VEHICLE DYNAMICS

ISO 3833 give us the terminology of the different type of vehicles

- Vehicle dynamics deals with the interaction between:
  - driver
  - vehicle
  - loads
  - enviroment

type of interaction

DRIVER → VEHICLE

LOAD → VEHICLE

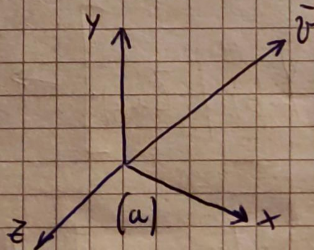
ENVIROMENT → VEHICLE

NOTATION

SCALAR , s

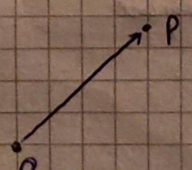
VECTOR , $\bar{v} \in \mathbb{R}^3$

VECTOR in BASE $\bar{v}_{(a)}$



$\bar{v} = \{ v_x, v_y, v_z \}$

VECTOR FROM O to P $\overline{OP}_{(a)} = P_{O(a)}$



NB the same vector can be measured also using another basis

· MATRICES $\quad [M] \in \mathbb{R}^{n \times m}$ $\quad n = $ row, $m = $ column

property in the slides

ROTATION MATRIX

Very important for us, are 3×3 matrix

$$R^{3\times 3} \rightarrow \text{ex} \quad R = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix}$$

using this we are able to rotate a vector from one base to another

$$\bar{v}' = [R]\,\bar{v}$$

$$\bar{v}_{(b)} = [R_{a,b}]\,\bar{v}_{(a)}$$

$$[R_{a,b}] = \left[X_{a(b)} \,/\, Y_{a(b)} \,/\, Z_{a(b)} \right] \rightarrow \text{Composed by 9 number!}$$

reconne the vectors respect the ~~x~~ new base

(NB) Is an orthogonal matrix $\Rightarrow$ inverse = transpose

PARAMETRIZATION

$$[R(\alpha_x)] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_x & -\sin\alpha_x \\ 0 & \sin\alpha_x & \cos\alpha_x \end{bmatrix} \qquad [R(\alpha_y)] = \begin{bmatrix} \cos\alpha_y & 0 & \sin\alpha_y \\ 0 & 1 & 0 \\ -\sin\alpha_y & 0 & \cos\alpha_y \end{bmatrix}$$

$$[R(\alpha_z)] = \begin{bmatrix} \cos\alpha_z & \sin\alpha_z & 0 \\ \sin\alpha_z & \cos\alpha_z & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

So multiplying we obtain a global rotation that is the product of the three

→ EXTRINSIC rotation X - Y - Z

→ we have 27 combination, some with singularities

SAE REGULATION → X → longitudinal

Y → side

Z → downward!

SINGULARITIES happen when we are not able to go back from rotation matrix to the angle.

→ a type of parametrization that doesn't suffer the problem of singularities is the QUATERNION

↓

are an extension of the COMPLEX NUMBERS

$$q = e_0 + i e_1 + J e_2 + K e_3$$

How we use the quaternions?

- unit quaternions represent rotation in 3D about generic axis u:

If I have the vector $\bar{u}$ and ϕ I can compute

$$q_0 = \cos\left(\frac{\phi}{2}\right) \quad q_1 = u_x \sin\left(\frac{\phi}{2}\right) \quad q_2 = u_y \sin\left(\frac{\phi}{2}\right) \quad q_3 = u_z \sin\left(\frac{\phi}{2}\right)$$

→ rotation of point $\bar{v}$ as a double quaternion product:

$$\underset{\substack{\uparrow \\ v'}}{\left(0, \bar{v}'\right)} = q \underset{\substack{\uparrow \\ v}}{\left(0, \bar{v}\right)} \underset{\substack{\nwarrow \\ \text{conjugate}}}{q^*} \quad \longleftrightarrow \quad \bar{v}' = [R]\,\bar{v}$$

There is a formula to compute the ROTATION matrix given a quaternion

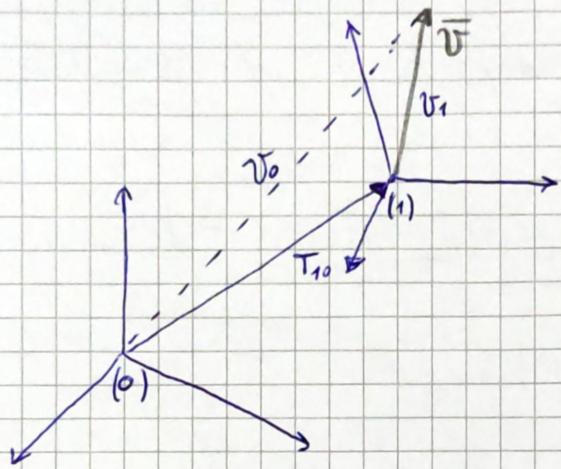
SINGULARITY FREE → we are always able to find the rotation matrix given the quaternion

COORDINATE TRANSFORMATION

Consider the problem to TRANSFORM the position of a point moving with a rigid reference

- a reference 1 moves away from a reference 0
- ROTATION $[R_{1,0}]$ of 1 respect to 0
- TRANSLATION $T_{10}(0) = \bar{O}_1(0)$

$$* \quad \bar{v}_0(0) = \bar{T}_{10}(0) + \overbrace{[R_{1,0}]\,\bar{v}_1(1)}^{= \bar{v}_1(0)}$$



Something start from 0 and travel to 1, and we want to know V respect to the point 0 and expressed in 0 reference!

