VEHICLE DYNAMICS AND PERFORMANCE

Vehicle dynamics and performance are broad topics that deal with vehicle's drivability, fuel economy, braking performance, handling characteristics, noise, vibration and harshness (NVH), etc. The research for improving vehicle dynamics and performance never ceased in 100 years since vehicles have been invented. Vehicle dynamics and performance are broad topics that deal with vehicle’s drivability, fuel economy, braking performance, handling characteristics, noise, vibration and harshness (NVH), etc. The research for improving vehicle dynamics and performance never ceased in 100 years since vehicles have been invented. The research in this area has been developed for the purposes of basic understanding of the system operation behaviors, system and components design,

objectives

Introduction
Objective vehicle dynamics testing has a key role in the development and assessment of a new vehicle. Testing activity is performed:

- Benchmarking and target setting
- Development
- Verification and validation
# Contents

Chapter-1 .............................................................................................................................................. 7
Automotive Mission Plan India ............................................................................................................. 5
Passenger Car-Anatomy and Packaging .............................................................................................. 9
SAE-Vehicle Co-ordinate System .......................................................................................................... 14
Wheel Base and Track Width of Cars .................................................................................................... 16
Centre of Gravity -Positions .................................................................................................................. 17
Truck/Trailer dimensions and Terms .................................................................................................... 21
Trucks .................................................................................................................................................. 20
Terminology ........................................................................................................................................ 23
Jounce and Bounce Motion .................................................................................................................... 24
Wheel Excitations-Frequency and Vehicle Speed .................................................................................. 26
Damping .............................................................................................................................................. 27
Under and Oversteer .............................................................................................................................. 31
Metrics (Characteristics) of Ground Vehicle .......................................................................................... 35
Acceleration Performance ..................................................................................................................... 39
Road mu .............................................................................................................................................. 41
Bugatti Veyron 2005 .............................................................................................................................. 43
Volkswagen Touareg ............................................................................................................................... 44
Lateral Acceleration ............................................................................................................................... 46
- Circle ............................................................................................................................................... 47
Traction Limits ..................................................................................................................................... 48
Ride .................................................................................................................................................... 50
Vehicle Dynamics

1. Vehicle Dynamics and Fundamentals of Load Transfer
2. Acceleration and Braking Performance
3. Wheel Alignment, K & C and Steering Performance
4. Roll Centers, Roll Axis, Squat and Dive
5. Handling and Vehicle Dynamic Tests
6. Vehicle Roll Over and Fish Hook Test
7. Ride and Excitation Forces
8. Bounce and Pitch Centers
9. Suspension Technologies: Passive, Semi Active and Active Suspension
10. Tyres and Carpet Plots
11. Design & Development Process for Vehicle Dynamics
12. Vehicle Dynamic Examples
13. Vehicle Dynamic Field Tests
Chapter-1

- Vehicle Dynamics and Fundamentals of Load Transfer
  - Metrics
  - Road Loads - Tractive Resistances
  - Tractive Effort and Forces
  - Basics of Weight Transfer
    - Longitudinal Load Transfer
    - Lateral Load Transfer
  - Forces Between Road and Wheel
The growth of mobility

Source: Arne Thoni, WBCSD, Sustainable Mobility
Organisation for Economic Co-operation and Development (OECD)
By 2016, India will emerge as the destination of choice in Asia for the design and manufacture of automobiles and automotive components. The output of the India’s automotive sector will be US$ 145 billion by 2016, contributing to 10% of India’s GDP and providing employment to 25 million persons additionally.
Ground Vehicles

Non Guided Ground Vehicles

Guided Ground Vehicles

Road Vehicles

Off Road Vehicles
Passenger Car

Square Back

Fast Back

Hatch Back

Notch Back
Passenger Car-Anatomy and Packaging
Passenger Car Main Parts

- Battery
- Distributor cap
- Spark plug cable
- Air filter
- Cylinder head cover
- Radiator
- Cooling fan
- Fan belt
- Alternator
- Exhaust manifold
- Braking circuit
- Disc brake
- Clutch
- + Cooling system
- Gas supply system
- + Electrical system
- + Gasoline engine
- + Brake boosting system
- + Exhaust system
- + Transmission system
- + Suspension system
- Steering system
- Brake pedal
- Hand brake
- Exhaust pipe
- Gearbox
- Catalytic converter
- Axle shaft
- Suspension arm
- Muffler
- Tail pipe
- Exhaust pipe
- Filler neck
- Gas tank
- Differential
- Shock absorber
- Coil spring
- Drive shaft
- Gas line
Vehicle Weights

<table>
<thead>
<tr>
<th>Sprung Mass (kg)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Small cars</td>
<td>650 – 900 kg</td>
</tr>
<tr>
<td>Intermediate cars</td>
<td>900 – 1300 kg</td>
</tr>
<tr>
<td>Large cars</td>
<td>1300 – 1750 kg</td>
</tr>
<tr>
<td>Small SUVs</td>
<td>900 – 1600 kg</td>
</tr>
<tr>
<td>Large SUVs</td>
<td>1600 – 3000 kg</td>
</tr>
</tbody>
</table>
Weight Distribution-Front/Rear

PuntoPower weight distribution

354 kg
1078 kg
724 kg

177 kg
177 kg
362 kg
362 kg
Automobile Drive Systems

Front Wheel Drive Powertrain

Front Wheel Drive
Rear Wheel Drive

Four Wheel Drive
SAE-Vehicle Co-ordinate System
Centre of Gravity of the Vehicle

GL

L

Rear Axle

C

Front Axle

Y

Z

h

W_{rs}

W

W_{fs}
## Wheelbase (mm)

Typical values are:

<table>
<thead>
<tr>
<th>Category</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small cars</td>
<td>2300 – 2500 mm</td>
</tr>
<tr>
<td>Intermediate cars</td>
<td>2500 – 2800 mm</td>
</tr>
<tr>
<td>Large cars</td>
<td>2800 – 3050 mm</td>
</tr>
<tr>
<td>Small SUVs</td>
<td>2000 – 3000 mm</td>
</tr>
<tr>
<td>Large SUVs</td>
<td>2300 – 3300 mm</td>
</tr>
</tbody>
</table>

## Track width

Typical values fall in the range as follows:

