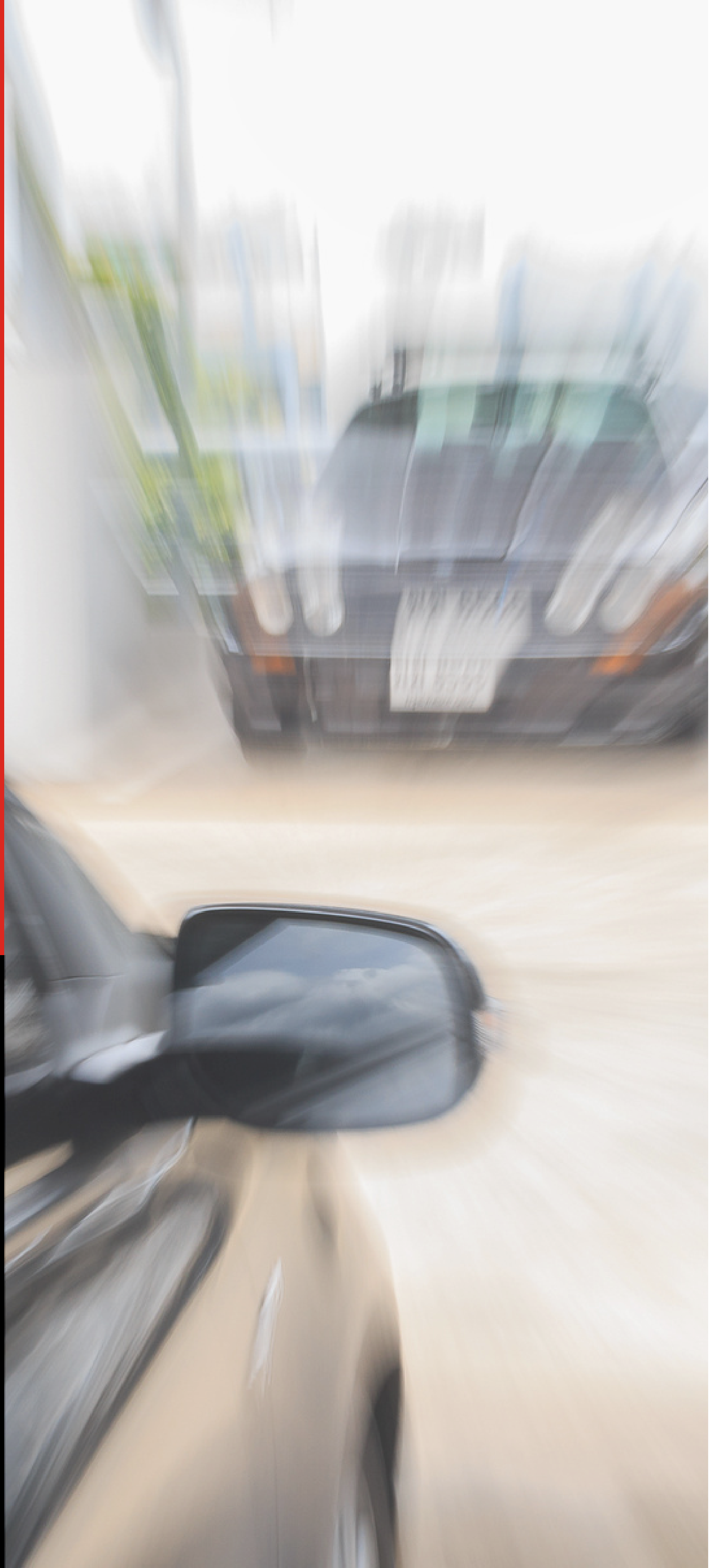
VOL. 2

VEHICLE DYNAMICS



FEATURES

Interactive Note

More Examples

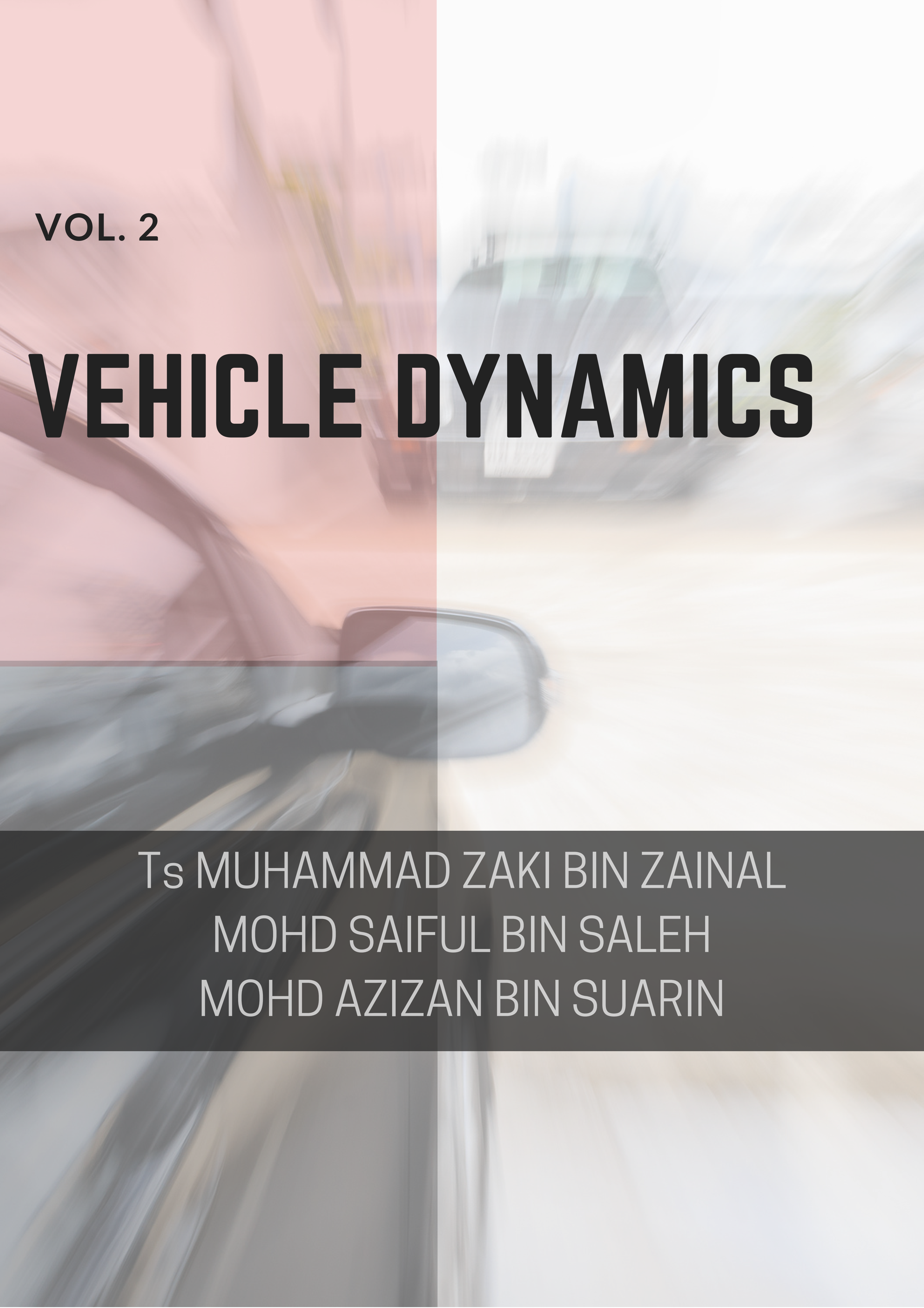
More Tutorial

Ts MUHAMMAD ZAKI BIN ZAINAL
MOHD SAIFUL BIN SALEH
MOHD AZIZAN BIN SUARIN

VOL. 2

VEHICLE DYNAMICS

Ts MUHAMMAD ZAKI BIN ZAINAL
MOHD SAIFUL BIN SALEH
MOHD AZIZAN BIN SUARIN



FIRST PUBLISHED 2023
eISBN 978-967-2421-97-9

WRITER:
TS MUHAMMAD ZAKI BIN ZAINAL
MOHD SAIFUL BIN SALLEH
MOHD AZIZAN BIN SUARIN

EDITOR:
MOHD AZIZAN BIN SUARIN

PUBLISHED BY:
POLITEKNIK UNGKU OMAR,
JALAN RAJA MUSA MAHADI, 31400 IPOH, PERAK.
TEL: 1-300-88-1693 FAX: 05-5471162

SYNOPSIS

ALL ABOUT MOVEMENTS

1. ROAD LOADS

The summation of the rolling resistance and aerodynamic forces (and grade forces, if present) constitutes the propulsion load of the vehicle, and is normally referred to as "road load."

2. RIDE

The vibration environment is one of the most important criteria by which people judge the design and construction "quality" of a car. Being a judgment, it is subjective in nature, from which arises one of the greatest difficulties in developing objective engineering methods for dealing with ride as a performance mode of the vehicle.

PREFACE

***VEHICLE DYNAMICS* introduces the principals involved dynamics for various types of vehicles regarding forces acting on vehicles propelled by engine. It focuses on the dynamics and the basic operations of the vehicle related to dynamics. Most of the discussion and examples focuses on passenger cars, although these principles are equally applicable to large and small trucks and buses.**

AUTHORS

Ts. MUHAMMAD ZAKI BIN ZAINAL obtain his Bachelor of Mechanical Engineering with Automotive Engineering from Universiti Malaysia Pahang (UMP) 2009 and Master of Mechanical Engineering (Energy Engineering) from Universiti Teknikal Malaysia Melaka (UTeM). He is currently a Senior Lecturer attached to Mechanical Engineering Department, Politeknik Ungku Omar. He has tought Vehicle Dynamics for Diploma level students in Automotive Engineering since 2013.