↓ set of three number (the axis)

---

without rotation, what happen?

$$\bar{V}_0(0) = \bar{T}_{10} + V_1(0)$$

we have a sum if all the vector are measured in the same basis

* we can obtain the inverse

$$V_1(1) = [R_{1,0}]^T \left(\bar{V}_0(0) - T_{10}(0) \right)$$

19 operation for doing ~~the~~ this

EXAMPLE in the notebook

SPEED

to compute the speed is necessary to do the derivative!

$$\dot{v}_0(0) = \overbrace{\dot{T}_{10}(0) + [R_{1,0}][\tilde{\omega}_{(1)}]\, v_{1(1)}}^{\text{VELOCITÀ DI TRASCINAMENTO}} + \underbrace{[R_{1,0}]\, \dot{v}_{1(1)}}_{\text{RELATIVE VELOCITY}}$$

What is the meaning of $[\dot{R}]$?

is the rotation matrix multiplied by the angular velocity vector

$$[\tilde{\omega}_{0(1)}] = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}$$

- $\omega(1)$ INTRINSIC angular velocity
- $\omega(0)$ EXTRINSIC angular velocity

ACCELERATION

Computing another acceleration, we find the acceleration of a ROTO TRASLATING object

$$\ddot{v}_0(0) = \ddot{T}_{10}(0) + \underbrace{[R_{1,0}][\tilde{\omega}_{(1)}][\tilde{\omega}_{(1)}]\, v_{1(1)}}_{\text{CENTRIPETAL ACCELERATION}} + [R_{1,0}][\dot{\tilde{\omega}}_{(1)}]\, v_{1(1)} + 2[R_{1,0}][\tilde{\omega}_{(1)}]\dot{v}_{1(1)}$$

$$+ [R_{1,0}]\, \ddot{v}_1(1)$$

this is the coriolis acceleration!

example 2 in the notebook

DYNAMICS

there are two classes for equation of motion ↗ ODE ↘ DAE

ODE ordinary differential equations

$$\frac{dx}{dt} = f(x,t)$$

- as many equations as degrees of freedom
- in dynamics : index 2 $\quad M\frac{dv}{dt} = f(v,x,t)$
- index-n can be always converted to index 1

ex. $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} f(v,x) \\ v \end{bmatrix}$$

$$\frac{ds}{dt} = f(s,t) \qquad s = \begin{bmatrix} v \\ x \end{bmatrix}$$

DAE differential algebraic equation

- more complex than ODE, they contain also CONSTRAINT

ex. $$\frac{dx}{dt} = f(x,y,t)$$

$$g(x,y,t) = 0$$

CONFIGURATION → expressed by position, rotation

state of a system is equal to ~~position~~ CONFIGURATION + velocity

LAGRANGE EQUATIONS

variational approach to solve problem with complicated structure and small number of coordinates.

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{q}_i} - \frac{\partial T}{\partial q_i} + \frac{\partial R}{\partial \dot{q}_i} + \frac{\partial V}{\partial q_i} = Q_i$$

EXAMPLE 3 in the notebook

for a free-rotating bodies in space

in the slide the values

inertia tensor

$$\begin{cases} F = m\ddot{x} \\ M = [J_G]\,\dot{\Omega} + \underbrace{\Omega \wedge [J_G]\,\Omega}_{\text{GYROSCOPIC torque}} \end{cases}$$

→ angular velocity

torque applied to the body

NO if the angular velocity vector is alligned to on the three axis

PRECESSION RATE

TIRE MODEL

Tire forces are the most important loads

F is imposed by (normal, lateral, longitudinal) the tire state

$$F = \{ F_x, F_y, F_z \} = f(\text{tire state})$$

can be: - slip angle
- slip ratio
- temperature

- STUCK TO THE ROAD
- SLIDES ACROSS

⇑

TIRE POINT CAN BE

⇑

TIRE FOOTPRINT FORCES

In real life is a pressure ⇒ we need a PATCH but in our case we will consider a single point (average of the points)

SAE TIRE REFERENCE

(PAG 63 MILLIKEN for an accurate explanation)

6 scalars ⇒ three forces : F_x, F_y, F_z

- LONGITUDINAL
- LATERAL
- VERTICAL (NORMAL)

⇓

a WRENCH

three torques : M_x, M_y, M_z

- OVERTURNING → during an inclination
- ROLLING RESISTANCE
- ALIGNING TORQUE → try to align the tire in the direction of rolling

