that it provides a simple method of supporting axle shafts and wheels, and universal joints are not required on axle shafts. In this type of axle, vertical displacement of one wheel results in the vertical displacement of the opposite wheel. This feature results in jarring across the entire width of the vehicle when one wheel hits an obstruction on the road. There are three variations of rigid drive axles; the difference being the wheel bearing arrangement at the outer end of the axle tubes. (See Figure 6.)

A) Semi-Floating Axle: This design employs one wheel support bearing mounted on the outer end of the axle shaft and inside the axle tube. All the wheel forces including vehicle weight, wheel side skid, wheel traction, and torsional drive, are supported by the axle shaft. This design is less complicated, lighter weight, less costly, and is used in passenger cars.

The diagram on Figure 7, developed by anti-friction bearing engineers, has been used to calculate the axle shaft diameter at the wheel bearing location. The analysis consists of summing the moments around the center of the outer bearing and equating them to the flexure of length, C, of the axle shaft:

$$M = (W_R B - .6 W_R R_r) = SI/C$$

M = maximum bending moment in in-lbs around the center of the outer bearing.

W_R = maximum rear end weight of the vehicle in pounds. ($.6W_R$ = side skid load.)

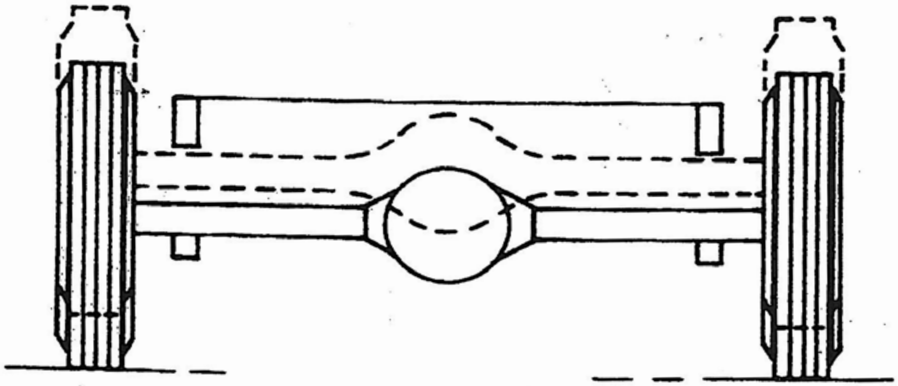
B = axial distance from the center of the wheel to the center of the outer bearing.

R_r = radius of tire in inches.

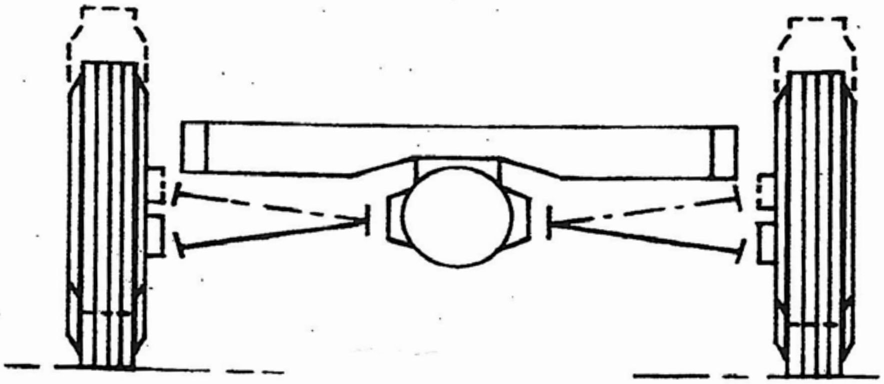
SI/C = allowable axle shaft stress times section modulus.