MOHD SAIFUL BIN SALEH obtain his Bachelor of Engineering (Mechanical - Automotive) from Universiti Teknologi Malaysia (UTM) 2009 and Master of Mechanical Engineering from Universiti Tun Hussein Onn Malaysia (UTHM) 2015. He is currently a Senior Lecturer attached to Mechanical Engineering Department, Politeknik Ungku Omar. He has tought Vehicle Dynamics for Diploma level students in Automotive Engineering since 2013.

MOHD AZIZAN BIN SUARIN obtain his Bachelor of Engineering (Mechanical - Automotive) from Universiti Teknologi Malaysia in 2009 and Master of Science in Mechanical Engineering from Universiti Teknikal Malaysia Melaka (UTeM) in 2021. He is currently a Lecturer attached to Mechanical Engineering Department, Politeknik Ungku Omar. He has 10 years of experience in teaching Automotive Engineering Courses for Diploma and Certificate level.

Contents

"The cars we drive say a lot about us. "

1. ROAD LOADS

1.1 Vehicle Aerodynamics

1.2 Rolling Resistance

1.3 Total Road Loads

1 ROAD LOAD

1.1 Aerodynamic

Vehicle Aerodynamics

- Is the study of how air resistance and drag affect a vehicle.
- Aerodynamics makes its major impact on modern cars and trucks through its contribution to "road load."
- Aerodynamic forces interact with the vehicle causing drag, lift (or down load), lateral forces, moments in roll, pitch and yaw, and noise.
- These impact fuel economy, handling and NVH (noise, vibration, and harshness)

Effect of Improvement of Flow Past Vehicle Bodies

- Reduction of fuel consumption.
- More comfort characteristics (mud deposition on body, noise, ventilating and cooling of passenger compartment).
- Improvement of driving characteristics (stability, handling, and traffic safety).

Vehicle Aerodynamics Includes Three Interacting Flow Fields

- Flow past vehicle body.
- Flow past vehicle components (wheels, heat exchanger, brakes, windshield).
- Flow in passenger component.

Aerodynamics Resistance Composed

- Turbulent air flow around vehicle body (85%).
- Friction of air over vehicle body (12%).
- Vehicle component resistance, from radiators air ventilation (3 %).

Vehicle Aerodynamics Includes Three Interacting Flow Fields

- Flow past vehicle body.
- Flow past vehicle components (wheels, heat exchanger, brakes, windshield).
- Flow in passenger component.

Mechanics of Air Flow Around a Vehicle

- The air flow around the vehicle is following the Bernoulli's principle.
- Bernoulli's principle stated that for a in viscid flow, the increased of speed of the air resulted the decreasing in pressure or vice versa (speed increase, pressure decrease) or (speed decrease, pressure increase).

Bernoulli Equation (Incompressible Flow)

$$P_{static} + P_{dynamic} = P_{total}$$

$$P_s + \frac{1}{2}\rho V^2 = P_t$$

$$\rho = 1.225(\frac{P_r}{101.325})(\frac{288.16}{273.16 + T_r})$$

Where:

$\rho =$ density of air

$V =$ velocity of moving air

$P_r =$ atmospheric pressure (kPa)

$T_r =$ air temperature (° Celcius)

Pressure Distribution on a Vehicle

- These basic mechanisms account for the static pressure distribution along the body of a car.
- The pressure is indicated as negative and positive with respect to ambient pressure measured with some distance as Figure 1.1
- Front edge of the hood developed negative pressure because the rising flow over the front vehicle and has the potential to creating drag in this area.

- Near the windshield and cowl, the flow is upward and high pressure. Ideal location for inducting air for climate control system, engine intake and lower velocity to keeping the windshield wiper.
- Negatives pressure again over roof line because the air flow follow the roof contour like billowing action of the fabric roof on convertible (folding or detachable roof) as Figure 1.2.

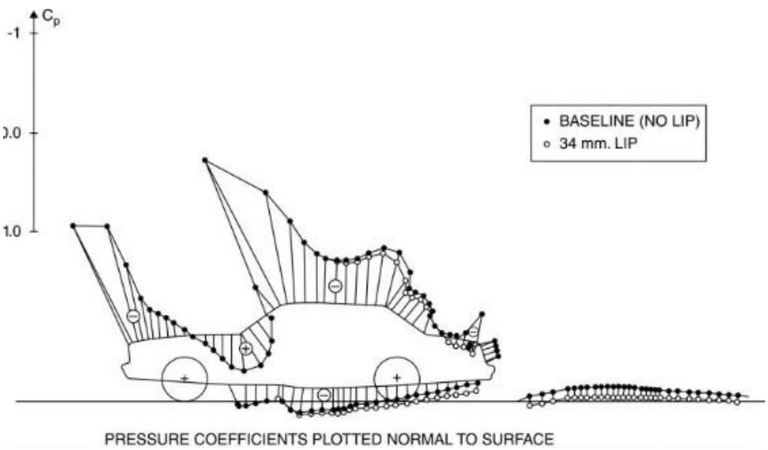


Figure 1.1 Pressure distribution along the centerline of a car

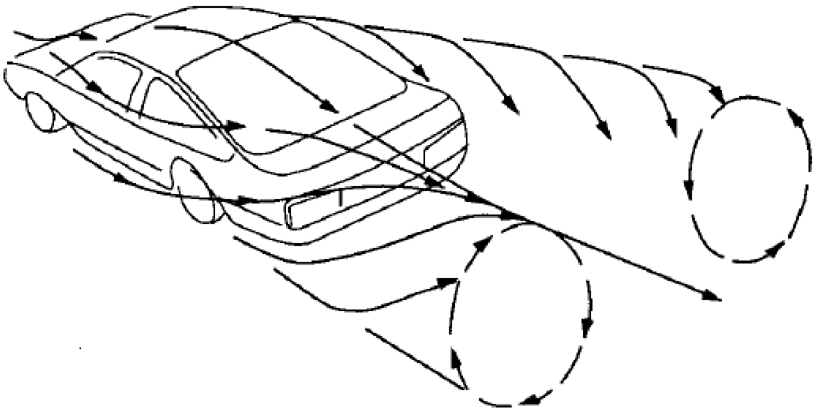


Figure 1.2 Vortex system in the wake of a car

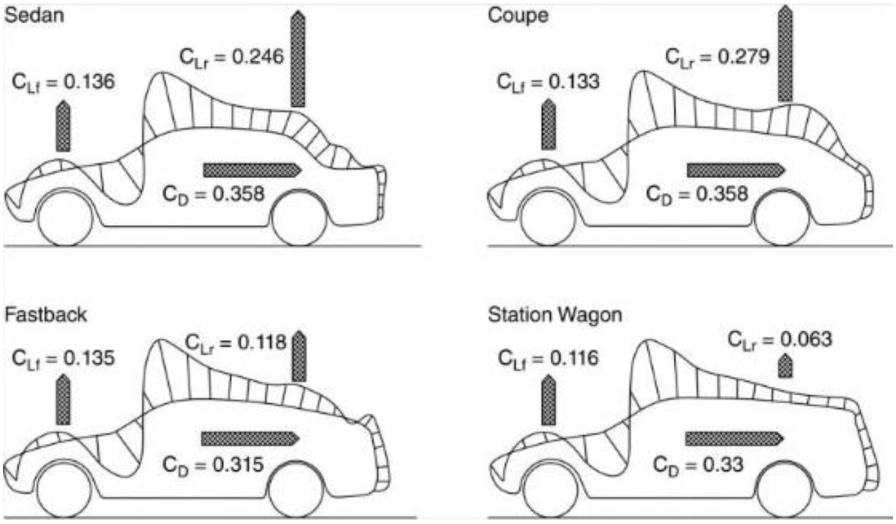


Figure 1.3 Aerodynamics lift and drag forces with different vehicle style

Effect of Separation Point on Dirt Deposition at the Car

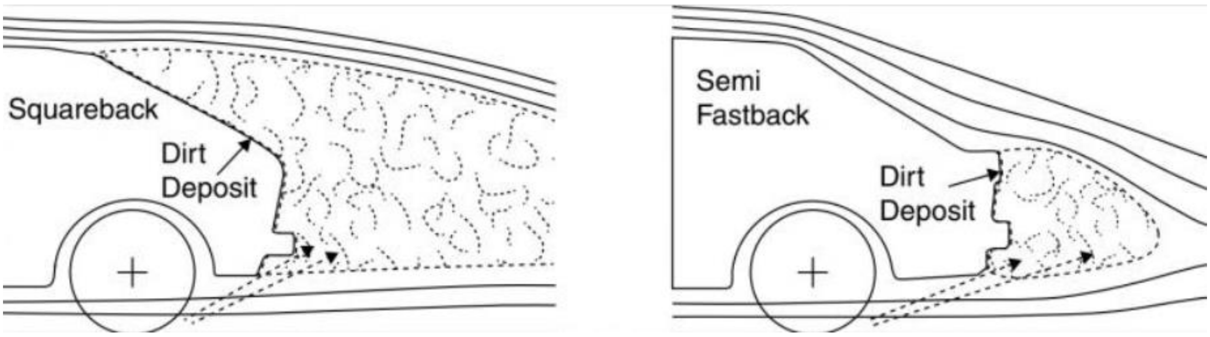


Figure 1.4 Effect on dirt decomposition at the rear squareback and semi fastback

- The potential of dirt decomposition on backlite and taillight because of high degree turbulence in the separation zone.
- For squareback, sharp edge at roof line makes the separation at this point and minimize aerodynamic buffeting.
- Promotes dirt deposition on the window and taillight.
- For semi fastback, sharp counter at end of deck, help stabilize the separation zone and minimize aerodynamic buffeting.
- Promotes dirt deposition on the taillight.

