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LECTURE NOTE 4

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Vehicle Dynamics

Vehicle rollover is a complex event that has been the subject of many investigations since the 1950s. The term “rollover” describes the condition of at least a 90-degree rotation about the longitudinal axis of a vehicle. When lateral forces create a large enough roll moment about the vehicle’s center of gravity for a sufficient length of time, the vehicle will roll over. These lateral forces can be generated under a variety of conditions, such as contact with a mechanical obstacle (a curb, pothole, or furrow plowed during an off-road manoeuvre), or during manoeuvres on the roadway.

A wide variety of testing has been performed in an effort to understand rollover. Vehicle tests and simulations typically deal with the onset of rollover rather than a full 90-degree roll. Testing generally falls into one of two categories:

- *Static testing* is performed in the laboratory. It may involve the measurement of vehicle parameters (e.g., center of gravity height, track width) that are then combined to yield static metrics related to a vehicle’s rollover propensity—for example, static stability factor (SSF). Alternatively, static tests of entire vehicles, such as the tilt table and side pull tests described may be performed to obtain data that can be correlated with a vehicle’s rollover propensity.
- *Dynamic testing* is performed on a test track and involves driving maneuvers. Although dynamic tests are potentially helpful in understanding the events immediately preceding rollover, they are expensive and require safety precautions for test drivers. Furthermore, repeatability may be difficult to achieve. In view of the challenges associated with dynamic testing, computer stimulations have been undertaken using mathematical models to predict vehicle behavior associated with rollover.

BACKGROUND

With few exceptions, vehicles that may roll over during a vehicle test are constrained by outriggers that prevent rollover. Test engineers define the onset of roll in a variety of ways. Most conservatively, the onset of roll is defined as at least one wheel leaving the ground during the course of a test; less conservative definitions require two-wheel liftoff or contact of the outriggers with the test pad. From the viewpoint of simulation, the onset of rollover may also be determined in a variety of ways. The vehicle model leading to SSF characterizes the onset of rollover as a scenario in which the lateral forces become large enough that, if they continue long enough, rollover must result. As Figure 2-1 indicates, *T* is the track width (strictly, the average of the front and rear track widths), and *H* is the height of the vehicle's center of gravity. SSF is defined as the track width divided by twice the center of gravity height; i.e., SSF = $T/2H$. The theoretical basis for SSF calls for rollover if the sum of the lateral forces on the tires, divided by the weight of the vehicle, is greater than $T/2H$ for a sufficient length of time (Gillespie 1992). Using more complex models, analysts focus on the instant when both of the normal forces between the tire and the road on one side of the vehicle drop to zero in the course of a given maneuver. Alternatively, incipient roll can be categorized by the instant in time when the vehicle's center of gravity moves beyond the balance point above the leading side tires, as illustrated in Figure 2-2.

Rollover events are sometimes classified as either tripped or un-tripped. A rollover that occurs as a result of forces on the tire created by a mechanical obstacle, such as a curb or other surface irregularity (e.g., a furrow plowed during an off-road maneuver), is described as tripped. In contrast, a rollover is described as untripped if the vehicle rolled solely as a result of the lateral forces created at a smooth tire–road interface. The National Automotive Sampling System Crashworthiness Data System categorizes rollovers as either tripped or un-tripped on the basis of interpretation of crash scene and vehicle inspections, as well as other supporting evidence. However, the physics governing the motion of vehicles reveals that it is the magnitude and duration of the forces on the vehicle that determine whether