Figure 5

Types of Drive Axles



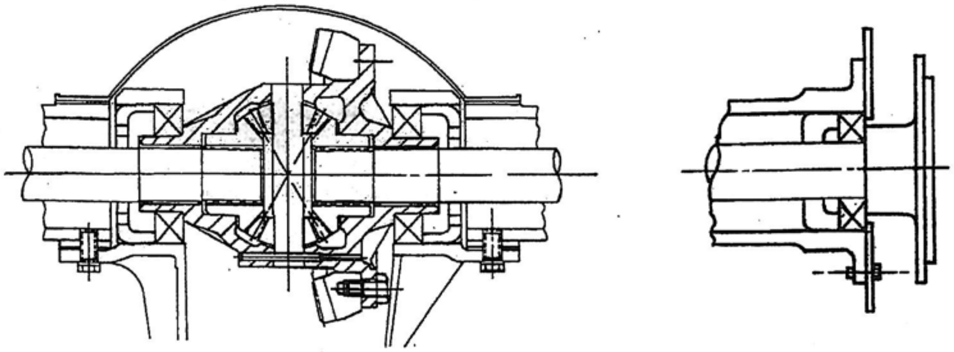
Rigid Axle



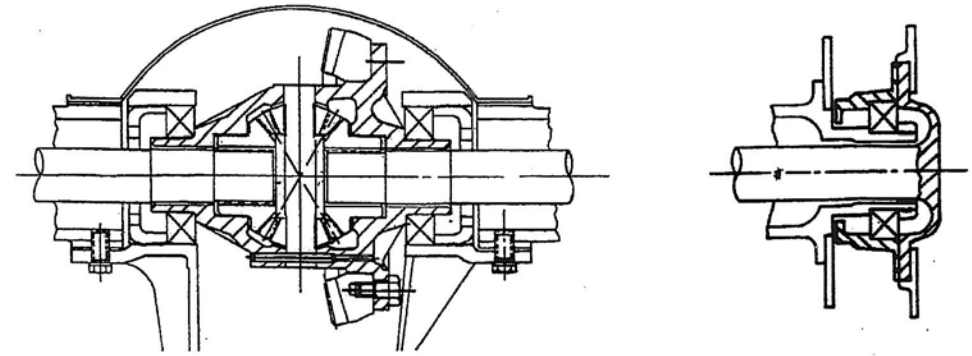
Independent Suspension Axle

Figure 6

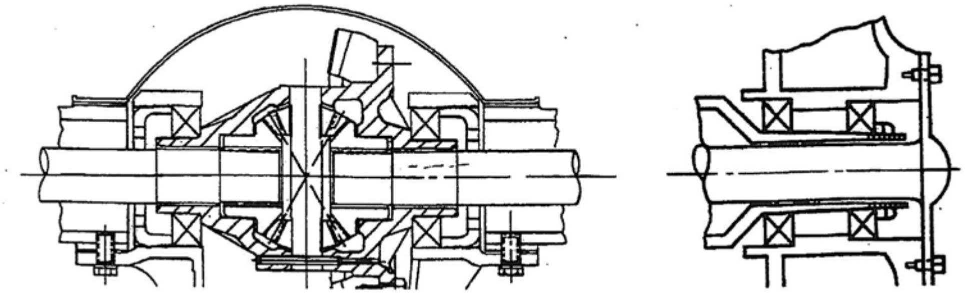
Types of Rigid Axles



Semi-Floating Axle



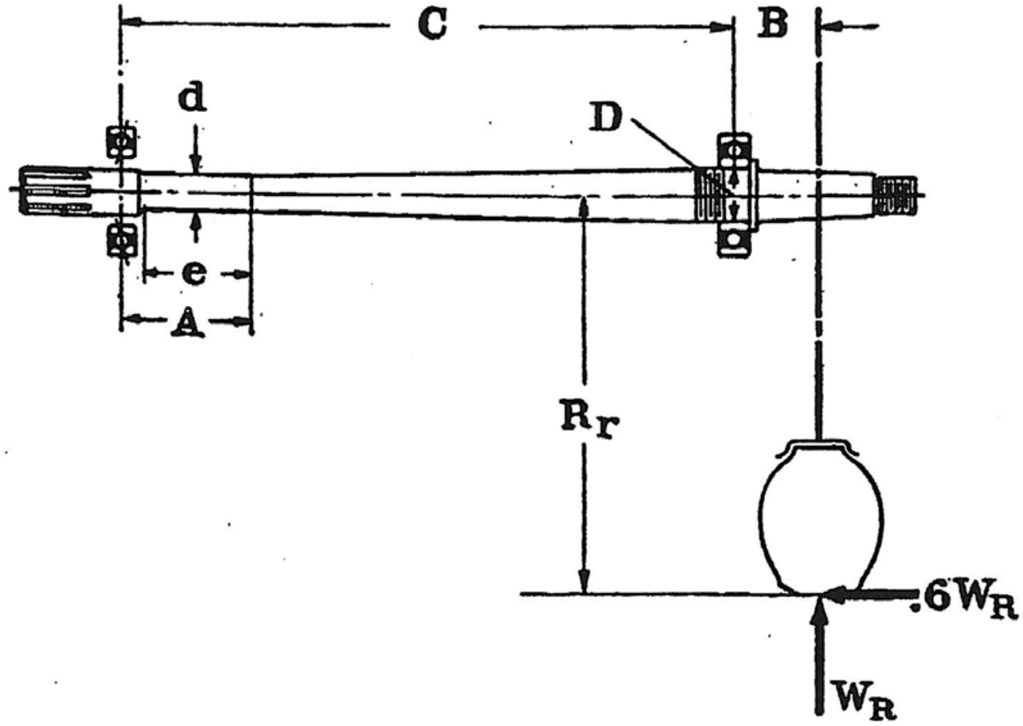
Three-Quarter Floating Axle



Full-Floating Axle

Figure 7

Semi-Floating Axle Analysis



From the above information, the diameter of the axle shaft is calculated as follows:

$$D = 2.168\ (M/S)^{1/3}$$

D = the diameter of the axle shaft at the outer bearing center in inches.

B) Three-Quarter Floating Axle: This design uses one wheel support bearing mounted on the outer end of the axle tube. The wheel forces due to vehicle weight and tractive effort are supported by the axle tubes. The vehicle force due to wheel side skid loads and torsional drive forces are supported by the axle shaft which is then said to be "three-quarter floating". This design has limited application in the automotive industry.

Figure 8 has a sketch of a three-quarter floating axle design. The following equation sums the moment loading around the outer bearing center which is the result of the side skid load only:

$$M = .6W_RR_r$$

M = moment load in inch-pounds around outer bearing center.

$.6W_R$ = maximum side skid load in pounds.

R_r = radius of tire in inches.

Using the same analysis as was done for the semi-floating axle above; the diameter of the axle shaft is as follows:

$$D = 2.168\ (M/S)^{1/3}$$

D is the diameter of the axle shaft at the outer bearing in inches.

M = the moment load in inch pounds calculated above.

S = the maximum allowable shaft stress in inch-pounds.

In this three-quarter design configuration, the axial shaft supports the side skid load only. The radial load is supported by the axle tube.