Aerodynamic Forces

- x- axis
  - Direction: Longitudinal (positive rearward)
  - Force: Drag
  - Moment: Rolling
- y- axis
  - Direction: Lateral (positive to the right)
  - Force: Side
  - Moment: Pitching
- z - axis
  - Direction: Vertical (positive upward)
  - Force: Lift
  - Moment: Yawing

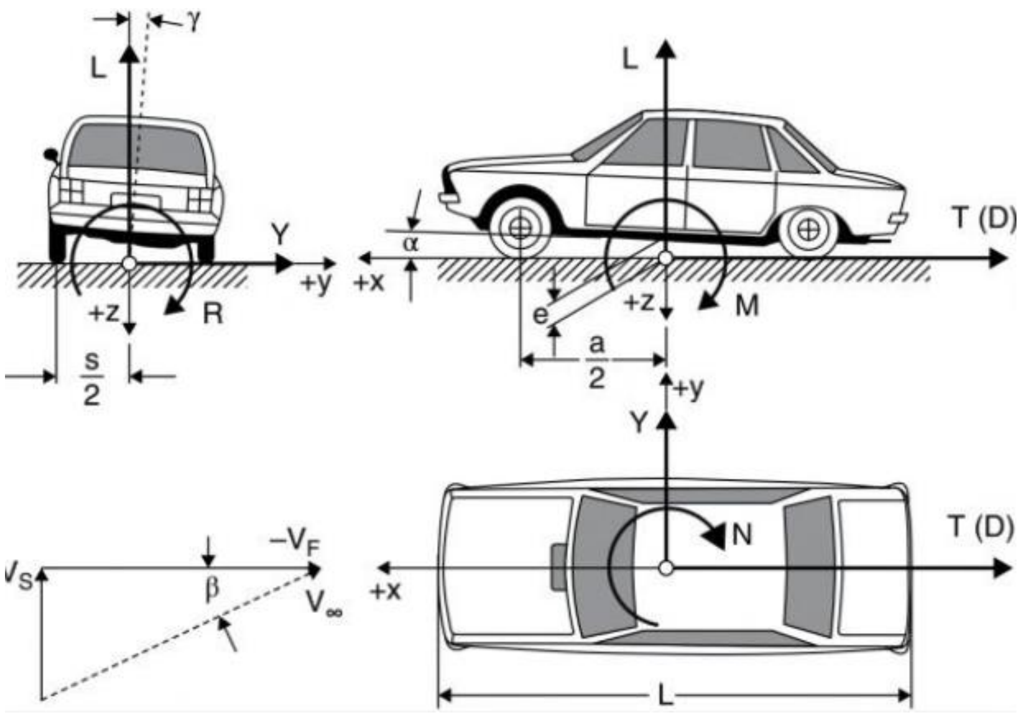


Figure 1.5 Aerodynamics forces and moments act on a car.

Drag Components

- Drag resistance is a force acting opposite to the relative motion of any object moving with respect to a surrounding fluid.
- Drag Coefficient Component for **BODY** of the vehicle:
  - Forebody
  - Afterbody
  - Underbody
  - Skin Friction
- Drag Coefficient Component for **PROTUBERANCE** drag:
  - Wheels and wheel wells
  - Drip rails
  - Window recesses
  - External mirrors
- Drag Coefficient Component for **INTERNAL** drag of the vehicle:
  - Cooling system

Reduction of Fore Body Drag

- The most significant drag reduction can be achieved by rounding up the vertical and upper horizontal leading edges on the front face.
- Relatively small amendments can result considerable drag reduction.
- The drag reduction of front spoiler is large if its use is combined with rounded leading edge.

Reduction of Base Drag

- Tapering of rear part results is reduction of the size of rear separation bubble and increase of pressure.
- Rear spoiler and increases of boot height reduces drag and lift simultaneously.
- Slanted trailing edges can cause longitudinal vortices increasing the drag list.
- Increase pressure on rear end.

Reduction of Roof, Windshield and Side Wall Drag

- Roof and side wall drag can be reduced by reduction of roughness of the wall.
- The windshield establishes the flow direction as it approaches the horizontal roof.
- Shallow angles reduce drag at windshield but complicate vehicle design by allowing increased solar heating load and placing more critical demands on the manufacturer of the windshield to minimize distortion at shallow angle.
- Steep angle causes the air velocity reduces by the high pressure in that region.

Reduction Of Under Body

- Suspension, exhaust system and other protruding component on the under body responsible for the drag. Smooth under body panel help to minimize under body drag.
- The wheel and wheel wells are major contributor for under body drag in Figure 1.6.
- Significant drag develops at the wheel because of the turbulent, recirculating flow in the cavities.
- Decrease the clearance between the underside and the ground and minimize the wheel cavity can decrease the total aerodynamic drag from the wheel.
- Underbody drag can be reduced by reducing the roughness (covering) and reducing the velocity in underbody gap (tight underbody gap or front spoiler).

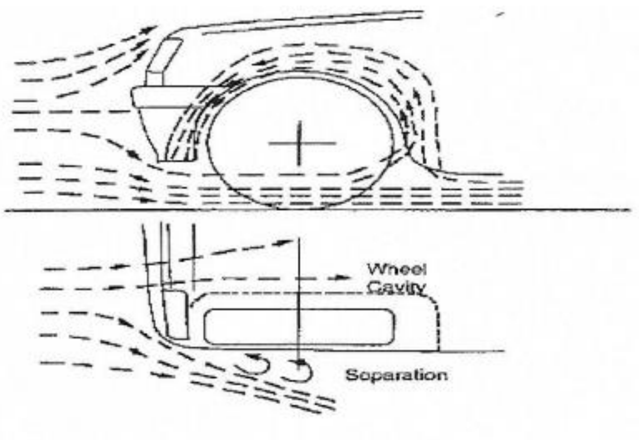


Figure 1.6 Air flow recirculation in a wheel well

Table 1.1 Typical value for drag coefficient component.

Drag Coefficient Component	**Typical Value**
Afterbody	0.05
Afterbody	0.14
Underbody	0.06
Skin Friction	0.025
Total Body Drag	0.275
Wheels and wheel wells	0.09
Drip rails	0.01
Window recesses	0.01
External mirrors	0.01
Total Protuberance Drag	0.12
Cooling system	0.025
Total Internal Drag	0.025
Overall Total Drag	0.42

Aerodynamic Aids

- Bumper Spoilers
- Air Dams
- Deck Lid Spoilers
- Window and Pillar Treatments
- Optimization

Bumper Spoiler

- Aerodynamic surfaces extending downward from the bumper to block and redirect the shear flow that impacts on the underbody components.
- Although it also contributes drag, it is significantly reducing underbody drag.
- Low pressure produced also has the effect of reducing front-end lift.

Air Dams

- Flow-blocking surfaces installed at the perimeter of the radiator.
- To improve flow through the radiator at lower vehicle speeds.
- Decrease pressure behind the radiator/fan.
- Reduce drag by reduction of pressure on the firewall.

Deck Lid Spoiler

- Deflecting the air upward, the pressure increases on the rear deck creating a down force at the most advantageous point on the vehicle to reduce rear lift as in Figure 1.7.
- The spoiler serves to stabilize the vortices in separation flow, thus reducing aerodynamic buffeting and increase drag.

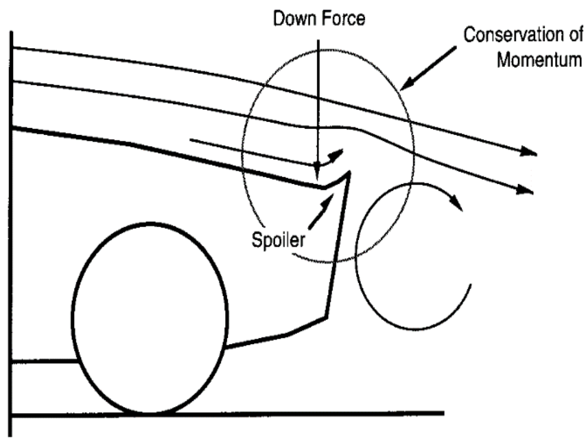


Figure 1.7 Influence of a spoiler on flow over the rear

Window and Pillar Treatment

- The disturbance of air in the high-velocity air stream causes momentum loss which creates drag.
- Smooth contours function as drag reduction and can reduce aerodynamic noise.
- The windshield establishes the flow direction as it approaches the horizontal roof with steep angle and shallow angle.

- Steep angles reduce drag but complicate vehicle design by allowing increased solar heating loads and placing more critical demands on the manufacturer of the windshield to minimize distortion at shallow angle.
- Steep angle causes the air velocity reduces by the high pressure in that region.
- While shallow angle causes high wind speed, adding to the aerodynamic load on the windshield wiper as Figure 1.8.