<table>
<thead>
<tr>
<th>Category</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small cars</td>
<td>1360 – 1450 mm</td>
</tr>
<tr>
<td>Intermediate cars</td>
<td>1450 – 1500 mm</td>
</tr>
<tr>
<td>Large</td>
<td>1500 – 1575 mm</td>
</tr>
<tr>
<td>Small SUVs</td>
<td>1300 – 1700 mm</td>
</tr>
<tr>
<td>Large SUVs</td>
<td>1400 – 2000 mm</td>
</tr>
</tbody>
</table>
Distance of CG aft of front axle (mm)

\[ L = \frac{b}{W_{rs}} W \]

Typical values are:
- Front engine, front wheel drive: 35 – 45% of wheelbase
- Front engine, rear wheel drive: 45 – 50% of wheelbase
- Rear engine, rear wheel drive: 50 – 55% of wheelbase

Height of vehicle sprung mass CG above the ground (mm)
Typical values are:

<table>
<thead>
<tr>
<th>Category</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small cars</td>
<td>500 - 560 mm</td>
</tr>
<tr>
<td>Intermediate cars</td>
<td>500 - 560 mm</td>
</tr>
<tr>
<td>Large cars</td>
<td>500 – 560 mm</td>
</tr>
<tr>
<td>Small SUVs</td>
<td>600 – 800 mm</td>
</tr>
<tr>
<td>Large SUVs</td>
<td>600 – 800 mm</td>
</tr>
</tbody>
</table>
• Please see the Longitudinal Weight Transfer equation during grades

\[ W_f = W_{fs} - W \left( \frac{h}{L} \right) \] (can be written as \( \tan \phi \))

\[ h = \left( \frac{L}{W} \right)[W_{fs} - W_f] \left( \frac{1}{\tan \phi} \right) \]

• \( L \) = Wheel Base Length
• \( W \) = Total weight in N
• \( W_{fs} \) = Load on front wheel on level ground = \( \frac{W_c}{L} \) in N
• $W_f =$ Load on front wheel when raised by $\square$ angle in N
Truck/Trailer dimensions and Terms
TERMS
Chassis: Basic vehicle-cab, frame, and running gear
Body: Container in which the load is carried
Payload: Commodity to be carried
Curb Weight: Weight of chassis only
Body Weight: Weight of complete body to be installed on chassis
Payload Weight: Weight of commodity to be carried
Gross Vehicle Weight (GVW): Total or curb, body, and payload weight
A truck is specific to a transport requirement
Weight Distribution

- Cabin: 1100 kg
- Engine/gearbox: 1600 kg
- Battery + exhaust: 450 kg
- Tire winch: 150 kg
- Rear axle: 1350 kg
- Front axle: 750 kg
- Fuel tank: 100-1000 kg
- Frame: 350 kg
Terminology

- Sprung and Unsprung Mass
Frequency of Vibration: Natural frequency and

\[ f_n = \sqrt{\frac{k}{m}} \text{ rad/s} \]

\[ f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \text{ Hz} \]

**Input:**

\[ Z = Z_0 \sin(\omega t) \]

If \( \omega = \omega_n \) : Resonance

\[ w \]

If \( \omega \neq \omega_n \) : Isolated

\[ \frac{1}{mZ^2} \]
Jounce and Bounce Motion

V = Vehicle Velocity

Jounce Stroke - Compression
Bounce

e-Rebound Period for one Cycle
Wheel Excitations-Frequency and Vehicle Speed

- Let us consider 15” dia rim, Tire aspect ratio= 70, tire width=235 mm

- \( D = \text{diameter of the wheel} = 15” \times 25.4 + 2 \times 0.70 \times 235 = 710 \text{ mm} \)

- Distance travelled per revolution=
  \[ D = 710 \text{ mm} = 0.71 \text{ m} \]
  \[ D = 2230.5 = 2.2305 \text{ m} \]

- If the wheel makes one revolution per second, then the vehicle speed is
  \[ = 2.2305 \times 3600 / 1000 = 8.029 \text{ km/h} \]

- In every second if the wheel experiences a jounce and bounce stroke, vehicle experiences 1 Hz excitation

- If the vehicle speed increases, frequency of excitation also increases
Damping Coefficient

\[ \frac{V}{Z} \cdot \frac{F}{A} = \frac{cV}{Z} \]

\[ c \] Damping coefficient \( \frac{Ns}{m} \)

\[ \sqrt{mk} \]

\[ c \] Critical Damping Coefficient \( \frac{2}{2} \)

\[ \frac{c}{c} \] Damping ratio

\[ \frac{c}{1} \] Underdamped
\[ \frac{c}{1} \] Critically Damped
\[ \frac{c}{1} \] Overdamped

\[ d \] Damped natural frequency

\[ \sqrt{1 - \xi^2} \]

Dissipates Energy

Damper
Damping
Vibration Isolation and Vibration Damping

- A good vibration damper takes mechanical energy out of the system.
- Oil dampers (dashpots) have good damping capability but no isolation capability.
- A good vibration isolator lowers the natural frequency of a system to below the excitation (or disturbing) frequency. Keeping these two frequencies "out of sync" greatly reduces the problems of vibration.
- Properly designed metal springs and rubber mounts can be good isolators but have almost no damping capability.
- Foam products can be good isolators but have limited life.
If \( f > f_n \) Isolation can be achieved

Sprung mass natural frequency is 1Hz say, the excitation frequency is more than 1 Hz, then isolation happens, at 1 Hz, sprung mass resonates, however resonance amplitude is small because of damping. Human being is less tolerant to frequencies 2-8 Hz. Normally 1 Hz resonance is connected with low vehicle speed, the driver hardly experiences sprung mass resonance.
Under and Oversteer
Current Challenges

- Lowest Possible Emissions
- Reduced Green House Gas Emissions
- Occupant Safety

Power Train

Running System (Metrics)

- Stability and Comfort, Driving Experience

Diagram:

- Standby/Idle
- Accessories
- Driveline Losses
- Engine Losses
- Aerodynamic Drag
- Rolling Resistance
- Inertia
- Braking

Legend:

- 100%
- 17.2%
- 2.2%
- 18.2%
- 12.6%
- 5.6%
- 62.4%
Ground Vehicle - A Control System

- Driver
- Desired Speed and Direction
- Actual Performance
- Desired Performance
- Handling
- Ride
- Measure: Performance, Ride, Handling
- Visual, Aural and other inputs
- Disturbances
  - Surface Irregularities
  - Ground Condition
  - Aerodynamics
- Actual Performance
  - Handling
  - Ride
  - Speed
  - Direction
Metrics (Characteristics) of Ground Vehicle