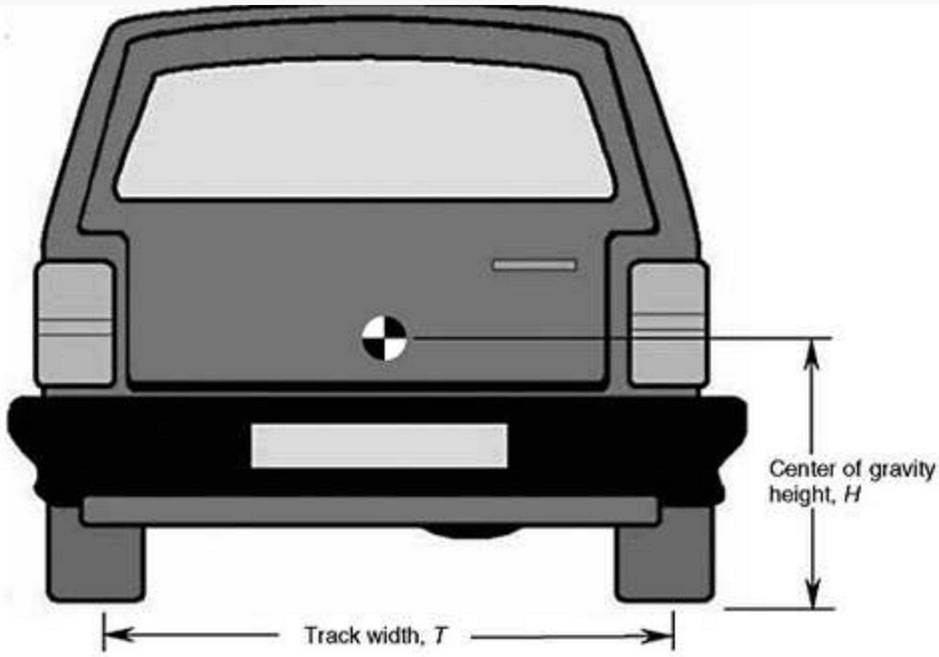


FIGURE 2-1 Important dimensions relating to SSF.

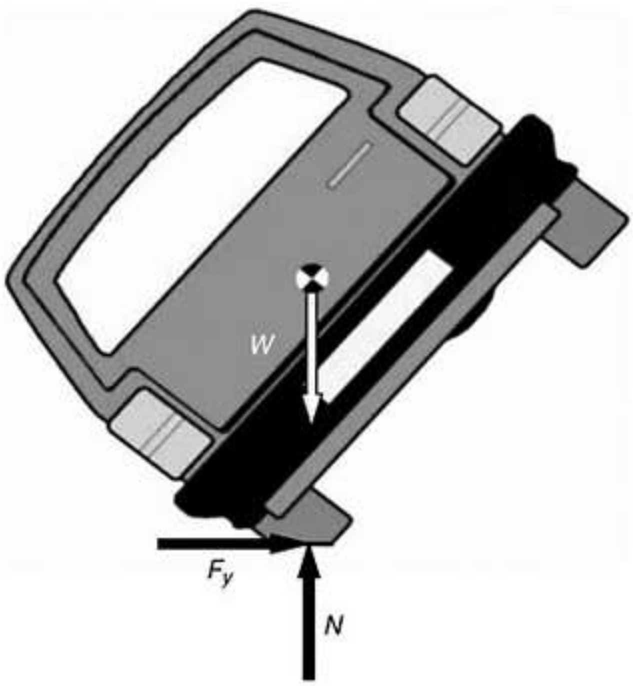


FIGURE 2-2 Vehicle at incipient rollover (the balance point).

(NOTE: F_y = lateral force; *N* = normal force; *W* = weight of vehicle.)

a rollover will occur (see the later discussion of SSF). Therefore, the present discussion focuses on the magnitude of the forces rather than the mechanism of force generation, and is not concerned with making the distinction between tripped and un-tripped rollovers.

STATIC MEASURES OF ROLLOVER PROPENSITY

Several static measures and tests have been developed to characterize a vehicle's rollover propensity (see, for example, Lund and Bernard 1995b). The commonly cited measures fall into two categories:

- Quantities such as SSF and critical sliding velocity (CSV) that are calculated from measured vehicle parameters; and
- Quantities derived from tests of entire vehicles—notably the tilt table test, side pull test, and centrifuge test—that depend on experimental results instead of measurements of vehicle dimensions and inertial properties.