Figure 8

Three-Quarter Floating Axle Analysis

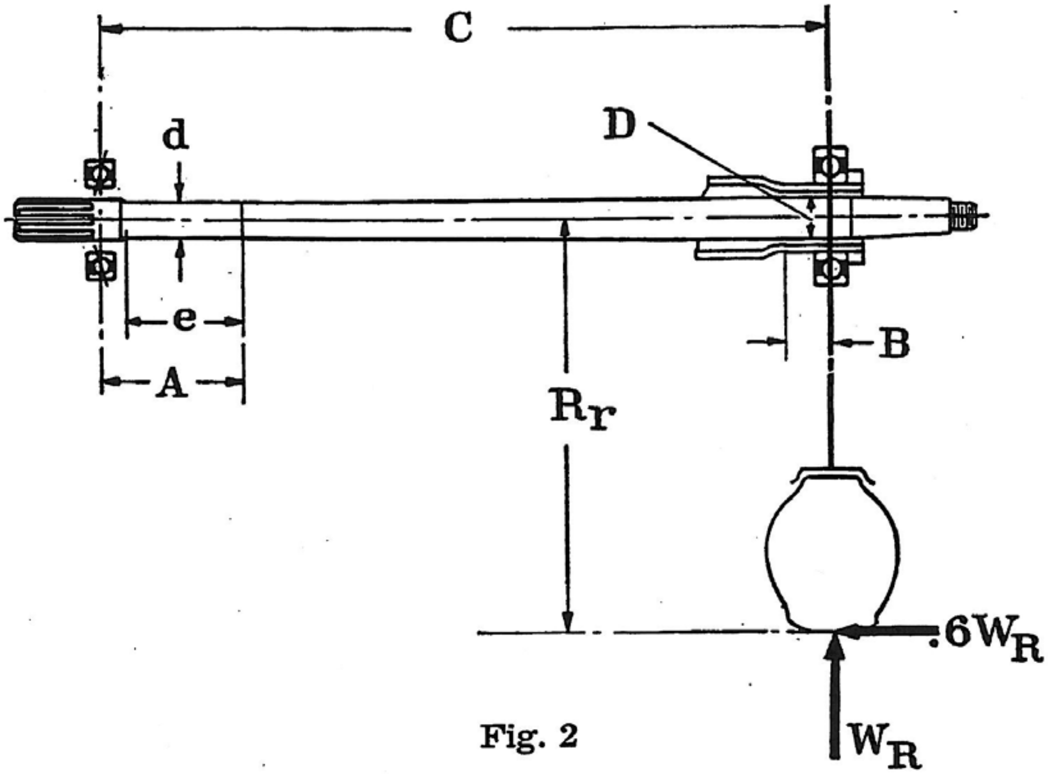


Fig. 2

C) Full-Floating Axle: In this design, the wheels are supported by two bearings that mount on the outer end of the axle tubes. Wheel forces due to vehicle weight, vehicle tractive effort, and side skid load are reacted by the axle tubes. The outer end of the axle shaft is unsupported or "floats" in the axle tube and transmits torsional drive forces only. This design is used for heavy duty applications.

Figure 9 has a sketch of the full-floating axle design. The axle shaft supports torsional loads only while the axle tube supports all other loads. The equation is as follows:

$$S = Q_1/(\pi/16)D^3$$

Rearranging:

$$D = 1.721(Q_1/S_S)^{1/3}$$

Q_1 = One-half maximum low gear torque in inch-pounds.

2) Independent Suspension Drive Axles: An independent suspension drive axle is one in which the vertical movement of one wheel is independent of the vertical movement of the wheel on the opposite side. This has the advantage of producing a better ride than the rigid axle type for the following reasons:

- The vertical movement of one wheel when striking an obstruction on the road is not transported across the entire width of the vehicle.
- The unsprung weight of the front suspension is decreased because the axle center section is fastened directly to the vehicle frame.
- Axle center section gear forces are absorbed directly by the vehicle frame without having to travel through the entire suspension system.

There are two major types of independent suspension axles: the "swing type" and the "parallel type". (See Figure 10.) Each of these types has the axle center section attached to the frame, and axle shafts that are attached by universal joints to the axle differential.

Figure 9

Full-Floating Axle Analysis

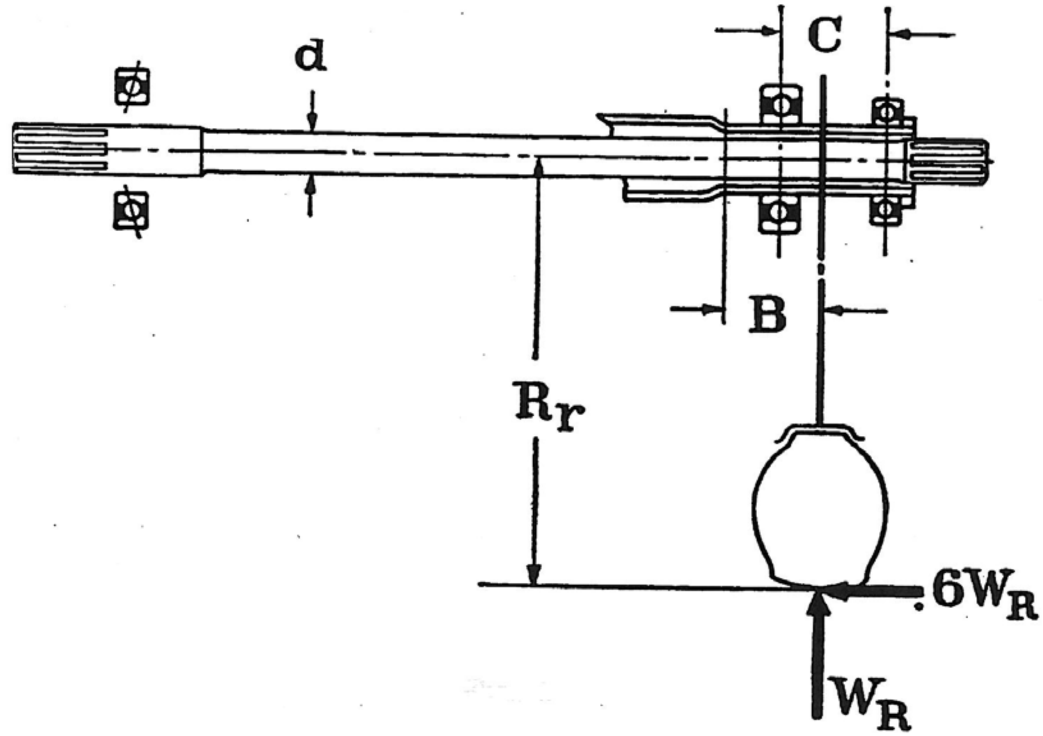
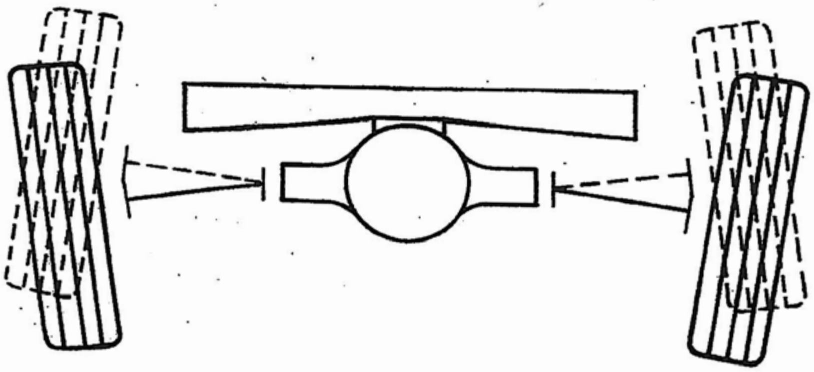
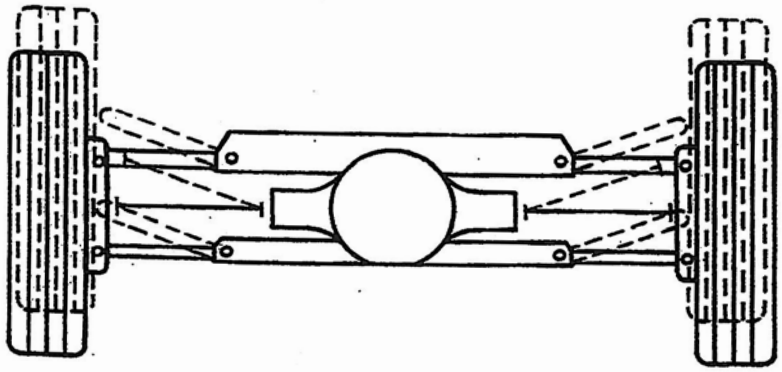