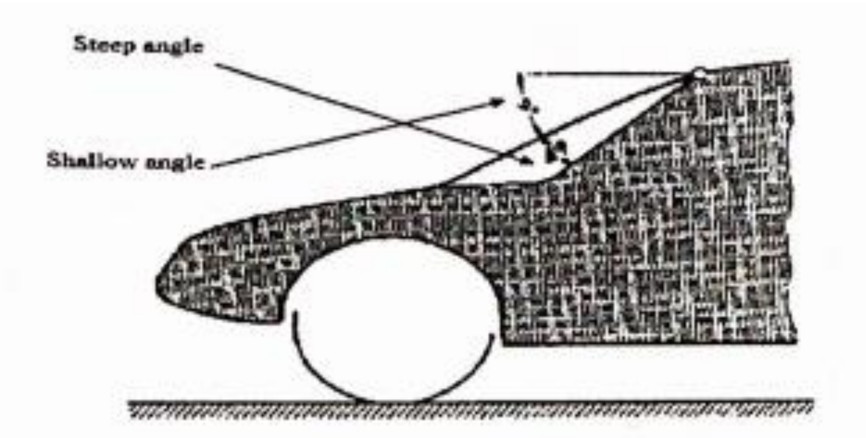


Figure 1.8 Position steep angle and shallow angle in windsheild

Optimization

- Is founded on the premise that the styling concept of the car is established, and aerodynamic improvement can only be attempted in the form of changes to detail in the styling.

Example Problem 1.1

i. Define drag resistance.

ii. The underbody is a critical area generating body drag. With a sketch, explain the air flow in this area to reduce drag.

iii. The windshield establishes the flow direction as it approaches the horizontal roof. Draw and explain how the angles are functioning to reduce drag.

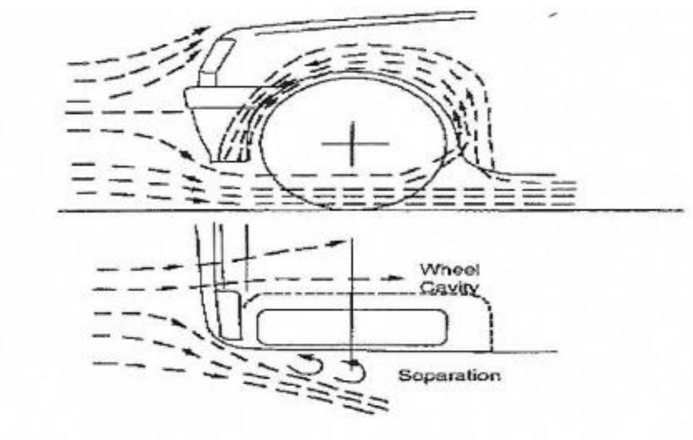
Solution Problem 1.1

i. Define drag resistance.

- **Drag resistance** is a force acting opposite to the relative motion of any object moving with respect to a surrounding fluid.

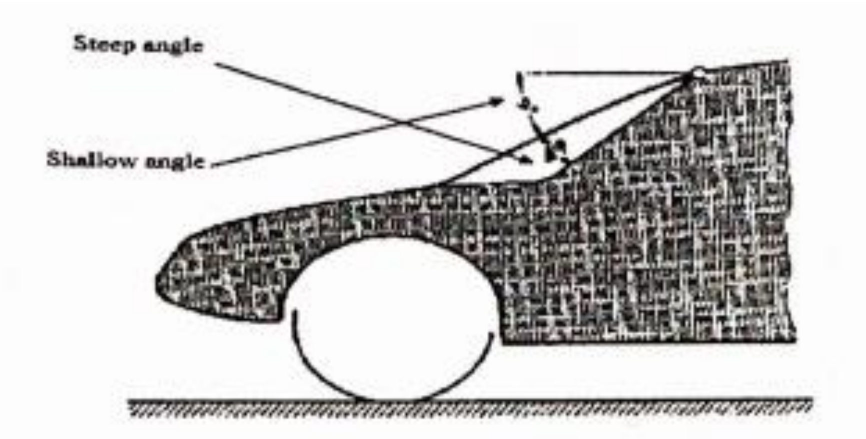
ii. The underbody is a critical area generating body drag. With a sketch, explain the air flow in this area to reduce drag.

- Underbody drag can be reduced by reducing the roughness (covering) and reducing the velocity in underbody gap (tight underbody gap or front spoiler)



iii. The windshield establishes the flow direction as it approaches the horizontal roof. Draw and explain how the angles are functioning to reduce drag.

- The windshield establishes the flow direction as it approaches the horizontal roof.
- Shallow angles reduce drag at windshield but complicate vehicle design by allowing increased solar heating load and placing more critical demands on the manufacturer of the windshield to minimize distortion at shallow angle.
- Steep angle causes the air velocity reduces by the high pressure in that region.



Aerodynamics Drag

$$D_A = \frac{1}{2}\rho V^2 C_D A$$

where:

C_D = Aerodynamic drag coefficient

A = Frontal area of the vehicle

ρ = Air density

V = Total wind velocity

Air Density

$$\rho = 1.225\,(\frac{P_r}{101.325})(\frac{288.16}{273.16 + T_r})$$

where:

P_r= Atmospheric pressure in kiloPascals

T_r= Air temperature in degrees Celsius

Drag Coefficient

$$C_D = \frac{D_A}{\frac{1}{2}\rho V^2 A} = \frac{Drag\ force}{(Dynamic\ pressure)(area)}$$

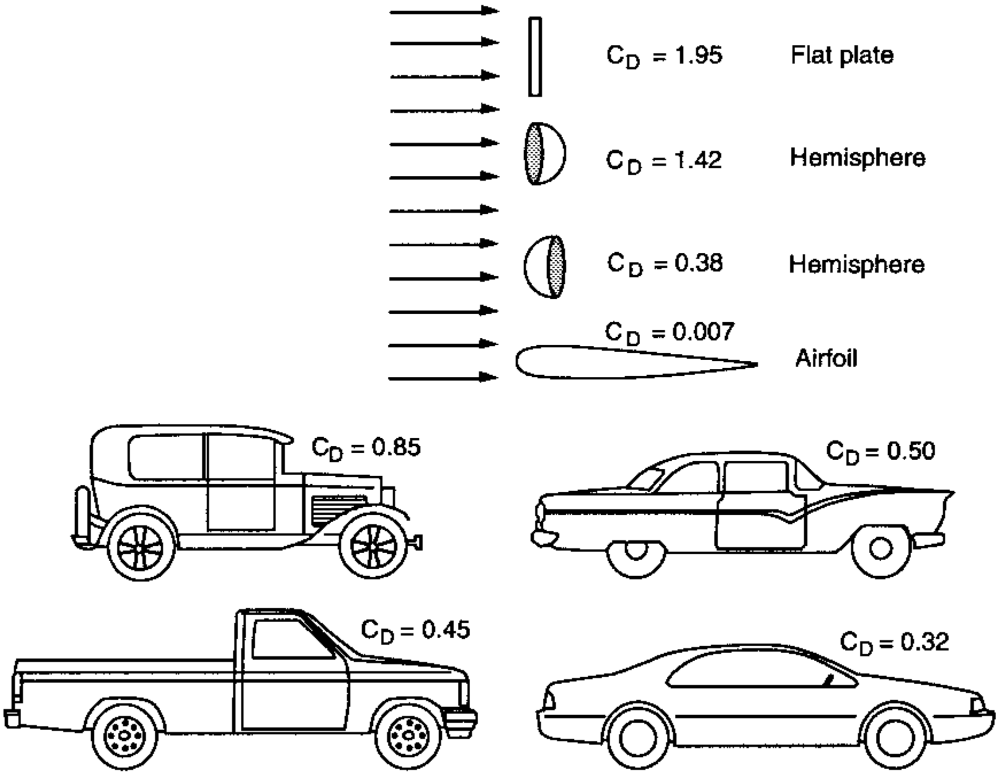


Figure 1.9 Drag coefficient value.

Table 1.2 Drag coefficient value for car model.

Car Model	C_D **Value**
Wolkswagen XL1	0.19
Mercedes-Benz CLA	0.22
Tesla Model S	0.24
Mercedes-Benz S-Class	0.24
Toyota Prius	0.25
Hyundai Sonata Hybrid	0.25
Peugeot 508	0.25

Side Force

- The lateral wind components will also impose a side force on the vehicle attempting to change its direction of travel.
- In strong crosswinds, the side force is typically greater than the drag force.

$$S_A = \frac{1}{2}\rho V^2 C_S A$$

Where:

S_A= Side force

C_S= Side force coefficient

A = Frontal area

ρ = Air density

V = Total wind velocity

Lift Force

- The pressure differential from the top to the bottom of the vehicle causes a lift force.
- These forces influence on driving stability.

$$L_A = \frac{1}{2}\rho V^2 C_L A$$

Where:

L_A= Lift force

C_L= Lift coefficient

A = Frontal area

ρ = Air density

V = Total wind velocity

Pitching Moment

- Pitching moment acts to transfer weight between the front and rear axles.

$$PM = \frac{1}{2}\rho V^2 C_{PM} A L$$

Where:

PM= Pitching moment

C_{PM}= Pitching moment coefficient

A = Frontal area

ρ = Air density

V = Total wind velocity

L = Wheelbase

Yawing Moment

- The lateral force caused by a side wind does not normally act at the mid-wheelbase position.

$$YM = \frac{1}{2}\rho V^2 C_{YM} A L$$

Where:

YM= Yawing moment

C_{YM}= Yawing moment coefficient

A = Frontal area

ρ = Air density

V = Total wind velocity

L = Wheelbase

Rolling Moment

- The lateral force caused by a side wind acts at a higher point on the vehicle.

$$RM = \frac{1}{2}\rho V^2 C_{RM} A L$$

Where:

RM= Rolling moment

C_{RM}= Rolling moment coefficient

A = Frontal area

ρ = Air density

V = Total wind velocity

L = Wheelbase

Crosswind Sensitivity

- Crosswind sensitivity refer to the effect of driver ability to hold the vehicle in position and on course when the presence of transverse wind disturbances in lateral and yawing response of a vehicle.
- The crosswind sensitivity is dependent on:
    - Aerodynamic properties
    - Vehicle dynamic properties (weight distribution, tire properties and suspensions)
    - Steering system characteristics (compliances, friction, and torque assist)
    - Driver closed-loop steering behaviour and preferences.