- The following discussion addresses the advantages and disadvantages of these different static measures, with particular emphasis on SSF—the metric that forms the basis for NHTSA's star ratings for rollover resistance.
- *Static Stability Factor*

When a vehicle has a velocity vector at a large angle from the direction in which it is aligned, the tire–road interface can generate large lateral forces on the tires, as illustrated in Figure 2-3. Assuming a rigid-body model, that is, a model that does not deflect under the influence of the applied forces, straightforward physics yields the insight that if the sum of the lateral forces on all four tires is large enough for a sufficiently sustained period of time, the vehicle will roll over. Note that the rigid-body model cannot predict time-dependent details of the rollover, which are scenario-specific. Simulation of time-dependent rollover requires a much more complex model (see, for example, Chrstos and Heydinger 1997).

- In particular, the vehicle model predicts rollover if, for a sufficiently sustained period of time

$$\sum F > W(T/2H)$$

- where W is the weight of the vehicle, $\sum F$ indicates the sum of the lateral forces on all four tires, and $T/2H$ is the vehicle's SSF.
- Relationship 1 is often viewed another way. Fundamental physics states that

$$\sum F = ma$$

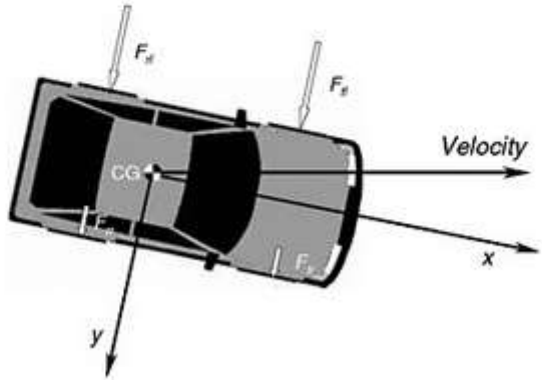


FIGURE 2-3 Lateral forces leading to rollover: plan view with steered wheels to the front.

(NOTE: *xy* axis = vehicle coordinate axis; F_{rl} = lateral force on the rear left tire; F_{fl} = lateral force on the front left tire; F_{rr} = lateral force on the rear right tire; F_{fr} = lateral force on the front right tire; and CG = center of gravity.)

- where a is the lateral acceleration, and m is the mass of the vehicle (= W/g, where g is the gravitational constant).

It follows directly from Relationship 1 and Equation 2 that if, for a sustained period of time,

$$a/g > T/2H$$

the vehicle model will predict rollover. This relationship is a scientifically valid statement of the physics of the motion of this vehicle model and the cornerstone of the utility of SSF. In particular, the model predicts that rollover will occur when the lateral acceleration in g's exceeds the SSF for a sustained period of time.

- Consider now Relationship 3 in the context of a smooth road surface. For the scenario depicted by Figure 2-3, it is common to characterize the relationship between the lateral forces on the tires and the normal load upward on the tires by a coefficient of friction, μ. This can be stated as

$$\sum F = \mu W$$

That is, the sum of the lateral forces is equal to the product of a tire–road friction coefficient, μ, and the weight of the vehicle. In this case, Relationship 1 yields the information that if, for a sustained period of time,

$$\mu > T/2H$$

rollover will occur. For a good dry paved surface, μ may be in the neighborhood of 0.9; for a wet or icy surface, μ is considerably less.