Figure 10



Swing-Type Independent-Suspension Axle



Parallel-Type Independent-Suspension-Axle

The angle between the horizontal plain of the vehicle and the axle shafts centerline can vary.

A) The swing type has axle shafts that attach directly to the wheels, consequently; the wheels are not necessarily held perpendicular to the road.

B) The parallel type has a second set of universal joints at each wheel. This configuration fixes the wheel position perpendicular to the road.

Rigid Drive Axle Housings

Rigid drive axle housings are divided into three major types: “unitized housing” (Salisbury, Spicer), “separable housing” (banjo), and “trumpet”:

1) Unitized Housing: This version as shown on Figure 11 is designed as a one-piece casting into which the axial shaft tubes are inserted and act as load supporting members. There is an opening in the rear of the housing which allows assembly of the parts inside. A sheet metal cover is used to cover the rear opening. In this design, the ring gear bearings are enclosed by the casting and are preloaded by physically spreading their mounts and installing the correct shims behind each bearing. (The pinion gear bearings are adjusted using a special machine which sets the preload by rotating the pinion shaft clamping nut against a compressible sleeve until a predetermined torque value is reached.) This carrier design has large ribs extending from the pinion housing to the axial shaft sockets giving ample support to internal drive gear reaction forces.

2) Separable Housing: This is a two-piece design as shown on Figure 12 featuring a carrier/differential unit which fits into the large opening in the center of the axle housing. Since the space between the ring gear bearing supports is limited, the size of the ribs is minimal making it difficult to achieve adequate support for the gears. In this design, the carrier housing supports the pinion and gear forces while the axle housing supports the weight of the vehicle. Ring gear preload is readily adjusted by means of internal nuts in the bearing supports. The carrier can be removed from this axle without separating it from the suspension system or removing brake lines.

3) Trumpet Type: This design as shown on Figure 13 consists of a center section enclosing the right angle gearset and carrier/differential unit. Attached to each side of this, are two long tubular members with flanged ends which carry the ring gear bearing seats. Since this design allows complete containment of the differential bearings by an adequately ribbed housing, it is possible to achieve a very rigid unit. However, because of a blind assembly, it is relatively difficult to manufacture and service and; therefore, not frequently used.