- Visual and Other Inputs
- Ground Conditions
- Driver
  - Accelerator
  - Brakes
  - Steering System
  - Surface irregularities
- Vehicle
- Performance
- Handling
- Ride
Aerodynamic Inputs
Vehicle Performance

- Performance refers to motor vehicle ability to
  
  - Accelerate $A_1$
    - Spinning $SP$ (Acceleration 0.3g)
  
  - Decelerate, $B_1$
    - Skidding $Sk$ (wheel lockups)
  
  - Develop Drawbar Pull $D_1 = \text{Tractive Effort-Rolling Resistance}$
  
  - Overcome Obstacles
    - Wheel slipping (insufficient friction)
    - Climbing hills (very high gradients)
Acceleration and Deceleration Limits

\[ F_x - W - mg = ma_x \]

\[ a_x = \mu g \]

\[ d_x = \mu g \]
### Acceleration Performance

The time car takes to accelerate from **0 to 60 mph** (0 to 97 km/h or 0 to 27 m/s) in the US and the UK, 0 to 100 km/h in rest of the world

<table>
<thead>
<tr>
<th>Car Model</th>
<th>Acceleration Time</th>
<th>Acceleration Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suzuki Grand Vitara</td>
<td>0 to 60 mph in 7.2 secs</td>
<td>5.73 m/s²</td>
</tr>
<tr>
<td>Honda CR-V</td>
<td>0 to 60 mph in 8.6 secs</td>
<td>3.13 m/s²</td>
</tr>
<tr>
<td>Family Car</td>
<td>0 to 60 mph in 10.5 secs</td>
<td>2.55 m/s²</td>
</tr>
<tr>
<td>Tata Nano</td>
<td>0 to 60 km/h in 8 seconds</td>
<td>2.08 m/s²</td>
</tr>
<tr>
<td>Motor Bike (Honda Unicorn)</td>
<td>0 to 60 km/h in 5 secs</td>
<td>3.324 m/s²</td>
</tr>
</tbody>
</table>
Performance of Cars 0-60mph

<table>
<thead>
<tr>
<th>Year</th>
<th>Make</th>
<th>0-60mph Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>McLaren F1</td>
<td>2.63</td>
</tr>
<tr>
<td>2006</td>
<td>Bugatti Veyron 16.4</td>
<td>2.65</td>
</tr>
<tr>
<td>1998</td>
<td>Mercedes-Benz CLK-GTR</td>
<td>2.74</td>
</tr>
<tr>
<td>1966</td>
<td>AC Cobra 427</td>
<td>3.50</td>
</tr>
<tr>
<td>1996</td>
<td>Ferrari F50</td>
<td>3.60</td>
</tr>
<tr>
<td>2002</td>
<td>Porsche 911 GT2</td>
<td>3.70</td>
</tr>
<tr>
<td>1991</td>
<td>Ferrari F40</td>
<td>3.70</td>
</tr>
<tr>
<td>1995</td>
<td>Lamborghini Diablo SE 5.7</td>
<td>3.75 s</td>
</tr>
<tr>
<td>2003</td>
<td>Dodge Viper SRT-10</td>
<td>3.94</td>
</tr>
<tr>
<td>2002</td>
<td>Chevrolet Corvette Z06</td>
<td>4.20</td>
</tr>
<tr>
<td>1998</td>
<td>Dodge Viper GTS-R</td>
<td>4.30</td>
</tr>
<tr>
<td>2000</td>
<td>BMW Z8</td>
<td>4.30</td>
</tr>
<tr>
<td>2003</td>
<td>Ferrari 575M Maranello F1</td>
<td>4.33 s</td>
</tr>
<tr>
<td>2007</td>
<td>BMW Alpina B7</td>
<td>4.35</td>
</tr>
<tr>
<td>1998</td>
<td>Subaru Impreza WRX 22B STi</td>
<td>4.40 s</td>
</tr>
<tr>
<td>2004</td>
<td>Mercedes-Benz E 55 AMG</td>
<td>4.49</td>
</tr>
<tr>
<td>2000</td>
<td>Maserati 3200 GT</td>
<td>4.50</td>
</tr>
<tr>
<td>1997</td>
<td>Ferrari F355 Spider</td>
<td>4.60</td>
</tr>
<tr>
<td>2001</td>
<td>BMW M3</td>
<td>4.69</td>
</tr>
<tr>
<td>1997</td>
<td>Lotus Esprit Turbo</td>
<td>4.70</td>
</tr>
<tr>
<td>2002</td>
<td>Maserati Spyder Cambiocorsa</td>
<td>4.70 s</td>
</tr>
<tr>
<td>2003</td>
<td>Ford Mustang SVT Cobra</td>
<td>4.70</td>
</tr>
<tr>
<td>2002</td>
<td>Mitsubishi Lancer EVO VII (Jap)</td>
<td>4.72 s</td>
</tr>
<tr>
<td>2001</td>
<td>BMW M5</td>
<td>4.80</td>
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<tr>
<td>2002</td>
<td>Subaru Impreza WRX Sedan Access ECU2 17&quot;</td>
<td>4.86 s</td>
</tr>
<tr>
<td>2004</td>
<td>Subaru Impreza WRX STi (USA)</td>
<td>4.88 s</td>
</tr>
<tr>
<td>1994</td>
<td>Toyota Supra Turbo</td>
<td>4.90</td>
</tr>
<tr>
<td>1970</td>
<td>Ford Mustang Boss 429</td>
<td>4.90</td>
</tr>
<tr>
<td>2003</td>
<td>Mitsubishi Lancer Evolution (USA)</td>
<td>4.94 s</td>
</tr>
<tr>
<td>2001</td>
<td>Holden GTS R (Aus)</td>
<td>5.00</td>
</tr>
<tr>
<td>2002</td>
<td>Porsche 911 Targa</td>
<td>5.00</td>
</tr>
<tr>
<td>2002</td>
<td>Mercedes-Benz C 32 AMG</td>
<td>5.00</td>
</tr>
<tr>
<td>1993</td>
<td>Mazda RX-7 Twin Turbo</td>
<td>5.00</td>
</tr>
<tr>
<td>1999</td>
<td>Chevrolet Corvette LS1 Hardtop</td>
<td>5.00 s</td>
</tr>
<tr>
<td>1989</td>
<td>Pontiac Trans Am Turbo</td>
<td>5.10</td>
</tr>
</tbody>
</table>

1 sec = 26.869, 2 sec = 13.43, 3 sec = 8.95, 2.63 sec = 10.21 m/s²
• The coefficient of friction depends on the materials used;

• for example, ice on steel has a low coefficient of friction, while rubber on pavement has a high coefficient of friction.