- The importance of Relationship 5 is that if situations such as that depicted in Figure 2-3 continue for a long enough period of time, the model yields rollover if the friction coefficient characterizing the tire–road interface exceeds the SSF. If μ is relatively low, as on a wet or icy road, the vehicle will slide rather than roll because the lateral forces will be small, and the lateral accelerations will be far less than *T*/2*H*. In other scenarios not involving a smooth road surface, the large lateral forces resulting in rollover can be generated by interactions between the tire(s) and a curb, a pothole, a roadside slope, a furrow plowed during an off-road maneuver, or some other tripping mechanism. The model that leads to Relationships 3 through 5 presumes that the vehicle is a rigid body. For real vehicles, rollover is expected in maneuvers that are less severe than called for by Relationships 3 through 5 because *T* is reduced as a result of lateral compliance of the suspension and tires, suspension kinematics (geometry changes), and body roll. In addition, for large roll angles, *H* can be increased by suspension kinematics. In particular, the lateral acceleration that, in time, produces rollover is lower than the level called for by Relationship 3. Thus for a real vehicle,

- Relationship 5 indicates that rollover is expected even if μ is less than *T*/2*H*. In each case, a 15 percent lower rollover threshold is a reasonable expectation, with the variation among particular vehicles being significant (Lund and Bernard 1995b).

More detailed mathematical models can yield information about the decrease in lateral acceleration that causes rollover compared with the value indicated by SSF. In a generic sense, simple additions to the model that yields SSF give an indication of the likely decrease (see, for example, Bernard et al. 1989). However, the provision of information applicable to specific vehicles requires far more detail. Furthermore, implementing vehicle-specific details in a complex simulation involves a great deal more time and expense than testing the vehicle itself. Thus the compelling feature of SSF, as seen in Relationships 3 through 5, is that it provides a clearly defined bound: if the sustained lateral acceleration exceeds this bound, rollover occurs. Follow-up analysis, not obvious from the preceding discussion, indicates that although the lateral acceleration in *g*'s can exceed *T*/2*H* for a short time without causing rollover, the more this acceleration exceeds *T*/2*H*, the less will be the time to rollover. Rollover events involving very large lateral accelerations far in excess of *T*/2*H g* are sometimes classified as tripped rollovers.

Critical Sliding Velocity

Like SSF, CSV is calculated using measurements of vehicle parameters. CSV is an estimate of the minimum sideways velocity required for a vehicle to just barely tip over as a result of sliding sideways into a curb, as illustrated schematically in Figure 2-4. [A simple derivation of CSV is presented by Meriam (1959) and Jones (1973), with slightly more complicated versions presented by Lund and Bernard (1995a).] Like SSF, CSV increases when track width increases and decreases when center of gravity height increases. A criticism of this measure is that it is based on the presumption of no energy loss after the collision with the curb, thus ignoring important losses in the suspensions (Gillespie 1992). Furthermore, in contrast to SSF, which is about equally sensitive to changes in *T* and *H*, CSV is much more sensitive to *T* than to *H*. This greater sensitivity derives from CSV's focus on curb trip as opposed to the more general focus of SSF—a vehicle sliding out of control on a smooth surface (Lund and Bernard 1995b).

Tilt Table Ratio

To determine tilt table ratio (TTR), the vehicle is positioned at rest on a table. As indicated by Figure 2-5, the table is tipped up until the (restrained) vehicle attempts to roll downhill. TTR is the tangent of the angle of the table when the front and rear wheels on the uphill side of the vehicle first lift up. If the suspension of the vehicle and its tires were rigid rather than compliant, the measurement of TTR would be the same as SSF. Some believe TTR is a better measure than SSF and CSV because it includes some of the effects of the compliance of the suspensions and tires. Thus, TTR yields a lower threshold of minimum lateral acceleration needed to pro-