Figure 11

Rigid Axle Unitized Housing

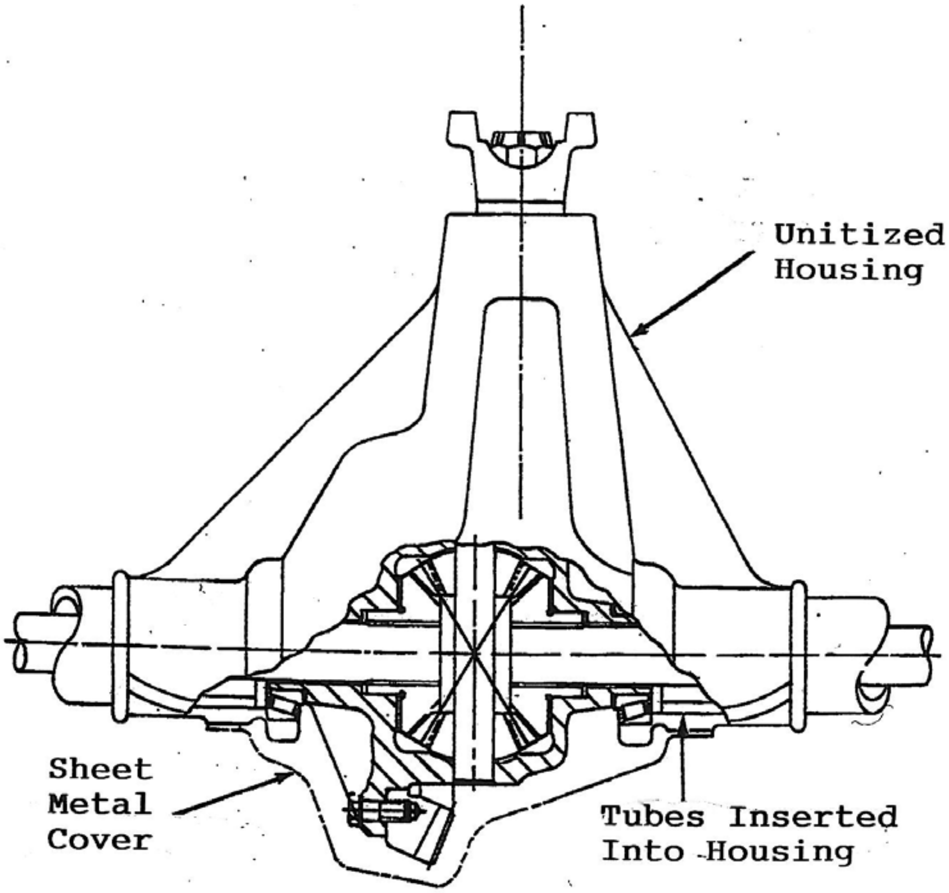


Figure 12

Rigid Axle Separable Housing

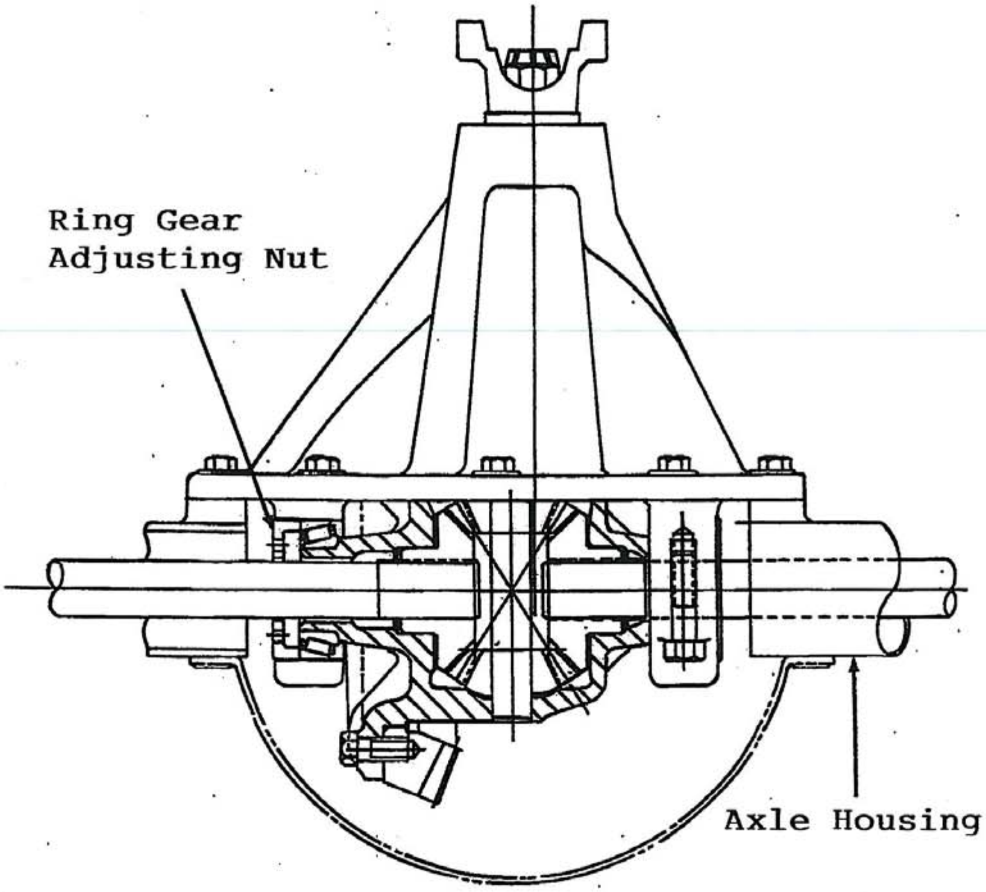
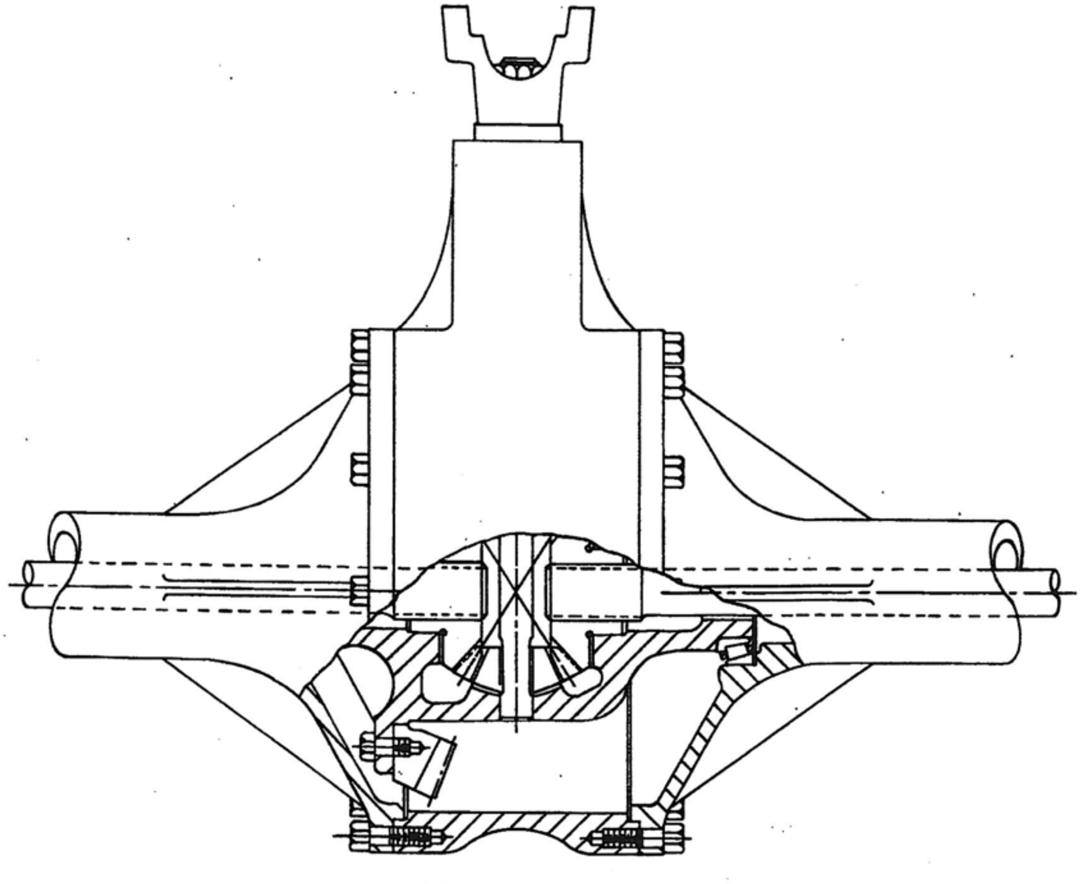