Example Problem 1.2

A heavy truck weighing 32800 kg accelerates at a speed of 80 km/h. the air temperature is 50°C and the barometric pressure is 24.5 kPa. The truck is 2.03m wide by 1.87m high and has an aerodynamic drag coefficient of 0.58. Calculate the aerodynamic drag of this truck.

Solution Problem 1.2

$$\frac{80\ \mathrm{km}}{\mathrm{h}} \times \frac{\mathrm{lh}}{3600\ \mathrm{s}} \times \frac{10^3\ \mathrm{m}}{1\ \mathrm{km}} = \mathbf{22.222\ m/s}$$

$$\begin{aligned}
\rho \quad &= 1.225\left(\frac{\mathrm{Pr}}{101.325}\right)\left(\frac{288.16}{273.16+\mathrm{Tr}}\right) \\
&= 1.225\left(\frac{(24.5)}{101.325}\right)\left(\frac{(288.16)}{273.16+50}\right) \\
&= 1.225(0.2418)(0.8917) \\
&= \mathbf{0.2641\ kg/m^3} \\
D_A \quad &= \frac{1}{2}\rho \mathrm{V}^2\mathrm{CdA} \\
&= 0.5(0.2641)(22.22)^2(0.58)(2.03)(1.87) \\
D_A \quad &= \mathbf{143.55\ N}
\end{aligned}$$

Example Problem 1.3

A truck weighing 32500kg moves at a speed 80 km/h. The truck is 2.6m in width and 4.2 m height and has an aerodynamic coefficient of 0.65. Calculate the aerodynamic drag where the air density is 1.222kg/m³.

Solution Problem 1.3

$$80\ \mathrm{km/h} = \frac{80 \times 1000}{3600} = \mathbf{22.222\ m/s}$$

$$\mathrm{A} = 2.6 \times 4.2 = \mathbf{10.92\ m^2}$$

$$\mathrm{D_A} = \frac{1}{2}\rho \mathrm{C_D A V^2}$$

$$\mathrm{D_A} = \frac{1}{2}(1.222)(0.65)(10.92)(22.222)^2$$

$$\mathrm{D_A} = \mathbf{2141.67\ N}$$

1.2 Rolling Resistance

Rolling Resistance

- Rolling resistance is a force resisting the motion when a body such as a ball, tire, or wheel roll on surface.
- The major vehicle resistance force on level ground is the rolling resistance of the tires.
- At low speeds on tough roadway, rolling resistance is the primary motion resistance force.

$$R_x = R_{xf} + R_{xr} = f_r W$$

Where:

R_{xf}= Rolling resistance of the front wheels

R_{xr}= Rolling resistance of the rear wheels

f_r = Rolling resistance coefficient

W = Weight of the vehicle

Factor Affecting Rolling Resistance

- Tire temperature
- Tire inflation pressure/load
- Velocity
- Tire material and design
- Tire slip
- Typical coefficient

Tire Temperature

- The temperature of tire has significant effect on the resistance.
- Tire begins rolling from cold condition, the temperature will rise, and the rolling resistance will decrease over a first period of travel.

- The Figure 1.10 shows at least 20 mile (32 km) need before the tire become stable and normally for typical tires need 20 minutes or more to worm up the tire.

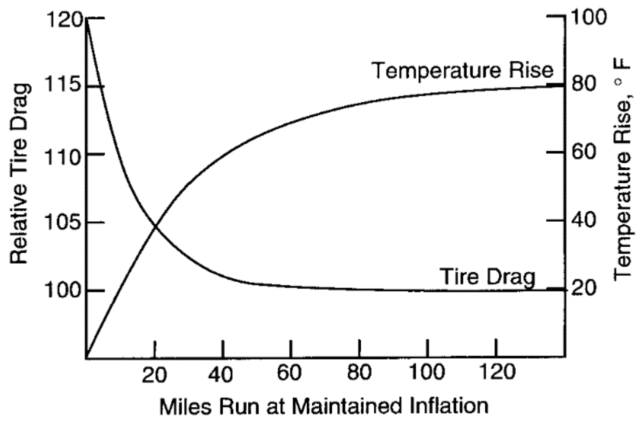


Figure 1.10 Relative tire temperature and rolling resistance during warm- up.

Tire Inflation Pressure / Load

- Tire inflation pressure determines the tire elasticity and combination with the load, determines the deflection in the side walls and contact region.
- The overall effect on rolling resistance also depends on the elasticity of the ground.
- On soft surfaces like sand, high inflation (increase) pressure result in increased ground penetration work (contact area) and therefore higher coefficients.
- On medium surface the effect of inflation pressure on tire and ground approximately balance and the coefficient nearly independent for inflation pressure.
- On hard surface the coefficient decreases with higher inflation pressure due to flexure for tire greatly reduce

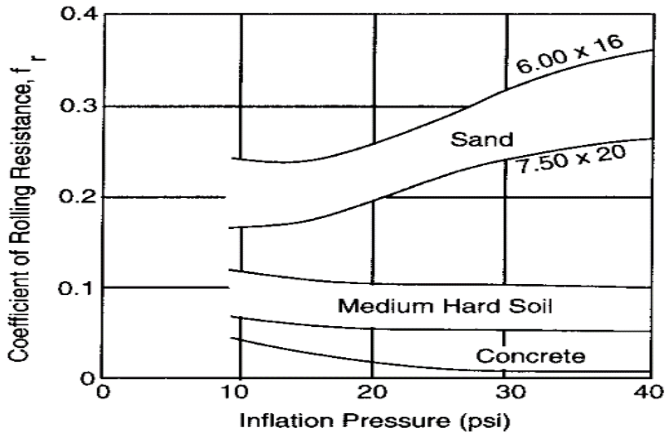


Figure 1.11 Coefficient of rolling resistance vs inflation pressure

Velocity

- The coefficient is directly proportional to speed because of increased flexing work and vibration in the tire body.
- The influence of speed become more pronounced when speed is combined with lower inflation pressure.
- From the graph sharp upturn in coefficient at high speeds caused by a high energy standing wave developed in the tire behind the contact path. It can cause failure.
- Standing wave is a primary effect limiting a tire rate.
- Modern tire rated for high speed normally include stabilizer in the shoulder area to control development of standing wave.

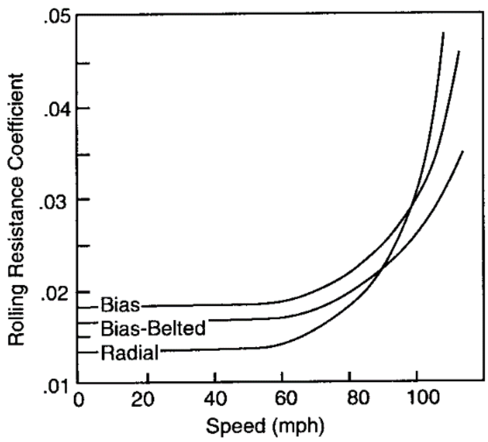


Figure 1.12 Rolling resistance vs speed

Tire Material and Design

- The materials and thickness of both the tire sidewalls and the thread determine the stiffness and energy loss in the rolling tire.
- Base on the figure below, although hysteresis in the tread rubber is important for good wet traction but it degrades rolling resistance performance.
- Worn-out, smooth-tread tires show coefficient values up to 20% lower than new tires.
- The cord material in the sidewall has only a small effect, but the cord angle and tire belt properties have a significant influence.

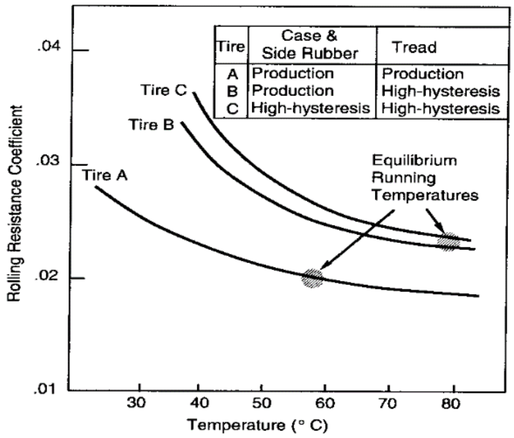


Figure 1.12 Rolling resistance vs temperature for tire with different polymer

Tire Slip

- Wheels transferring braking or tractive forces show higher rolling resistance due to wheel slip and the resulting friction scuffing as well as cornering force.