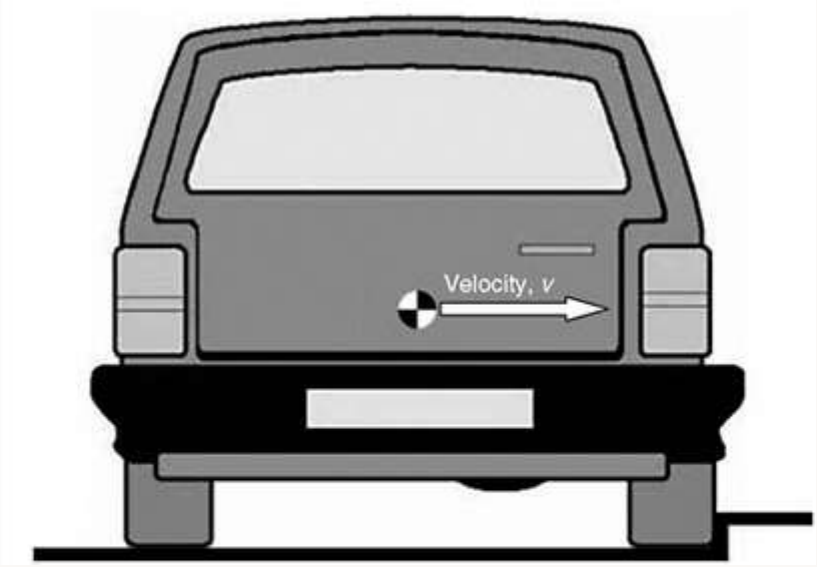


FIGURE 2-4 Configuration for use of critical slidingvelocity.

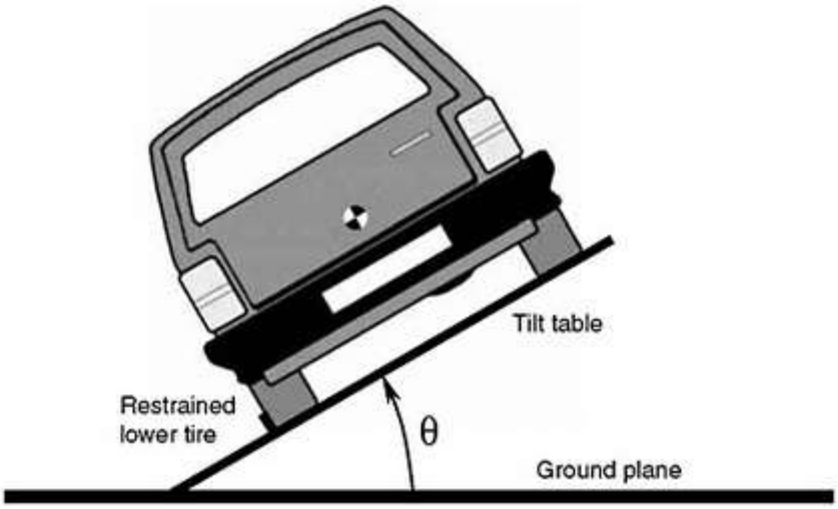
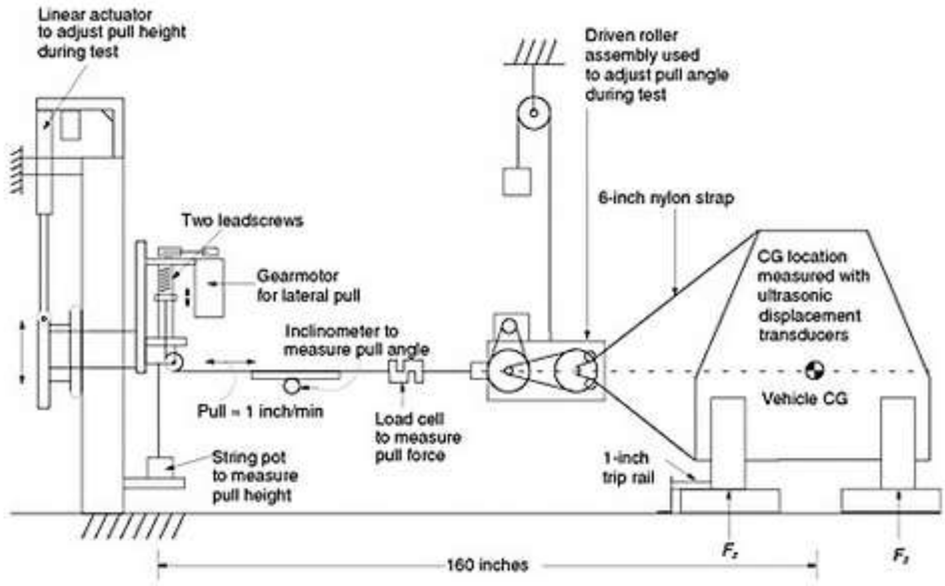