• Coefficients of friction range from near zero to greater than one – under good conditions, a tire on concrete may have a coefficient of friction of 1.7.

• Most dry materials in combination have friction coefficient values between 0.3 and 0.6.

• Values outside this range are rarer, but teflon, for example, can have a coefficient as low as 0.04.

• A value of zero would mean no friction at all, an elusive property – even magnetic levitation vehicles have drag.

• Rubber in contact with other surfaces can yield friction coefficients from 1 to 2. Occasionally it is maintained that \( \mu \) is always < 1, but this is not true.

• While in most relevant applications \( \mu < 1 \), a value above 1 merely implies that the force required to slide an object along the surface is greater than the normal force of the surface on the object. For example, silicone rubber or acrylic rubber-coated surfaces have a coefficient of friction that can be substantially larger than 1.
Road

is a dimensionless scalar value which describes the ratio of the force of friction between two bodies and the force pressing them together.

\[ F = \mu W \]
Bugatti Veyron 2005
• Bugatti Veyron16.4 is a mid-engine sports car produced by Volkswagen AG introduced in 2005.

• It is the quickest accelerating and decelerating road-legal production car in the world.

• The Bugatti Veyron 0-60 mph in 2.46 seconds.

• Powered by a 1,001 PS (987 hp/736 kW) W16 engine.

• It is able to achieve an average top speed of 408.47 km/h (253.81 mph).

• It is named after French racing driver Pierre Veyron, who won the 24 hours of Le Mans in 1939 while racing for the original Bugatti.

• Euro 1.4 million.
SSC Ultimate Aero TT

- SSC Ultimate Aero Twin Turbo, 'World's Fastest Production Car' with an average top speed of 255.83 mph.
• 1183 hp
World’s Fastest Car

Bugatti Veyron 16.4 (2011)
269.81 MPH (434.211 km/h)
Volkswagen Touareg

SUV, 3.0 L, TDI, 239PS, 45 degree hill climbing, 500 mm water wading, 35 degree tilt driving, AWD
Handling

- Handling is concerned with the response of the vehicle to drivers' command and its ability to stabilize its motion against external disturbances—ease of maneuvering and stability
  - Understeering $U_1$
  - Oversteering $O_1$

- Sliding may happen during maneuvers
  - Sliding $SL$
Lateral Acceleration

\[ CF = m \frac{V^2}{R} = m a_y \]

\[ a_y = \frac{V^2}{R} \]

\[ a_y \leq \frac{2V}{R} g \]

Lane Change Maneuver
Braking cornering
Ride

- Ride is related to the vibration of the vehicle excited by the surface irregularities and its effects on passengers comfort.
• Ride Comfort is a frequency weighted measure of vertical acceleration together with subjective assessments of harshness over various external road surface induced excitations.

• Ride is determined by spring stiffness, damper and bushing characteristics, component weights and natural frequencies
Road Holding
What do we perceive?

- A vibration under 20Hz can be felt by human beings.
What do we feel and hear?

- We can feel frequencies between 20Hz and 200 Hz.
What do we hear?

- We can hear frequencies between 200Hz and 20kHz

Sounds only (200 Hz to 20 kHz)
Channel 1: 1695 – Rear left axle position
Channel 3: 1697 – Rear left chassis position
Channel 4: 1698 – Rear left seat position
Channel 1: 1695 (Rear Left Axle Position)
Channel 1: 1695 (Rear Left Axle Position)

Acceleration (m/s²) vs Frequency (Hz)
Channel 3: 1697 (Rear Left Chassis Position)

**Acceleration (m/s²) vs Time (s)**
Channel 3: 1697 (Rear Left Chassis Position)

Acceleration (m/s^2) vs Frequency (Hz)
Channel 4: 1698 (Rear Left Seat Position)

Acceleration \( (m/s^2) \) vs Time \( (s) \)
Acceleration (m/s²) vs Time (s)
Channel 4: 1698 (Rear Left Seat Position)
Rolling Resistance

Aerodynamic Forces

Gravity

Road Loads - Tractive Resistance

\[ \text{Tractive Resistance} = (f_rW) + \frac{1}{2} \frac{A}{D} \frac{W}{V^2} \sin(\phi) \]

\[ \text{Power} = (f_rW) + \frac{1}{2} \frac{A}{D} \frac{W}{V^2} \]

\[ a_O = \text{total resistance on gradient} \]
\[ b_O = \text{total resistance on level road} \]
$A \square W \quad \sin \square )V \quad 64$
Rolling Resistance \( f_r \)

- It is due to hysteresis in tire material due to deflection of the carcass while rolling
  - Primary factor:
    - Hysteresis
  - Secondary factors:
    - Friction between the tire and the road caused by sliding
    - Air Circulation inside the tire
    - Fan effect of the rotating tire on the surroundings

\[
FR \quad f_r W
\]

\( f_r \) is the dimensionless rolling resistance coefficient or coefficient of rolling friction

\( W \) is the load on the wheel
Rolling Resistance

Rolling resistance comprises the resisting forces acting on the rolling wheel. It is made up of rolling resistance, road surface resistance and slip resistance.

\[ T_R = F_U r_{dyn} + R e \]

\[ F_{R, Roll} = \frac{e}{r_{dyn}} G_R \]

\[ F_{R, Roll} = f_R G_R \]

\[ f_R = \frac{e}{r_{dyn}} \]

Note: Use appropriate Symbols
Rolling Resistance
Factors Affecting Rolling Resistance ($f_r$)
Rolling Resistance Coefficients ($f_r$)

\[ f_r = \frac{R_x W}{W C} \cdot \frac{\sqrt{D}}{\sqrt{W}} \]

Where:

- $R_x$ = Rolling resistance force
- $W$ = Weight on the wheel
- $C$ = Constant reflecting loss and elastic characteristic of the tire material
- $D$ = Outside diameter
- $h_t$ = Tire section height
- $W$ = Tire section width
Rolling Resistance Coefficients ($f_r$)

- Sidewall deflection is not a direct measurement of rolling friction.
- In tires, tread thickness has much to do with rolling resistance. The thicker the tread, the higher the rolling resistance. Thus, the "fastest" bicycle tires have very little tread and heavy duty trucks get the best fuel economy as the tire tread wears out.
- Smaller wheels, all else being equal, have higher rolling resistance than larger wheels. In some laboratory tests, smaller wheels appeared to have similar or lower losses than large wheels, but these tests were done rolling the wheels against a small-diameter drum, which would theoretically remove the advantage of large-diameter wheels, thus making the tests irrelevant for resolving this issue. Virtually all world speed records have been set on relatively narrow wheels, probably because of their aerodynamic advantage at high speed, which is much less important at normal speeds.
Rolling Resistance

- Material - different fillers and polymers in tire composition can improve traction while reducing hysteresis. The replacement of some carbon black with higher-priced silica–silane is one common way of reducing rolling resistance

- Dimensions - rolling resistance in tires is related to the flex of sidewalls and the contact area of the tire. For example, at the same pressure, wider bicycle tires flex less in sidewalls as they roll and thus have lower rolling resistance

- Extent of inflation - Lower pressure in tires results in more flexing of sidewalls and higher rolling resistance. This energy conversion in the sidewalls increases resistance and can also lead to overheating and may have played a part in the infamous Ford Explorer rollover accidents.