Figure 13

Rigid Axle Trumpet Housing

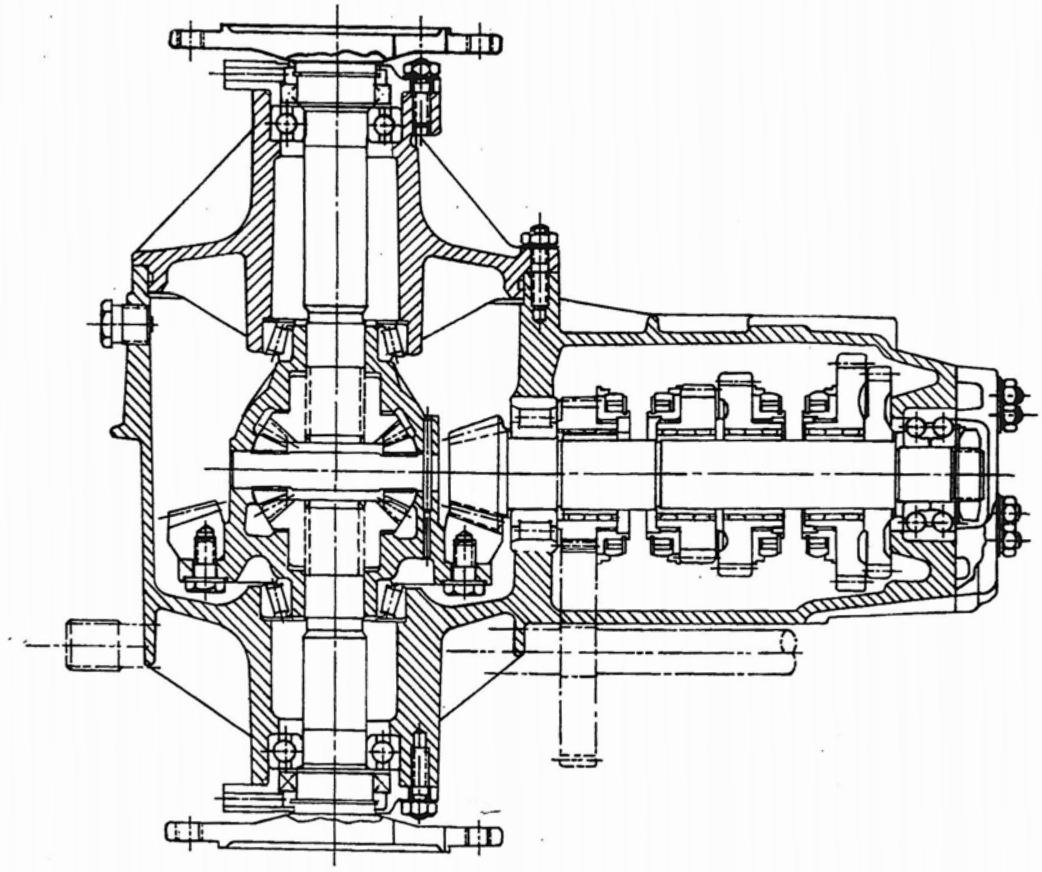


Transaxles

Transaxles are used in the new lightweight front engine, front drive cars. (See Figure 14.) A transaxle is one unit that combines the transmission and the drive axle. Each drive shaft between the transaxle and the front steering wheels contain a Rzeppa joint. Rzeppa assemblies are constant velocity universal joints that are extremely valuable design tools. They combine universal angle and constant velocity operation; features that are not available on other similar products. (Rzeppa joints were invented by American automotive engineer Alfred Rzeppa in 1926.)

Figure 14

Automotive Transaxle



Drive Gear Comparison

Drive axle bevel gears can be either spiral bevel or hypoid; the main difference being the vertical distance from the pinion shaft axis to the larger ring gear axis and; therefore, from the vehicle drive shaft with respect to the vehicle passenger compartment and the road. As previously mentioned, when the axes of the pinion and ring gear intersect, the gearset is called “spiral bevel”. When the axis of the pinion is either below or above the axis of the ring gear, the gearset is called “hypoid”. Spiral bevel gears were first used, but when the hypoid was introduced, it was used to either lower or raise the vehicle drive shaft to the designer’s advantage. The following compares the performance of spiral bevel to that of hypoid gears:

- Offset: The ability to move the pinion gear axis vertically with respect to the ring gear axis gives hypoid gears a distinct advantage over spiral bevel gears in the design of automotive vehicles.
- Strength: For ratios of 4.5/1 and above, hypoid gears are stronger. For moderate ratios, the strength of the two types is comparable. For ratios of 2/1 and below, it should be noted that the diameter of the hypoid pinion may become excessive reducing vehicle ground clearance.
- Efficiency: Spiral bevel gears operate at efficiencies as high as 99% while hypoid gears operate at efficiencies as high as 96%; a characteristic that is important in the design of today’s fuel efficient vehicles.
- Manufacture: Spiral bevel and hypoid gears are manufactured on the same machines making the cost of production about the same; however, because of the larger pinion of the hypoid, the cutter is more durable and the teeth may be lapped faster and more uniformly.
- Quietness: Hypoid gears operate quieter than spiral bevel gears; an attribute that is important for vehicle passenger convenience. Extreme pressure lubricants are used with both spiral bevel and hypoid gears because of sliding between the teeth tending to break down elastohydrodynamic lubricating films.

Drive Gear Design

The selection of drive axle gears should theoretically be based on the most power demanding driving schedule of a maximum loaded vehicle. Since this information is hard to obtain, in the past, it was based on maximum engine torque delivered through the transmission lowest gear. This only occurs if this value is greater than wheel slip torque. Wheel slip torque is dependent on the load on the driving axle, vehicle rate of acceleration, coefficient of friction between the tire and road, condition of road surface, and the highway grade. The above analysis does not apply to high performance sports cars with manual transmissions, where it is possible to obtain maximum torques 2 to 5 times greater when the clutch is suddenly released.

A more recent method of analyzing torque on drive axle gears based on normal loads and overall car performance (performance torque) has resulted in a more reliable estimate of the minimum drive gear sizes required for passenger cars. It bases gear size not on occasional peak loads but maximum sustained loads during the life of the vehicle. The stresses endured from the sustained load driving must not exceed the endurance limit of the gear material.