FIGURE 2-5 Tilt table test—tilt table ratio equals tangent of angle theta (θ).

duce a rollover than is the case with SSF. The flaw in the test is that as the table is tipped up, the total weight supported by the tires (perpendicular to the tilt table) drops, and the suspension tends to move into rebound (i.e., the suspension loads drop) and away from the curb equilibrium position. This in turn causes the vehicle center of gravity to move away from the tilt table, and thus makes the car more prone to rollover than it would be on a horizontal surface. There is also a potential undesirable consequence of using TTR to assess rollover propensity. In some cases, measured TTR values can be increased by altering suspensions in a way that degrades vehicle directional response. In particular, best test results are obtained by having front and rear uphill wheels lift at the same time. This means vehicles with balanced front and rear roll stiffness will yield better TTR test results than otherwise similar vehicles with unequal roll stiffness, even though unequal roll couple distribution often produces improved dynamic performance (*Federal Register* 2001). Thus, a vehicle rating system that used TTR to rank rollover propensity could encourage undesirable design trade-offs and vehicles with inferior directional response characteristics.

Side Pull Test

The side pull test provides another static measure of vehicle rollover propensity; Figure 2-6 shows a schematic of a side pull test facility. In this case, test engineers pull the vehicle sideways with a horizontal force at the height of the vehicle's center of gravity. If there were no compliance in the suspensions and tires, the force required to tip the vehicle over, divided by the weight of the vehicle, would be the same as the SSF. Because of suspension and tire



compliance, however, the side pull test yields results lower than SSF; in other words, it predicts a lower sustained lateral acceleration level required for vehicle rollover. As in the case of TTR, some believe the inclusion of suspension and tire compliances makes the side pull test superior to SSF. Detractors point out that the side pull test has one of the same flaws as TTR: it is possible in some cases to obtain improved results by making suspension changes that degrade the vehicle's directional response. Furthermore, the side pull test is difficult to perform.

- *Centrifuge Test*

Another vehicle-based static measure of rollover propensity derives from the centrifuge test, illustrated in Figure 2-7. The centrifuge device uses an arm attached to a powered vertical shaft. The test vehicle is parked on a horizontal platform at the end of the arm. As the platform rotates, the parked vehicle is subjected to lateral acceleration. When the lateral acceleration is high enough, the vehicle will tip up against its restraints. If there were no compliance in suspensions and tires, the acceleration required to tip the vehicle up would be the same as that predicted by SSF. A positive aspect of this test is that, as with TTR and side pull, compliance in the tires and suspensions influences the measurements. This test also shares an important flaw with TTR and side pull: it is possible in some cases to obtain improved results by making suspension changes that degrade the vehicle's directional response (*Federal Register* 2001).