- Over inflating tires (such a bicycle tires) may not lower the overall rolling resistance as the tire may skip and hop over the road surface. Traction is sacrificed, and overall rolling friction may not be reduced as the wheel rotational speed changes and slippage increases
### Rolling Resistance Coefficients ($f_R$)

<table>
<thead>
<tr>
<th>Road surface</th>
<th>Rolling resistance coefficient $f_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Firm road surface</strong></td>
<td></td>
</tr>
<tr>
<td>Smooth tarmac road</td>
<td>0.010</td>
</tr>
<tr>
<td>Smooth concrete road</td>
<td>0.011</td>
</tr>
<tr>
<td>Rough, good concrete surface</td>
<td>0.014</td>
</tr>
<tr>
<td>Good stone paving</td>
<td>0.020</td>
</tr>
<tr>
<td>Bad, worn road surface</td>
<td>0.035</td>
</tr>
<tr>
<td><strong>Unmade road surface</strong></td>
<td></td>
</tr>
<tr>
<td>Very good earth tracks</td>
<td>0.045</td>
</tr>
<tr>
<td>Bad earth tracks</td>
<td>0.160</td>
</tr>
<tr>
<td>Tracked tractor on acre soil</td>
<td>0.070–0.120</td>
</tr>
<tr>
<td>Clamp wheels on acre soil</td>
<td>0.140–0.240</td>
</tr>
<tr>
<td>Loose sand</td>
<td>0.150–0.300</td>
</tr>
</tbody>
</table>
A tyre is being run on a rolling drum

Sharp Rolling Resistance is due to standing waves

When the tyre rotates at its critical speed, standing wave occurs

In such conditions rolling resistance increases, and energy gets dissipated into heat

A **standing wave**, also known as a **stationary wave**, is a wave that remains in a constant position. This phenomenon can occur because the medium is moving in the opposite direction to the wave, or it can arise in a stationary medium as a result of interference between two waves traveling in opposite directions.
Coast-down Test

<table>
<thead>
<tr>
<th>Run num</th>
<th>Time(s)</th>
<th>Time(s)(Delta)</th>
<th>Speed(kmh)</th>
<th>Dist(m)(Delta)</th>
<th>Dist(m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>100.5</td>
<td>0.00</td>
<td>0.00</td>
<td>Trigger start</td>
</tr>
<tr>
<td>1</td>
<td>0.27</td>
<td>0.27</td>
<td>100.0</td>
<td>7.81</td>
<td>7.81</td>
<td>Speed line</td>
</tr>
<tr>
<td>1</td>
<td>6.76</td>
<td>6.49</td>
<td>90.0</td>
<td>171.07</td>
<td>178.88</td>
<td>Speed line</td>
</tr>
<tr>
<td>1</td>
<td>14.35</td>
<td>7.59</td>
<td>80.0</td>
<td>179.25</td>
<td>358.13</td>
<td>Speed line</td>
</tr>
<tr>
<td>1</td>
<td>23.05</td>
<td>8.70</td>
<td>70.2</td>
<td>181.61</td>
<td>519.75</td>
<td>Trigger end</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>78.1</td>
<td>0.00</td>
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</tr>
<tr>
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<td>6.69</td>
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</tr>
<tr>
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<td>16.93</td>
<td>10.23</td>
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<td>184.36</td>
<td>322.02</td>
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<td>5.83</td>
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<td>77.54</td>
<td>577.53</td>
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<td>0.00</td>
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<tr>
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<td>11.95</td>
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<td>148.25</td>
<td>159.58</td>
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<td>30.0</td>
<td>155.93</td>
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<td>441.94</td>
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<tr>
<td>3</td>
<td>86.60</td>
<td>17.01</td>
<td>4.3</td>
<td>33.99</td>
<td>566.57</td>
<td>Trigger end</td>
</tr>
</tbody>
</table>

**Results / Conclusion**

The table below shows the data loaded into Excel from the Report Generator screen. This shows that the total time for the Coastdown deceleration from 100Kph to 10Kph is 113.67 seconds and the distance it was done in is 1423 meters.

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**Total**

\[
\text{Tractive Resistance} = \frac{1}{2} AC^2 D
\]

\[
f_r = \frac{D}{W}
\]
Coast Down Test

1. dx = deceleration = (final velocity-initial Velocity)/time

2. dx = Fx/M

3. Fx= dx.M…..Total Tractive Resistance

4. Draw a graph of Total Tractive resistance V/S Speed

5. Draw a graph of Aerodynamic resistance V/S Speed

6. Subtract one graph from the other and get rolling Curve
Aerodynamic Loads

Pressure Distribution On a Vehicle
Aerodynamic Forces and Moments

**Drag Force**

\[ D_A = \frac{1}{2} \rho v^2 C_D \]

Where:
- \( D_A \) = Aerodynamic drag coefficient
- \( C_D \) = Aerodynamic drag coefficient
- \( A \) = Frontal area of the vehicle
- \( \rho \) = Air density

**Lift Force**

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

Where:
- \( L_A \) = Lift force
- \( C_L \) = Lift Coefficient
- \( A \) = Frontal area

**Side Force**

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

Where:
- \( S_A \) = Side force
- \( V \) = Total wind velocity
- \( C_S \) = Side force coefficient (function of the relative wind angle)
- \( A \) = Frontal area
Aerodynamic Lift and Drag with Different Vehicle Styles

- **Sedan**
  - Lift Coefficient: $C_L = 0.246$
  - Drag Coefficient: $C_D = 0.358$