The sustained loads result from vehicles accelerating on highway grades with rolling resistance. Following is a formula that has been used for calculating performance torque based on an equivalent grade, taking into account actual highway grades, acceleration characteristics of the vehicle, and road rolling resistance. The highway grade factor is based on an 8% incline which is very rarely exceeded. Vehicles will be able to climb steeper grades but they will be encountered infrequently. The performance factor is based on the ratio of vehicle weight to engine power and is a measure of vehicle acceleration. Road rolling resistance is dependent on the type of road surface and its condition.

$$T_{PFG} = W_C\, r_R / n_a\, (G_H + G_P + G_R)$$

T_{PFG} = performance torque, in lb in or Kg m

W_C = gross combination weight, lb or Kg. This is the curb weight plus weight of passengers and luggage plus loaded trailer if used.

r_R = tire rolling radius, in or m

n_a = efficiency of drive axle. 90% for hypoid and 95% for spiral bevel gears

G_H = highway grade factor. Use 8 for normal passenger car.

G_P = performance factor = $16 - (K_N\, W_C / T_E)$, Use zero when negative.

K_N = conversion factor, Use 0.64 English or 0.195 metric

T_E = maximum net engine output torque to the drive axle, lb-ft or kg-m

G_R = road rolling resistance, See Figure 15.

When the performance torque has been calculated, a preliminary ring gear diameter for overhung pinions can be determined from Figure 16 for a hypoid pinion offset to ring gear diameter ratio of 0.15 and a maximum tooth contact stress of 250,000 psi. Other offsets with a maximum tooth bending stress of 30,000 psi can be calculated using similar graphs. The ring gear diameter determined above is the minimum gear size. Other factors may require a larger gear, such as a large diameter differential side gear or a high performance sports car with a manual transmission.

Using the same performance torque as above, the differential side (larger) gear diameter may be determined using a similar method.

Figure 15

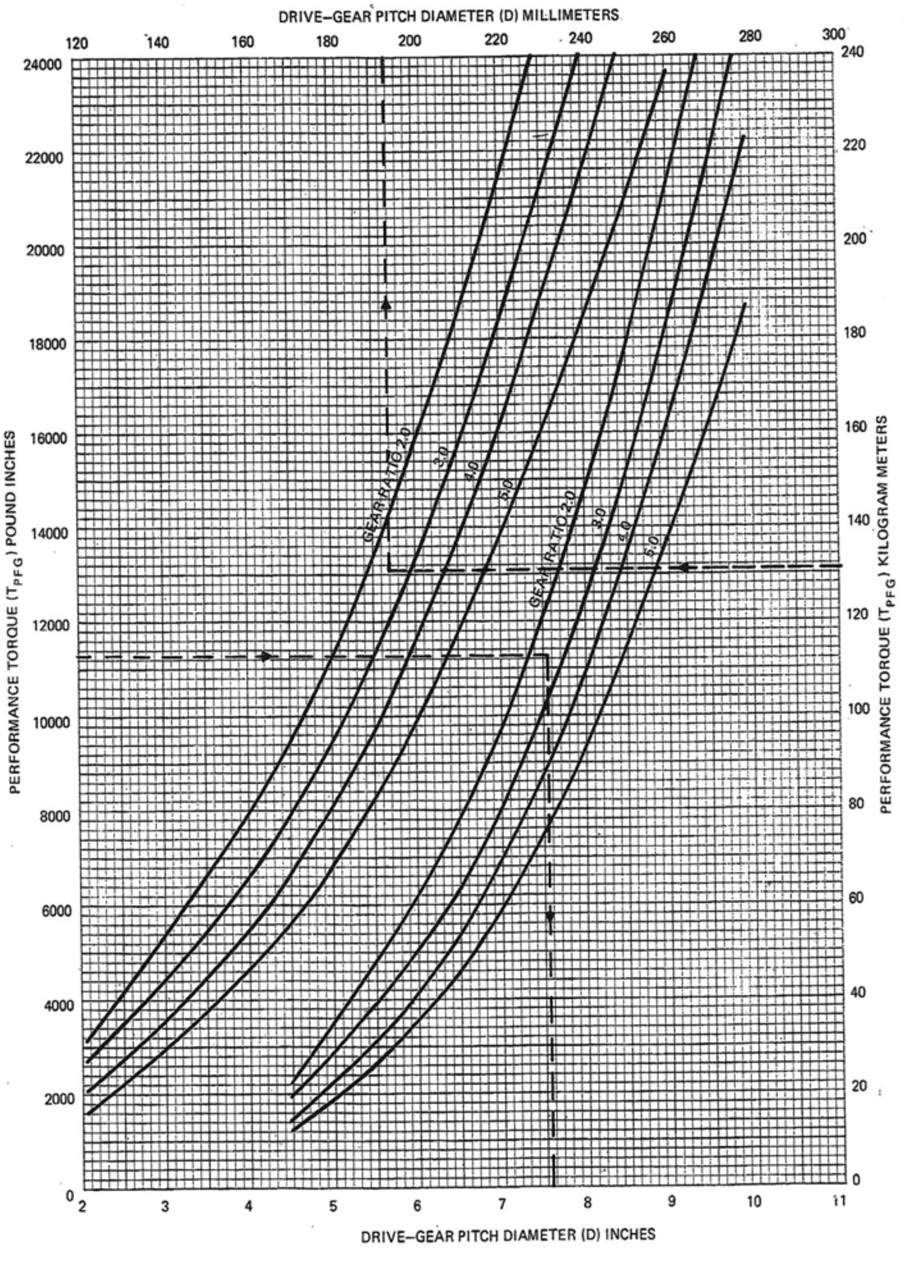
Road Rolling Resistance Factor

		G_R Factor Condition of Surface		
Road Class	Road Surface Type	Good	Fair	Poor
I	Cement concrete Brick Asphalt block Alphalt plank Granite block Sheet Asphalt Asphaltic concrete Bituminous macadam (high type) Wood block	1.0	1.1	1.2
II	Bituminous macadam (low type) Bituminous (tar) Oil mats (oiled macadam) Treated gravel	1.2	1.6	2.0
III	Sand-clay Gravel Crushed stone Cobbles	1.5	2.0	2.5
IV	Earth Sand	2.0	2.5	3.5

Figure 16

Chart for selecting preliminary drive-gear pitch diameter (hypoid) based on the following:

- gear face width approximately 30 percent of the cone distance
- pinion offset approximately 15 percent of the gear diameter
- pinion spiral angle selected
- 19 degree average pressure angle
- cutter radius selected
- tilted rootline taper
- maximum contact stress of 250,000 psi.