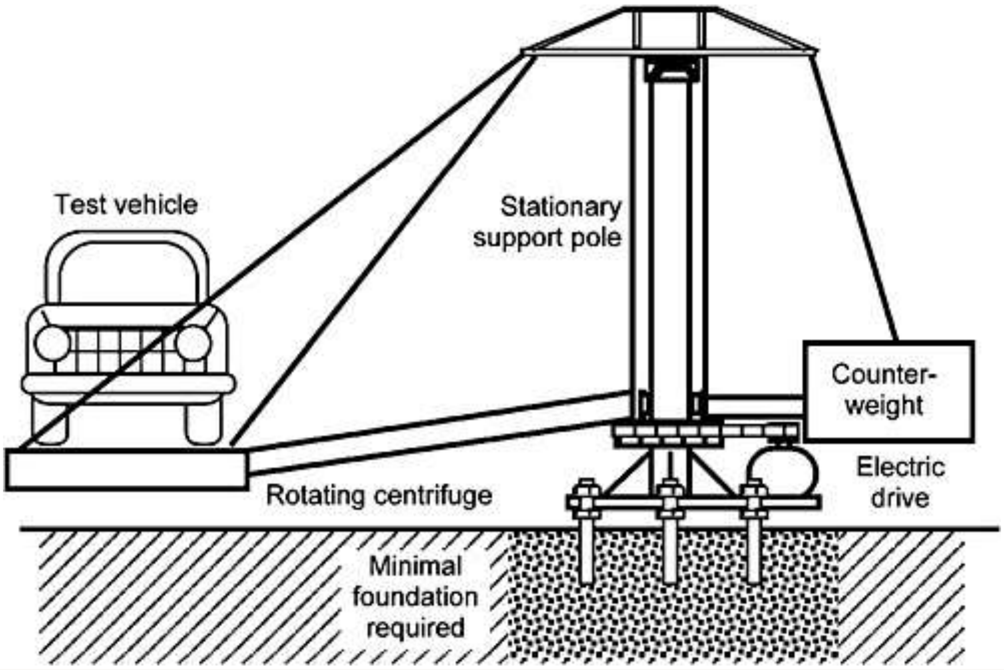
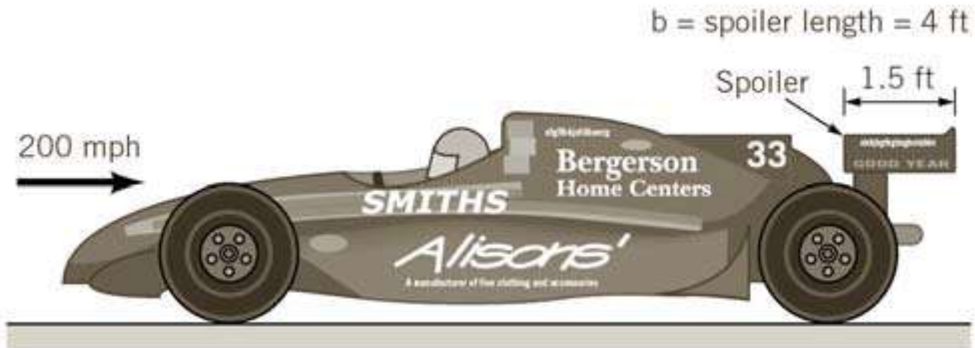


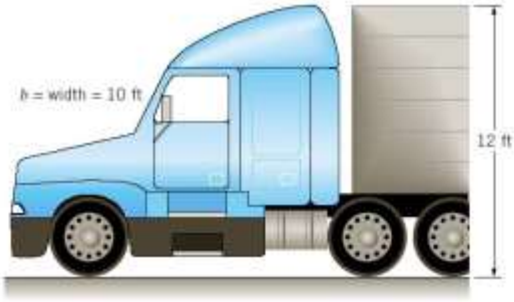
FIGURE 2-7 Schematic of centrifuge test. (SOURCE: *Federal Register* 2001.)

ASSIGNMENT.

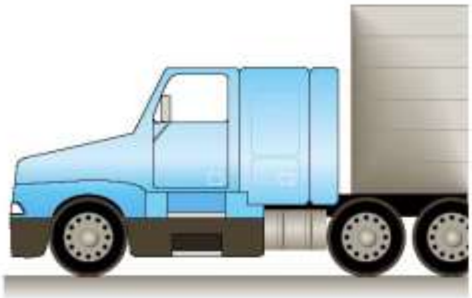
1. As shown in the Figure below, a spoiler is used on race cars to produce a negative lift, thereby giving a better tractive force. The lift coefficient for the airfoil shown is C_L = 1.1 and the coefficient of friction between the wheels and the pavement is 0.6. At a speed of 200 mph, by how much would use of the spoiler increase the maximum tractive force that could be generated between the wheels and ground? Assume the air speed past the spoiler equals the car speed and that the airfoil acts directly over the drive wheels. Ans. 405 lb.