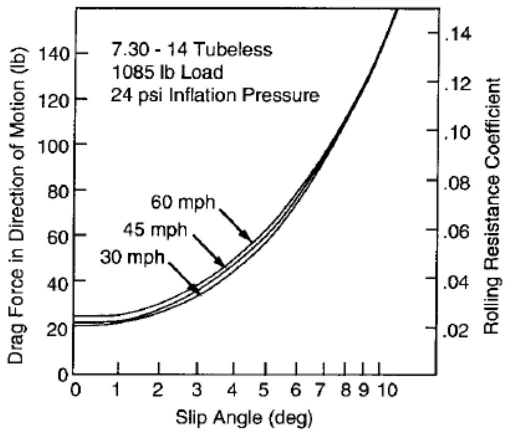


Figure 1.13 Rolling resistance coefficient versus slip angle

Typical Coefficients

- The multiple and interrelated factors affecting rolling resistance make it virtually impossible to devise a formula that takes all variables into account.
- Rolling resistance is clearly a minimum on hard, smooth, dry surfaces.
- A worn-out road almost doubles rolling resistance.
- On wet surfaces, higher rolling resistance is observed probably due to the cooler operating temperature of the tire which reduces its flexibility.

1.3 Total Road Load

Total Road Load

- The summation of the rolling resistance and aerodynamics forces (and grades forces, if present) constitutes the propulsion load for the vehicle and is normally referred to as "Road Load".

- The Road Load: -

$$R_{RL} = f_r W + \frac{1}{2}\rho V^2 C_D A + W \sin\theta$$

Where:

$f_r W$ = Rolling resistance

$\frac{1}{2}\rho V^2 C_D A$ = Aerodynamics force

$W \sin\theta$ = Grade force

The Road Load Horsepower

$$HP_{RL} = R_{RL}\frac{V}{550} = (f_r W + \frac{1}{2}\rho V^2 C_D A + W \sin\theta)\frac{V}{550}$$

Rolling Resistance Coefficient

$$f_r = \frac{R_x}{W} = C\frac{W}{D}\sqrt{\frac{h_t}{w}}$$

Where:

R_x = Rolling resistance force

W = Weight of the vehicle

C = Constant reflecting loss and elastic characteristic of tire material

D = Outside diameter

h_t = Tire section height

w = Tire section width

Table 1.3 Value of rolling resistance coefficient

Vehicle Type	Concrete	Medium hard	Hard
Passenger car	0.015	0.08	0.3
Heavy trucks	0.012	0.06	0.25
Tractors	0.02	0.04	0.2

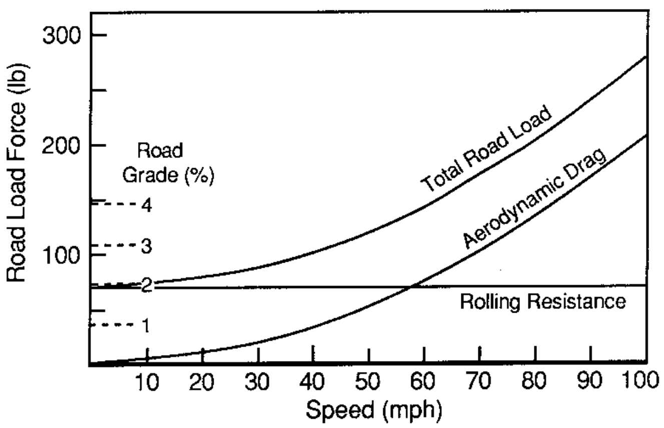


Figure 1.14 Road load plot for a typical passenger car

- The sum of forces is plot for a typical vehicle with the assumption constant coefficient 0.02, vehicle weight 1656 kg (~16236N), aerodynamic drag 0.34 and frontal area 2.16m^2.
- The total road load curve rises with speed due to aerodynamic components. Meanwhile the rolling resistance and grade consistency upward in proportion to the size.

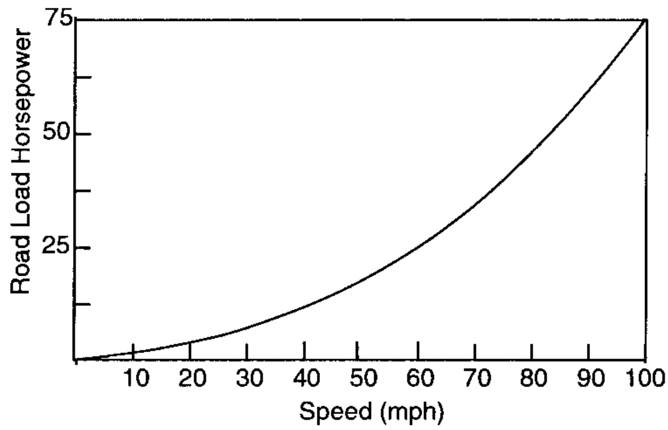


Figure 1.15 Road load power plot for a typical passenger car

- The road load in horsepower as figure below corresponding to the graph above for a level road condition.
- Power increases much more rapidly with velocity due to relationship in the equation road load horsepower.
- At high speeds a small increase in speed result in a large increase in vehicle power required with the effect of fuel consumption.

1.4 Exercises

i. The underbody is a critical area generating body drag. Explain how the air flow in this area would reduce drag.

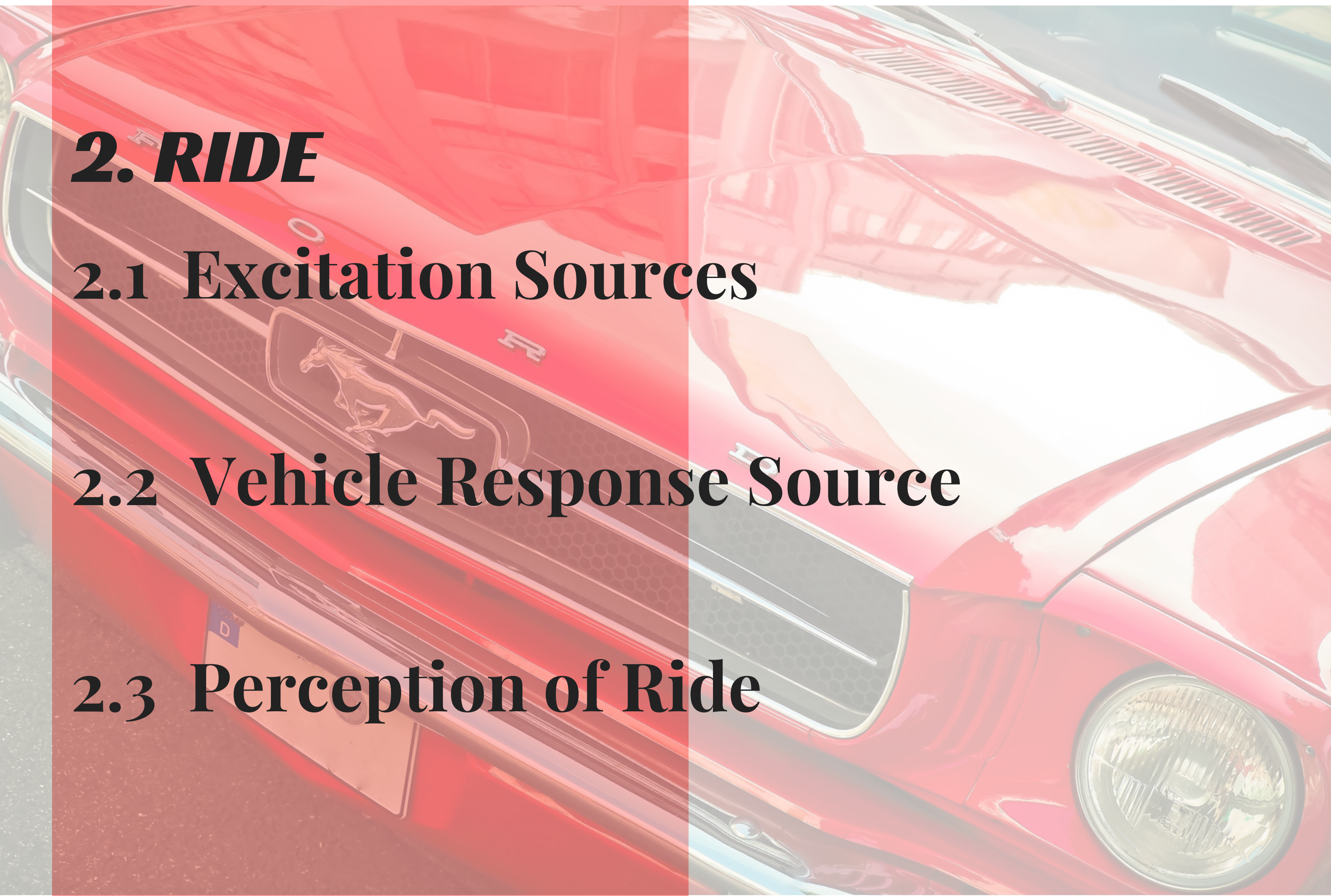
ii. Explain THREE (3) aerodynamic aid that reduces the effect of drag on a vehicle.

iii. A sport car weighing 1650kg accelerates at a speed of 150 km/h in a wind turner with the control air temperature is 35°C and barometric pressure 25kPa. The car width and height are 1.92m and 1.38m respectively. The aerodynamic drag is 142.67N. Determine:

   a. Air density
   b. Aerodynamic drag coefficient

iv. A car has 1190kg and moves at a speed of 110 km/h. The height and width of a car is 1.4m and 1.65m respectively with the aerodynamics drag of 550N. The car travels along solid sand road with rolling resistance coefficient of 0.05. Given air density is 1.222 kg/m³. Determine

   a. Drag coefficient, C_D
   b. Rolling resistance, R_X



2. RIDE

2.1 Excitation Sources

2.2 Vehicle Response Source

2.3 Perception of Ride

"The cars show who we are"

2 RIDE

2.1 Excitation source

Understanding Ride

- The term "ride" is commonly used in reference to **PHYSICAL AND VISUAL VIBRATIONS** while audio vibrations are categorized by "noise".
- The lower-frequency ride vibrations are related to dynamic behavior common to all rubber-tired motor vehicles.