- **Coupe**
  - Lift Coefficient: $C_L = 0.279$
  - Drag Coefficient: $C_D = 0.358$

- **Fastback**
  - Lift Coefficient: $C_L = 0.118$
  - Drag Coefficient: $C_D = 0.315$

- **Station Wagon**
  - Lift Coefficient: $C_L = 0.063$
  - Drag Coefficient: $C_D = 0.33$
Pitching Moment

\[ PM = \frac{1}{2} \frac{1}{V} \sqrt{\frac{2}{C}} PM \cdot A L \]

Where:
- \( PM \) = Pitching moment
- \( CP_M \) = Pitching moment coefficient
- \( A = \) Frontal area
- \( L = \) Wheelbase

Yawing Moment

\[ YM = \frac{1}{2} \frac{1}{\sqrt{V}} \sqrt{\frac{2}{C}} YM \cdot A L \]

Where:
- \( YM \) = Yawing moment
- \( CY_M \) = Yawing moment coefficient
- \( A = \) Frontal area
- \( L = \) Wheelbase

Rolling Moment

\[ RM = \frac{1}{2} \frac{1}{\sqrt{V}} \sqrt{\frac{2}{C}} RM \cdot A L \]

Where:
- \( RM \) = Rolling moment
- \( CR_M \) = Rolling moment coefficient
- \( A = \) Frontal area
- \( L = \) Wheelbase
Moments Due to Aerodynamic Forces

Rolling

Pitching

Side Coefficients

Yawing
Gradient Resistance

- Gradeability
- It is the rise over run

\[
G = \frac{T \cdot R \cdot 10200}{r \cdot GVW \cdot RR}
\]

**Where:**
- \(10200\) = Factor
- \(T\) = Motor torque in newton metres
- \(R\) = Overall gear reduction including both axle and transmission
- \(r\) = Rolling radius of loaded driving type in millimetres
- \(GVW\) = Gross vehicle weight in kilograms
- \(RR\) = Rolling resistance expressed in percentage grade.

"Heeresversuchsgelände" Kummersdorf", south of Berlin

The "slope hill" to test the gradeability of military vehicles. There are several slopes, beginning with around 10% grade ("1 : 10" or 5.7 degrees), the steepest slope is around 70% ("1 : 1.66" or 35 degrees)
Tractive Effort

\[ T_r = T_{nfe} \]

and

\[ TE = \frac{T_{nfe}}{r} \]

rev/min of the roadwheels

engine rev/min

overall reduction ratio

Nr

nf
Tractive Force Vs Tractive Resistance

Tractive force at the Wheels for acceleration

Force Available for acceleration

Tractive Effort to overcome Tractive resistance

Vehicle Speed kmph

Max. speed

Tractive Force (N)

Tractive Resistance (N)
Effort: The force applied to an object or machine to cause motion
Forces Acting on a Vehicle

\( W \): weight of the vehicle acting at its CG

\( W/\text{g}\alpha_x \): Inertial force, if the vehicle is accelerating

\( W_f, W_r \): Dynamic weights carried on the front and rear wheels.

\( F_{xf}, F_{xr} \): Tractive forces

\( R_{xf}, R_{xr} \): Rolling resistance at the tyre contact patch

\( D_A \): Aerodynamic force acting on the body of the vehicle

\( R_{bh}, R_{bh} \): Vertical and longitudinal forces acting at the hitch point when the vehicle is towing a trailer

\( L \): Wheel base length

\( h \): Height of the Centre of Gravity from the ground

\( b \): Distance of the Centre of gravity aft of the front axle

\( c \): Distance of the Centre of Gravity fore of rear axle

\( \theta \): Grade
Newton’s 2\textsuperscript{nd} Law

- **Translational Systems**
  
  \[ F_X = M \cdot a_X \]
  
  where: \( F_X \) = Forces in the X-direction
  
  \( M \) = Mass of the body
  
  \( a_X \) = Acceleration in the X-direction

- **Rotational System**
  
  \[ T_X = I_{XX} \cdot \alpha_X \]
  
  where: \( T_X \) = Torques about the X-axis
  
  \( I_{XX} \) = Moment of inertia about the X-axis
  
  \( \alpha_X \) = Acceleration about the X-axis
Loads on Axles

**Dynamic Axle Loads:**

\[
W_f = (W_c \cos \theta - R_{hx} h - R_{hz} h - (W/g) a_x h - D_A h - W h \sin \theta)/L
\]

\[
W_r = (W b \cos \theta + R_{hx} h + R_{hz} (d + L) + (W/g) a_x h + D_A h + W h \sin \theta)/L
\]

**Static Loads on Level Ground:**

\[
W_{fs} = W.(c/L)
\]

\[
W_{rs} = W.(b/L)
\]

The sine is zero and the cosine is one, and the variables \(R_{hz}, R_{hx}, a_x\) and \(D_A\) are zero.

*In Vehicles usually load on the front axle is greater than the rear axle*
Load on the Axles during Low Speed Acceleration

When the vehicle is accelerating on level ground at a low speed, $D_A$ is zero and assuming no trailer:

$$W = W(\frac{c}{g} \frac{h}{a} \frac{f}{L}) W_{fs} \frac{a}{h} W \frac{h}{g}$$

When the vehicle accelerates, load transfer takes place from the front axle to the rear axle.

Load on the Axles due to Grades

The common grades on highways are limited to 4 percent (2.3 deg) On primary and secondary roads they occasionally reach 10 to 12 percent:

$$W = W(\frac{c}{g} \frac{h}{a} \frac{f}{L}) W_{fs} \frac{h}{L}$$

$$W = W(\frac{b}{r}) W_{rs} \frac{h}{g} W \frac{h}{L}$$

$$W = W(\frac{r}{L} \frac{L}{L} \frac{rs}{L})$$

(6.8 deg).
Positive grade causes load to be transferred from the front to the rear axle
Longitudinal Load Transfer Due To Acceleration

Hard/Quick Acceleration
Force or Weight Movement

Direction of Travel
Longitudinal Load Transfer Due to Deceleration

Vehicle Movements

Hard/Quick Braking Force or Weight Movement

Direction of Travel
Gradeability

\[ W \sin \theta = W_f + (W \cos \theta - (W/g) a_x h - D_A h_a - W h \sin \theta)/L \]

Neglecting drag forces on a car, the grade can be calculated using the following equation for front wheel drive vehicle

\[ c \]

\[ \frac{(a_x/g)h}{L} \]