2. As shown in the Figure, the aerodynamic drag on a truck can be reduced by the use of appropriate air deflectors. A reduction in drag coefficient from C_D = 0.96 to C_D =0.7 corresponds to a reduction of how many horsepower needed at a highway speed of 65 mph? Ans. 58.4 hp

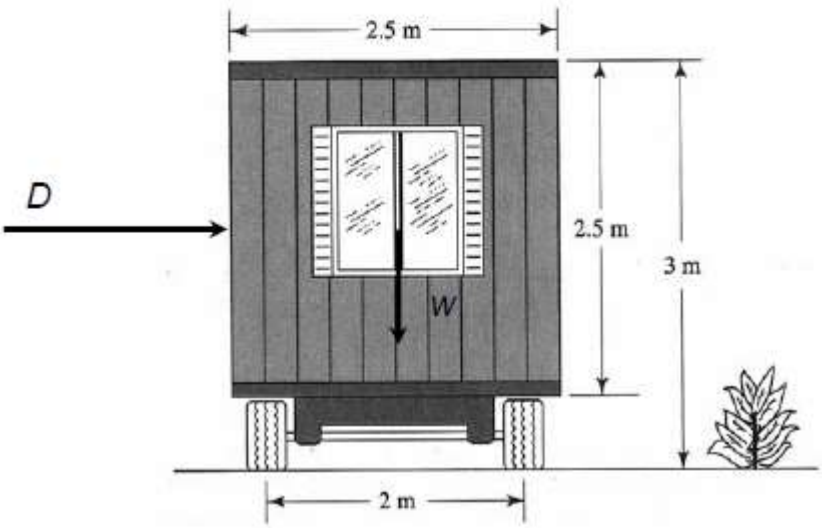


(a) C_D = 0.70



(b) C_D = 0.96

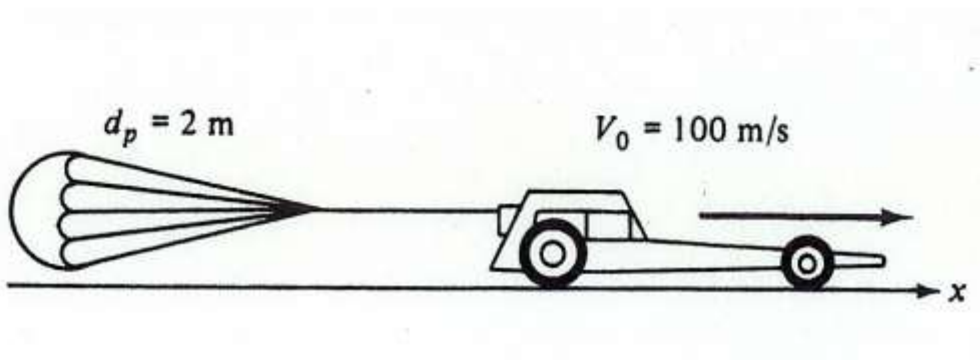
3. Determine the wind velocity required to overturn the mobile home sketched in the Figure if it is 10m long and weighs 50 kN. Consider it to be a square cylinder. Ans. 29.3 m/s



4. A high speed car with, m = 2000 kg, C_D = 0.3 and A = 1 m^2, deploys a 2-m parachute to slow down form an initial velocity of 100 m/s. Assuming constant C_D, brakes free, and no rolling

resistance, calculate the distance and velocity of the car after 1, 10, 100, and 1000 s. Neglect interference between the wake of the car and the parachute. Ans. 4.07m^2, α = 0.122s^{-1}.

t, s	1	10	100	1000
V, m/s	89	45	7.6	0.8
S, m	94	654	2100	3940



5. A 25000 kg truck coasts in a highway at 60 km/hr. Determine the power required assuming that the rolling resistance for a truck on concrete is 1.2% of the weight and the drag coefficient is 0.96. Ans. 61.3kW