Drive Gear Specifications

Number of Teeth: Figure 17 has a chart depicting the number of pinion teeth and the corresponding number of total teeth for commonly used drive gears with ratios from 2.000 to 4.500. When choosing which combination to use for a given ratio range, the following considerations should be made:

1) If the total number of teeth is less than that listed on the chart, the contact ratio is lowered and the gears may not operate smoothly. The contact ratio is a measure of how many teeth are in contact at any point in time.

2) If the total number of teeth is more than that listed on the table, cost is increased because of the increased production methods and time involved.

3) Within each range, higher tooth numbers result in quieter operation and less susceptibility to surface damage while lower numbers are less apt to fail because of tooth bending strength.

4) The darkened tooth totals represent those that have "hunting ratios". A hunting ratio is one where each tooth in the pinion will contact *every* tooth in the gear before it contacts any gear tooth a second time. This also holds true in the manufacturing process depending on the type of cutter and lapping equipment used. Hunting ratios result in more equalized tooth wear and tooth spacing although some of the tooth totals not darkened have operated successfully.

Diametral Pitch: Diametral pitch is a measure of tooth size. The diametral pitch is determined by dividing the number of teeth in the gear by the gear pitch diameter. In the metric system diametral pitch is called "module" and is determined by dividing the gear pitch diameter in millimeters by the number of teeth in the gear. For automotive passenger car axle drive axles, diametral pitches normally range from 4.0 to 6.6 (6.35 to 3.85 module). (See Figure 18.)

Figure 17

Number of Drive Gear Teeth

	PINION TEETH										
RATIO	11	12	13	14	15	16	17	18	19	20	21
2.000 2.039							34	36	38	40	42
2.040 2.079							35	37	39	41	43
2.080 2.119							36	38	40	42	44
2.120 2.159						34			41	43	
2.160 2.199						35	37	39			
2.200 2.239							38	40	42	44	
2.240 2.279						36		41	43	45	
2.280 2.319						37	39		44		
2.320 2.359					35		40	42			
2.360 2.399						38		43	45		
2.400 2.439					36	39	41		46		
2.440 2.479					37		42	44	47		
2.480 2.519						40		45			
2.520 2.559					38		43	46			
2.560 2.599				36		41	44				
2.600 2.639					39	42		47			
2.640 2.679				37	40		45				
2.680 2.719				38		43	46				
2.720 2.759					41	44					
2.760 2.799				39			47				
2.800 2.839					42	45	48				
2.840 2.879			37	40	43	46					
2.880 2.919 *											
2.920 2.959			38	41	44	47					
2.960 2.999*											
3.000 3.039			39	42	45	48					
3.040 3.079			40	43	46	49					
3.080 3.119	34	37									
3.120 3.159			41	44	47						
3.160 3.199	35	38									
3.200 3.239			42	45	48						
3.240 3.279	36	39			49						

	PINION TEETH						
RATIO	8	9	10	11	12	13	14
3.280 3.319			33			43	46
3.320 3.359					40		
3.360 3.399				37		44	
3.400 3.439			34		41		
3.440 3.479		31		38		45	
3.480 3.519			35		42		
3.520 3.559		32		39		46	
3.560 3.599					43		
3.600 3.639			36	40		47	
3.640 3.679		33			44		
3.680 3.719			37				
3.720 3.759				41	45		
3.760 3.799		34					
3.800 3.839			38	42	46		
3.840 3.879*							
3.880 3.919		35	39	43	47		
3.920 3.959*							
3.960 3.999*							
4.000 4.039	32	36	40	44	48		
4.040 4.079*							
4.080 4.119		37	41	45			
4.120 4.159	33						
4.160 4.199				46			
4.200 4.239		38	42				
4.240 4.279	34			47			
4.280 4.319			43				
4.320 4.359		39					
4.360 4.399	35			48			
4.400 4.439			44				
4.440 4.479		40		49			
4.480 4.500	36		45				

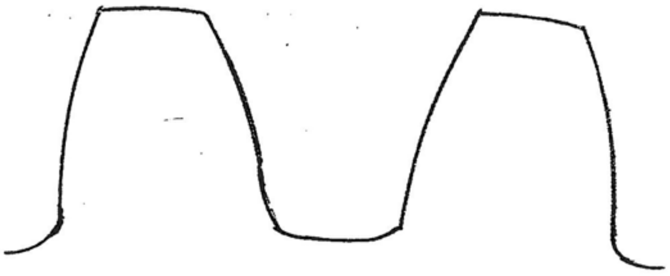
* *There are no combinations in these ratio ranges which are within recommended tooth number sums.*

Figure 18

Gear Teeth Drawn to Scale

7 Diametral Pitch
(3.63 Module)

4 Diametral Pitch
(6.35 Module)



1 3/4 Diametral Pitch
(14.51 Module)

Differential Gears

In order to power the two driving wheels at different speeds such as when rounding a corner, two sets of straight bevel gears which face each other are used. (See Figure 19.) The drive ring gear is rigidly attached to the carrier which has a pin driving the two differential straight bevel gear pinions. Each bevel ring gear is splined to an axle shaft which drives the vehicle wheels. This unique arrangement allows power to be delivered to each driving wheel at equal speeds as well as at different speeds.

Limited Slip Differential: One disadvantage of the differential is that when one wheel of a vehicle is on a surface such that it slips freely, all the driving torque is directed to its side of the differential and the vehicle becomes immobile. The slipping wheel rotates at twice the speed that it would under normal driving conditions. The limited-slip differential is a unit that allows normal differential action during cornering but allows some driving torque to be delivered to the wheel that is on a tractive surface when the opposite wheel is spinning freely on a non-tractive surface. This action allows the vehicle to free itself in some situations where, without it, it might become completely immobile.

Figure 19

Differential Gears