For a rear wheel drive

\[ c \]

\[ \frac{(a_x/g)h}{L} \]
Lateral Acceleration and Lateral Load Transfer

\[ CF = \frac{m V^2}{R} = m a_y a_y = \frac{V^2}{R} \]

Inner side

Outer side

\[ a_y \]

\[ \frac{2V^2}{R} \]
Lateral Weight Transfer

- Weight Transfer is directly a function of

  - Lateral Acceleration, $a_y/g$
  - Weight, $W$
  - Height of the Center of Gravity, $h$
  - Wheel Track width, $t$
Track Width $t$

$W_r$

$W_l$
Lateral Weight Transfer

- On a flat roadway the lateral weight transfer \( W_l \) is equal to

\[
W_l = \frac{a}{h} \quad W_{lateral} = W
\]

- The weight on the right side \( W_R \) in the turn is comprised of a static component and a component due to the lateral acceleration \( a_y/g \).

\[
W_R = W
\]

\[
W_l = W
\]

\[
l_L = \text{Lateral dist from CG to left tire}
\]

\[
\text{Track Width } t
\]
Lateral Load Transfer - Roll Over Potential

\[ M_r = W(t - y)F \]

\[ W_{r/l} \]

\[ h_{RA} \]

\[ F = \frac{W}{g} a_y \]

\[ \phi \]

\[ h \]

\[ \text{Track Width} \]

\[ 2 \]
Rollover potential

If the roll angle of the sprung mass is included in the analysis of a vehicle with a 50/50 L to R weight distribution.

\[
\text{If } W_0 \text{ then } M_r = \frac{W}{2} (\frac{t}{y} F h) 02 y (h \frac{h_{RA}}{Sin})
\]
Lateral Weight Transfer

Roll Over potential

The weight on the inside wheels is defined as

\[ W = \frac{1}{2} \frac{h}{g} \frac{t}{a_y} \]

Dividing through by \( W \)

\[ \frac{1}{2} \frac{h}{g} \frac{t}{a_y} \]

With further transposing

\[ \frac{a_y}{g} \frac{h}{2h} = \frac{h_{RA}}{h \sin} \]

\[ \text{(8)} \]
Lateral Weight Transfer

- Potential rollover is possible when $W_1 = 0$

$$\frac{a_y}{t} = \frac{h_{RA}}{2h}$$

- It should be noted that roll angle of the sprung mass has limited effect on the steady-state rollover potential.

- Static Stability Factor: SSF : $a_y/g = t/2h$
Rollover and SSF

Video
Cars will roll at: 1.2 - 1.3 G

Sport Utility Vehicles: about 1 G

Pick-up or Jeep: about 0.8 G

A fully loaded semi: only needs about 0.4 G
Lateral Load Transfer

1. Load Transfer due to Centrifugal Force – Non Rolling

2. Load Transfer due to change of gravity position - Rolling Load Transfer

3. Load Transfer due to un-sprung weight
Non Rolling Load Transfer

Centrifugal Force

Sprung Mass

Roll Centre

\[ F = \frac{W}{g} \frac{a}{c} \frac{1}{y} \]
W = 1250 kg  T = 1600 mm,  h = 500 mm,  \( \theta = 10 \) deg  d = 500 \( \sin 10 \) = 86.8 mm

\[ Wo = W \cdot \frac{li}{t} = 1250 \cdot (800 + 86.8)/1600 = 693 \text{ kg} \]

\[ Wi = 557 \text{ kg} \]
Load Transfer due to Unsprung Weight

Due to Unsprung Mass

Vehicle taking a left turn

\[ W_{us}/g \times h/t \times a_y \]
Lateral Load Transfer

Mechanism of Dynamic Weight Transfer

Sprung Mass
Non rolling Load Transfer through Roll Centre
(Centripetal force)

Rolling Load Transfer
through Suspension

Rolling Load Transfer through Suspension

Road Surface

Suspension Unsprung

Unsprung Mass Transfer

Lateral Load Transfer = Sprung Mass Rolling Mass Transfer + Sprung Mass Non Rolling Load Transfer + Unsprung Mass Load Transfer

\[ W_{TF} = W_T + W_{TFn} + W_{TFu} + W_{RS} + W_{TRn} + W_{TRu} \]

\[ W_{LAT} = W_{LATF} + W_{LATF} + W_{LATF} \]

\[ W_{LAT} = W_L \]
Lateral Load Transfer Simulations
Fish Hook – Maneuver-side

Fish Hook Maneuver
Variation of Load on Wheels-Simulations
Forces between Road and Wheel

- **Forces** \( \mathbf{F} \)
  - Horizontal forward forces at the contact of the tires with the road - Traction Forces
  - Vertical forces at the contact of the tires with the road - Reactions
  - Side forces at the tire contact with the road – While taking a turn
- **Study of response of vehicle to the forces that act at the four palm sized patches (at the tire and road contact)**
Forces between Road and Wheel Lateral and Vertical Forces
Exercise

Following data are given Wheel base length = 2500 mm Wheel Track width = 1450 mm Vehicle Weight = 1250 kg Load on front axle = 825 kg Front wheel drive front Engine vehicle R= wheel Radius = 300 mm Maximum gradient for equilibrium = 32 deg Rolling resistance coefficient = 0.015 Coefficient of Drag = 0.28 Frontal Area of Vehicle = 2.25 sq.m Maximum Vehicle Speed = 150 kmph Road μ = 0.7

Calculate:
Real axle load
Position of CG
Height of CG considering equilibrium gradient as 32 deg
Exercise

Max Tractive Resistance
Max Tractive Power assuming a maximum vehicle speed of 150 kmph Longitudinal load transfer at linear acceleration of 0.4g
Lateral load transfer at lateral acceleration of 0.4g
What is the body roll angle assuming the roll centre is 20 cm above the ground
Load on each of the wheel when linear acceleration is 0.2g and lateral acceleration is 0.2g
Maximum acceleration/deceleration possible
Maximum cornering velocity possible
Under what situation the Car Rolls Over
Assume road is flat for all the calculations unless mentioned

What should be the stiffness of each suspension spring assuming the stiffness ratio of tyre and suspension spring is 10
Forces on a Car with a Trailer

Diagram showing forces on a car with a trailer, with labeled points: $W_b$, $W$, $h_1$, $h_2$, $h_3$, $f$, $e$, $d$, $c$, $b$, and the hitch point.
Taking moment about the point where the tire contacts the ground-counterclockwise moment is considered positive

\[ \sum T_y = 0 = W_b h_3 \sin \Theta + F_{zb} (e + f) - W_b f \cos \Theta - F_{xb} h_2 \]  