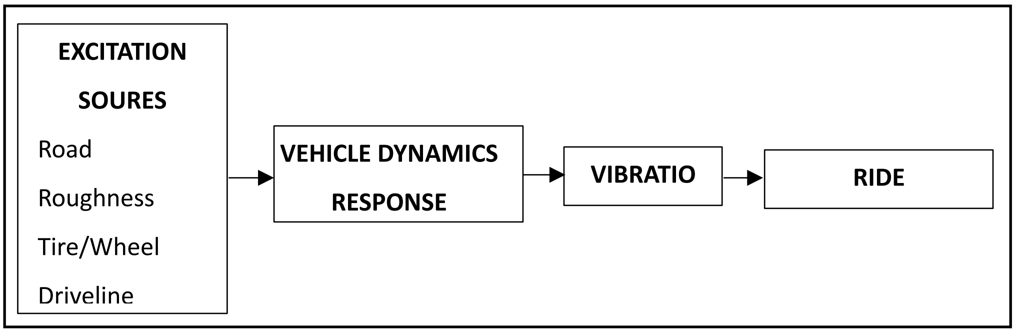


Figure 2.1: The Ride Dynamic System

Excitation Sources: Road Roughness

- By the elevation profile along the wheel tracks over which the vehicle passes.
- Pothole from pavement failure to ever- present road.

Excitation Source: On Board Sources

- Tyre and Wheel Assembly: Eccentricity
    - The tire, wheels and hubs individually may show radial eccentricity, produces both radial and tractive excitation on the axle.
    - The assembly has one high point and low point. (10 – 15 Hz at normal highway speeds)

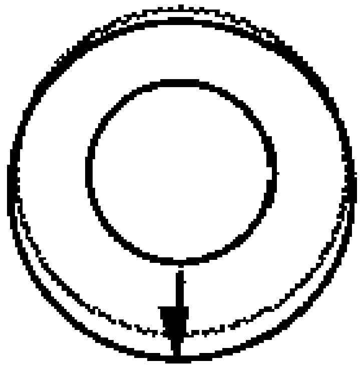


Figure 2.2: First Harmonic (Eccentric)

- Tyre and Wheel Assembly: Ovality
    - Tire and wheels may have elliptical variations that add or subtract depending on the mounting positions.
    - The assembly has two high points and two low points.

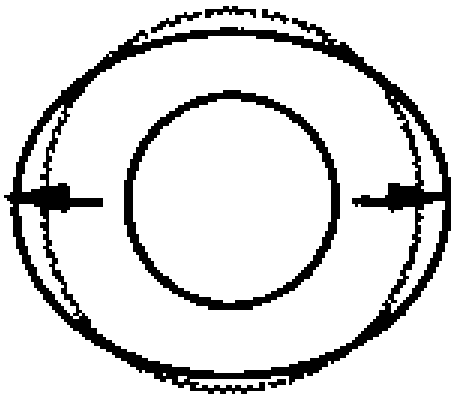


Figure 2.3: Second Harmonic (Oval or Elliptical)

- Tyre and Wheel Assembly: Triangular and Square
    - Triangular and square shape, while tires do not purposely have these shapes.
    - The effects may arise from construction methods.

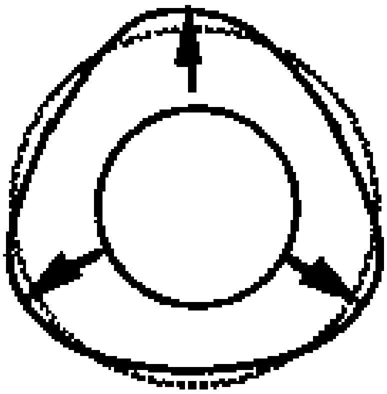


Figure 2.4: Third Harmonic (Triangular)

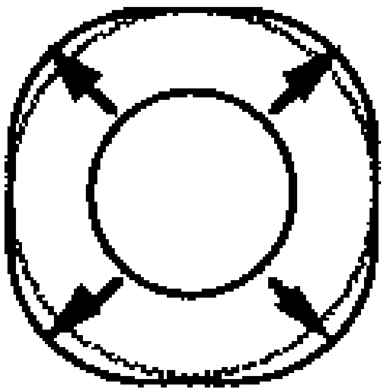


Figure 2.5: Fourth Harmonic (Square)

Driveline Excitation (Mass Imbalance Factors)

- Asymmetry of the rotating parts.
- The shaft may be off-center on its supporting flange or end yoke.
- The shaft may not be straight.
- Running clearances may allow the shaft to run off center.
- The shaft is an elastic member and may deflect.

Engine/ Transmission

- Imbalance rotating part create torque variation (Piston engine, flywheel, crank shaft, cam shaft etc.)
- Piston engine => Delivered power by cyclic process and the torque delivered is not consistent in magnitude.

- Crankshaft => Torque delivered to each power stroke cylinder.
- Flywheel => Initial damper and compliances in the transmission.
- Driveshaft => Torque output consists of a steady state component plus superimposed torque.

Example Problem 2.1

Explain how these factors below can influence ride excitation:

i. Road roughness
ii. Tire/wheel assembly
iii. Drive line

Solution Problem 2.1

i. Road roughness – Elevation profile along wheel track over which the vehicle passes act as a vertical displacement input to the wheel.
ii. Tire/wheel assembly – Imperfection in the manufacture of tires, wheel, hubs, and brakes.
iii. Drive line – Excited from driveshaft, U-joint, gear mating, torsional vibration.

2.2 Vehicle Response Properties

Vehicle Response Properties

- Suspension Isolation (Sprung Mass)
  - Portion of the vehicle's total mass that is supported above the suspension.
  - Sprung weight moves "indirectly" with the road surface.
  - Includes the body, frame, the internal components, passengers.

- Suspension Isolation (Unsprung Mass)
  - Mass of the suspension, wheels and other components directly connected to them.
  - Unsprung weight moves “directly” with the road surface.
  - Wheels, tires, brakes, some suspension etc.

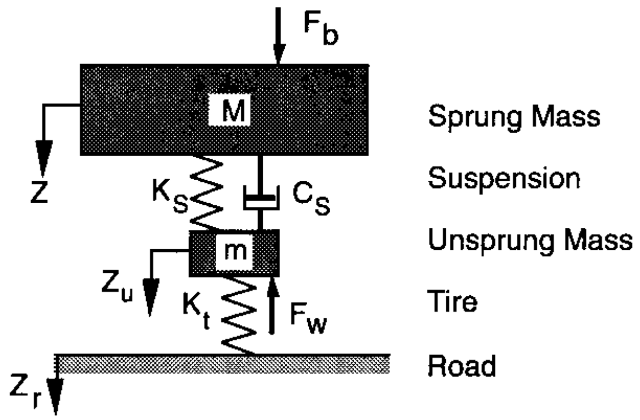


Figure 2.6: Quarter-Car Model

Suspension Isolation (The Effective of the Suspension and Spring)

- Ride Rate: The effective stiffness of the suspension and spring in series.

$$RR = \frac{K_s \times K_t}{K_s + K_t}$$

- The Bounce natural frequency.

$$\omega_n = \sqrt{\frac{RR}{M}} \qquad (radians/sec)$$

$$f_n = 0.159\sqrt{\frac{RR}{W/g}} \qquad (cycles/sec\ or\ Hz)$$

Where:

RR= Ride rate

K_s = Suspension stiffness

K_t = Tire stiffness

M = Sprung mass

W = Weight of the sprung mass

- Damped natural frequency.

$$\omega_d = f_n\sqrt{1 - {\zeta_s}^2}$$

$$\zeta_{sf} = \frac{C_s}{\sqrt{4 \times K_s \times M}}$$

Where:

ζ_{sf}= Damping ratio

C_s = Suspension damping coefficient

- For good ride the suspension damping ratio between 0.2 and 0.4

Example Problem 2.2

A motorcycle has the following dimension and suspension parameters:

- Wheelbase, ***L***: 2 m
- Front suspension stiffness, K_{sf}: 10 000 N/m
- Rear suspension stiffness, K_{sr}: 8000 N/m
- Front damper rate: 700 Ns/m
- Distance center of gravity from front wheel: 0.9m
- Tire vertical stiffness, K_t: 160 000 N/m
- Front or rear wheel mass, m_w: 15 kg
- Mass of motorcycle and rider (not include wheels): 250 kg

i. Calculate the load that acts on the front and rear wheels in Newton (N).

ii. Estimate the front suspension natural frequency, f_{nf}

iii. Estimate the rear suspension natural frequency, f_{nr}

iv. Estimate the front suspension damped natural frequency, ω_{df}

v. Estimate the rear suspension damped natural frequency, ω_{dr}

Solution Problem 2.2

i. Calculate the load that acts on the front and rear wheels in Newton (N).