(1)

Forces along longitudinal axis \( F_x = 0 \)
\[ \Sigma F_x = 0 = F_{xb} - W_b \sin \Theta \]
Force Analysis on Car
Taking moments about the rear tire contact point:

\[ \Sigma T_y = 0 = W h_1 \sin \Theta - W c \cos \Theta + F_{zb} d + F_{xb} h_2 + W_f (b + c) \]  

(3)

And for moments about the front axle:

\[ \Sigma T_y = 0 = W h_1 \sin \Theta + W b \cos \Theta + F_{zb} (b + c + d) + F_{xb} h_2 - W_r (b + c) \]  

(4)
Determination of Unknowns

Unknowns are: $W_f, W_r, F_{xb}, F_{zb}$

$F = W_b \sin b$

If there are drag forces and inertia forces they need to be considered while determining these forces.
Gradeability

\[(W + W_b) \sin \Theta = F_{xf} = \mu \ W_f\]

\[= \mu \left[ W \frac{c}{L} \cos \Theta - W \frac{h_1}{L} \sin \Theta - W_b \frac{h_2}{L} \sin \Theta\right.\]

\[+ W_b \frac{d}{L} \frac{h_3}{L_t} \sin \Theta - W_b \frac{d}{L} \frac{f}{L_t} \cos \Theta - W_b \frac{d}{L} \frac{h_2}{L_t} \sin \Theta\left.\right]\]

Taking

\[L = b + c = \text{Wheelbase of the van}\]

\[L_t = e + f = \text{Wheelbase of the trailer (hitch to wheels)}\]

\[\zeta = \frac{W_b}{W} = \text{Nondimensional weight of the trailer}\]
FWD

\[ \Theta = \mu \frac{c - \zeta \frac{d}{L} \frac{f}{L_\text{t}}}{1 + \mu \frac{h}{L} + \zeta (1 + \mu \frac{h_2}{L} + \mu \frac{d}{L} \frac{h_2 - h_3}{L_\text{t}})} \]

RWD

\[ \Theta = \mu \frac{b + \zeta (L + d) \frac{f}{L_\text{t}}}{1 - \mu \frac{h}{L} + \zeta (1 - \mu \frac{h_2}{L} - \mu \frac{(L + d)}{L} \frac{h_2 - h_3}{L_\text{t}})} \]
<table>
<thead>
<tr>
<th>Truck</th>
<th>Trailer Systems</th>
</tr>
</thead>
</table>


1. tractor unit
2. semi-trailer (detachable)
3. engine compartment
4. cabin
5. sleeper (not present in all trucks)
6. air dam
7. fuel tanks
8. fifth-wheel coupling
9. enclosed cargo space
10. landing gear - legs for when semi-trailer is detached
**LEFT-** Trailer "Dive" during heavy braking increases the effect of tongue weight.

**RIGHT-** Weight distributing hitch transfers loads to frame and to both axles of tow vehicle for safer stops and smoother ride.
Vehicle Movements of Interest

- **Along Y-Axis**
  - Side force due to Cornering
  - Side force responsible for Roll

- **About Y-Axis**
  - Pitching Caused by Diving (braking) and Squatting (Acceleration)

- **Handling**

- **Along Z-Axis - Vertical**
  - Bouncing (Ride)

- **About Z-Axis**
  - Yaw caused by side forces

- **Along X-axis - Longitudinal**
  - Acceleration of the Vehicle
  - Braking Performance

- **About X-axis**
  - Rolling caused by side forces
Timeline - Summary

- Roman carriage rim brake
  - Quadricycle (Ford - 1896)
  - 1919 First single foot pedal to operate coupled four-wheel brakes
    - 1922 hydraulic brakes
  - 1951 Hydraulic Power Steering

- The Model T (Ford - 1908)
  - 1986 Tire pressure Monitoring (TPM)
  - 1987 Traction Control (TCS, ASR)
  - 1987 4-wheel steering Honda Prelude
  - 1992 ESP/ESC
  - 1993 Electric power-steering
  - 2004 Active front steering (BMW)
  - 2002 Electric Parking Brake
  - 2005 Lane Assist (LDW)
  - Park Assist (PMA)
  - Dynamic Cruise Control (DCC)
  - Active Cruise Control (ACC)
  - Cornering Brake Control (CBC)
  - Electronic Brake force Distribution (EBD)
  - Dynamic Brake Control (DBC)

- Today
  - Steer-by-Wire Brake-by-Wire
  - ESP Load Sensing
## Action Domains of Chassis Control Systems

| EDC   | LF       | ARS | TPC   | CBS | ADB | HDC   | ASL | GMR   | DTC   | MSR   | EMF   | ASC   | EBV   | CBC   | DBC   | ABS   | HES   | AFS   | EPS   | HPS   | HPS   | LDW   | PMA   | PMA   | DCC   | ACC   |
|-------|----------|-----|-------|-----|-----|-------|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|       | Active Airsprings | Dynamic Drive | Tire Pressure Control | Condition Based Service | Aut. Differential Brake | Hill Descent Control | Trailer Stabilisation Logic | Yaw Torque Control | Dynamic Traction Control | Engine Drag Control | Parking Brake | Automatic Stability Control | Electronic Brake Distribution | Cornering Brake Control | Dynamic Brake Control | Anti Lock System | Active Rear Steering | Active Front Steering | Electric Power Steering | Hydraulic Power Steering | Lane Assist | Park Assist | Dynamic Cruise Control | Active Cruise Control |

### Domains
- **Vertical Domain** ("Ride")
- **Lateral Domain**
- **Longitudinal Domain**
- **Comfort**
- **Safety / Stability**
- **Dynamics / Agility**
**Draw Bar Pull**

The torque on the driving axle creates a force between the tyres and the road which is used to propel the vehicle. This gross force is termed the tractive effort and the net force, that is, gross force minus rolling resistance is the drawbar pull.

\[ DP = \frac{T \times R \times 1000}{r} - RR \]

**Where:**
- DP = Drawbar pull in newtons
- T = Motor torque in newton metres
- R = Overall gear reduction including both axle and transmission
- r = Rolling radius of loaded driving tyre in millimetres
- RR = Road rolling resistance in newtons
- GVW = Gross vehicle weight of motive vehicle in kilograms
Reference


https://vtechworks.lib.vt.edu/bitstream/handle/10919/36615/Chapter1.pdf?sequence=3&isAllowed=y

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