Total mass of motorcycle: (250+15+15) kg = **280 kg**

Weight of motorcycles, W = 280 kg x 9.81 m/s² = **2746.8N**

$$Load\ at\ front,\ W_f = \frac{Wc}{L} = \frac{2746.8\ \times 1.1}{2} = \mathbf{1510.74N}$$

$$Load\ at\ rear,\ W_r = \frac{Wb}{L} = \frac{2746.8\ \times 0.9}{2} = \mathbf{1236.06N}$$

ii. Estimate the front suspension natural frequency, $\boldsymbol{f_{nf}}$

Front suspension Ride Rate, RR_f

$$RR = \frac{K_s K_t}{K_s + K_t}$$

$$RR_f = \frac{10000 \times 160000}{10000 + 160000} = \mathbf{9411.74\ N/m}$$

Load that support at front wheel, W_f = **1510.74N**

Total mass at front wheel including tire.

$$\frac{1510.74}{9.81} = \mathbf{154\ kg}$$

Total mass at front wheel without tire = $154 - 15 = \mathbf{139\ kg}$

Natural frequency for front suspension.

$$\mathrm{f_{nf}} = 0.159\sqrt{\frac{RR_f}{M}}$$

$$= 0.159\sqrt{\frac{94110.74}{139}} = \mathbf{1.31\ Hz}$$

iii. **Estimate the rear suspension natural frequency, f_{nr}**

$$RR = \frac{K_s K_t}{K_s + K_t}$$

$$RR_r = \frac{8000 \times 160000}{8000 + 160000} = \mathbf{7619.05\ N/m}$$

Load that support at rear wheel, W_r = **1236.06N**

Total mass at rear wheel including tire.

$$\frac{1326}{9.81} = \mathbf{126\ kg}$$

Total mass at rear wheel without tire = $126 - 15 = \mathbf{111\ kg}$

Natural frequency for rear suspension.

$$\mathrm{f_{nr}} = 0.159\sqrt{\frac{RR_f}{M}}$$

$$= 0.159\sqrt{\frac{7619.05}{111}} = \mathbf{1.32\ Hz}$$

vi. Estimate the front suspension damped natural frequency, $\boldsymbol{\omega_{df}}$

$$\omega_{df} = f_{nf}\sqrt{1 - {\zeta_{sf}}^2}$$

$$\zeta_{sf} = \frac{C_s}{\sqrt{4 \times K_{sf} \times M_f}}$$

$$\zeta_{sf} = \frac{700}{\sqrt{4 \times 10000 \times 139}}$$

$$\zeta_{sf} = 0.29$$

$$\omega_{df} = f_{nf}\sqrt{1 - {\zeta_{sf}}^2}$$

$$\omega_{df} = 1.31\sqrt{1 - 0.29^2}$$

$$\boldsymbol{\omega_{df} = 1.25\ Hz}$$

vii. Estimate the rear suspension damped natural frequency, $\boldsymbol{\omega_{dr}}$

$$\omega_{dr} = f_{nr}\sqrt{1 - {\zeta_{sr}}^2}$$

$$\zeta_{sr} = \frac{C_s}{\sqrt{4 \times K_{sr} \times M_r}}$$

$$\zeta_{s5} = \frac{700}{\sqrt{4 \times 8000 \times 111}}$$

$$\zeta_{sr} = 0.37$$

$$\omega_{dr} = f_{nr}\sqrt{1 - {\zeta_{sr}}^2}$$

$$\omega_{dr} = 1.32\sqrt{1 - 0.37^2}$$

$$\boldsymbol{\omega_{dr} = 1.22\ Hz}$$

Example Problem 2.3

Consider a mass spring damping system with:

M = 2kg

RR = $k_s = 100000$ N/m

$C_s = 100$ Ns/m

Find

i. Natural frequency
ii. Damping ratio

Solution Problem 2.3

i. $Natural\ frequency, f_n = 0.159\sqrt{\frac{RR}{M}}$

$$= 0.159\sqrt{\frac{100000}{2}}$$

$$= \mathbf{35.6\ Hz}$$

ii. $Damping\ ratio, \xi = \frac{C_s}{\sqrt{4k_sM}}$

$$= \sqrt{\frac{100}{4 \times 100000 \times 2}}$$

$$= \mathbf{0.1118}$$

Example Problem 2.4

Based on the table below:

Tire vertical stiffness	126 000 N/m
Front suspension stiffness	18630 N/m
Rear suspension stiffness	10790 N/m
Load at front tires	3650 N
Load at rear tires	4205 N
Damping coefficient	1400 Ns/m

i. Calculate the front and rear suspension ride rates, RR.

ii. Calculate the damping ratio for front and rear suspension.

Solution Problem 2.4

i. Calculate the front and rear suspension ride rates, RR.

$$RR = \frac{K_s K_t}{K_s + K_t}$$

$$RR_f = \frac{(18630)(126000)}{(18630) + (126000)} = \mathbf{16230.24\ N/m}$$

$$RR_r = \frac{(10790)(126000)}{(10790) + (126000)} = \mathbf{9938.88\ N/m}$$

ii. Calculate the damping ratio for front and rear suspension.

$$Damping\ ratio, \xi = \frac{C_s}{\sqrt{4k_s M}}$$

$$Damping\ ratio\ for\ front\ suspension,\ \xi_{sf} = \frac{1400}{\sqrt{(4)(18630)(\frac{3650}{9.81})}} = \mathbf{0.27}$$

$$Damping\ ratio\ for\ rear\ suspension,\ \xi_{sr} = \frac{1400}{\sqrt{(4)(10790)(\frac{4205}{9.81})}} = \mathbf{0.33}$$

Example Problem 2.5

Calculate the front and rear suspension ride rates, RR for a vehicle that have the tire vertical stiffness, K_t is 126000 N/m. Given that the front suspension stiffness, K_{sf} is 17500 N/m and the rear suspension stiffness, K_{sr} is 10900 N/m. Also calculate the natural frequencies, f_n for front (Hz) and rear suspensions (Hz) when front tire is loaded to 4450 N and the rear tire are 3320 N respectively.

Solution Problem 2.5

Calculate the front and rear suspension ride rates, RR.

$$RR = \frac{K_s K_t}{K_s + K_t}$$

$$RR_f = \frac{(17500)(126000)}{(17500) + (126000)} = \mathbf{15365.85\ N/m}$$

$$RR_r = \frac{(10900)(126000)}{(10900) + (126000)} = \mathbf{10032.14\ N/m}$$

Calculate the natural frequencies, f_n for front (Hz) and rear suspensions (Hz)

$$\mathrm{f_n} = 0.159\sqrt{\frac{RR}{M}}$$

$$\mathrm{f_{nf}} = 0.159\sqrt{\frac{RR_f}{M_f}}$$

$$= 0.159\sqrt{\frac{15365.85}{4450/9.81}} = \mathbf{0.93\ Hz}$$

$$\mathrm{f_{nr}} = 0.159\sqrt{\frac{RR_r}{M_r}}$$

$$= 0.159\sqrt{\frac{10032.14}{3320/9.81}} = \mathbf{0.87\ Hz}$$

2.3 Perception of Ride

Tolerance to Seat Vibrations

- These studies, in general, tend to focus on tolerance as it relates to discomfort in a seated position to sort out the frequency sensitivity of the human body.
- Universally accepted standard exists for judgment of ride vibrations due to variables such as:
    - Seating position
    - Influence of hand and foot vibration input
    - Single-versus multiple-frequency input
    - Multi-direction input
    - Comfort sealing
    - Duration of exposure
    - Sound and visual vibration inputs

Other Vibration Forms

- One reason why seat vibration measurement are inadequate as objective measures of ride is that driver's judgement of the vibration in the vehicle includes far more than what comes through the seat.
- The point was well demonstrated in studies and testing of the influence of tire/wheel nonuniformities on the ride perception on the road.
- These test basically to rate the acceptability of the vehicle.
- The ratings reflect the judgement of industry engineers about the acceptability of vehicle as a product.

2.4 Exercises

i. Given that:

Tire spring rate	105 000 N/m
Front suspension rate	21 140 N/m
Rear suspension rate	15 600 N/m
Mass	1450 kg

Calculate:

a. Front suspension ride rate, RR_f

b. Rear suspension ride rate, RR_r

ii. Table show a detail parameter for MPV:

Tire vertical stiffness	136 000 N/m
Front suspension rate	18 630 N/m
Rear suspension rate	10 790 N/m
Load tires	3450 N (front) 4105 N (rear)

Given damping coefficient 1400 Ns/m. Calculate:

a. Front suspension ride rate, RR_f

b. The natural frequency for front suspension

iii. Table shows the dimensions and suspension parameters of motorcycle:

Tire vertical stiffness, K_t	150 000 N/m
Front suspension stiffness, K_{sf}	8000 N/m
Rear suspension stiffness, K_{sr}	10 000 N/m
Front and rear wheel mass. m_w	15 kg
Mass of motorcycle and rider (not included wheel), m_{motor}	250 kg
Wheelbase, L	2 m
Distance of center gravity from front wheel, b	1.1 m

a. Calculate the load on the front and rear wheel.

b. Calculate the front suspension natural frequencies, (Hz)

iv. Sketch the differences between sprung mass and unsprung mass by developing a schematic diagram for quarter car model.

Reference

Gillespie, T. R. (2021b). Fundamentals of Vehicle Dynamics. In *SAE International eBooks*. https://doi.org/10.4271/9781468601770

Gillespie, T. D., 1992, Fundamentals of Vehicle Dynamics, Society of Automotive Engineers.

Massimo Guiggiani, 2018, The Science of Vehicle Dynamic, Second Edition, Springer, ISBN: 978-3-319-73219-0G.

Nakhaie Jazar, 2017, Vehicle Dynamics - Theory and Application, Third Edition, Springer, ISBN: 978-3-319-53440-4

Masato Abe, 2015 Vehicle Handling Dynamics -Theory and Application, Second Edition, Elsevier Ltd., ISBN: 978-0-08-100390-9

VEHICLE DYNAMIC VOL. 2

e ISBN 978-967-2421-97-9