SIMPLIFIED DISK MODEL

made by SANDWICHING a sheet of hard rubber between two metal disks

assuming : - NO THICKNESS

- LOCAL LATERAL ELASTIC DEFORMATION

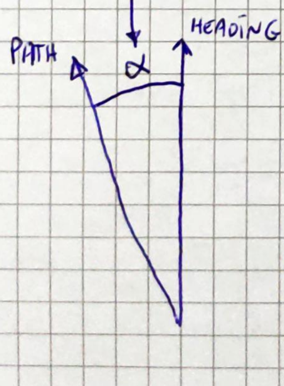
LOOK at slide 7!

the tire when is pushed sideways (small lateral force) the rubber deflects and the wheels moves a small amount laterally

defining so the $\boxed{\text{SLIP ANGLE } \alpha}$ = DERIVA

NB with the RUBBER deflection we can ROTATE and move laterally without sliping

SLIP ANGLE = tire is deflected laterally and then rolled along,
move in a direction at an angle to the wheel plane or heading



RELATIONSHIP BETWEEN LATERAL FORCE and SLIP ANGLE

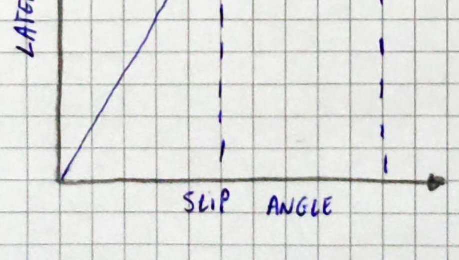
the lateral FORCE may be thought as a result of SLIP angle, or the SLIP angle as a result of lateral force.

EX

1. if front wheel are steered a slip angle is created which gives rise to a lateral force. This lateral force then TURNS the vehicle
2. on tire test machine is common to set a series of slip angle and measure the resultant lateral force.
3. When a lateral wind hit the vehicle a lateral force must be react due to the slip angle change
4. When cornering or on a banked road the lateral force is reacted by changes in tire slip angles

TIRE lateral FORCE (EFFECT of SLIP ANGLE α)

SLIDE 9



you can see the input and output as you can like (ex. increase of slip angle cause an increase of lateral force)

- we can observe the limit where we reach the maximum lateral force

In slide (10) we saw the effect of the vertical force (NORMAL)

⇒ From basic Coulomb friction all the curves should be the same

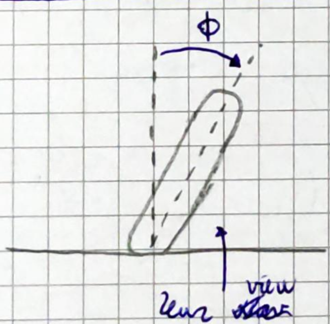
⇒ in reality! FOR THE SAME TIRE ~~as~~ a higher normal force leads to

* a lower lateral G forces. (start to be a PROBLEM)

so a good solution is to have a lower pressure and so increase the size of the tire

* this effect is called $\boxed{\text{TYRE LOAD SENSITIVITY}}$

CAMBER EFFECT



is POSITIVE!

DEF = is defined as the angle between ~~the~~ a tilted wheel plane and the vertical.

a bit of NEGATIVE camber in all the cars

- because increase a little bit the lateral force

- NEGATIVE is that we consume the tire (ruin)

⇒ the camber affect a little bit of ALIGNING TORQUE!

LONGITUDINAL FORCE

In order to accelerate or brake a vehicle, ~~a~~ LONGITUDINAL FORCES must be developed between the tires and the ground.

No change in speed (ACCELERATION) can take place without an applied force acting on a vehicle mass.

⇒ to generate a longitudinal force, ~~~~ a ~~~~ SLIP must ~~~~ be present (both tractive or braking)

- Shape of the force is different in tractive or braking (look slide 13)

SLIP RATIO

Is defined as the difference between the angular velocity of the driven (or braked) wheel Ω and the angular velocity of the free-rolling ~~~~ wheel Ω_0

LONGITUDINAL SLIP VELOCITY $S = \Omega - \Omega_0$

SLIP RATIO FOR SAE

$$\boxed{SR = \frac{\Omega - \Omega_0}{\Omega}}$$

$$SR = \frac{\Omega R_e}{V} - 1 \,, \quad \alpha = 0 \qquad \text{with} \quad \Omega_0 = \frac{V}{R_e}$$

R_e = radius of the free rolling wheel

- For FREE ROLLING the SR = 0
- LOCKED BRAKING SR = -1

slide 14 the graph is interesting!

- FOR traction SR could be ∞

increasing the slipe we increase also the TRACTION FORCE reaching a limit and then there is a decrease

⇒ there are different formulas to obtain the SLIP RATIO (slide 15)

COMBINING LONGITUDINAL - LATERAL FORCE

Use of SAKAI PLOTS

What we observe?

- increasing the slipe angle we decrease the longitudinal force ("traction force")

- increasing the slip ratio we decrease the lateral force (or the ability to steer)

In slide 18 the combined plot with lateral force and longitudinal force! ⇒ there are also SLIP ANGLE and SLIP ratio

The NAME is FRICTION CIRCLE DIAGRAM

What can we observe?

→ high lateral force when no ~~long~~ longitudinal force is present and also the OPPOSITE

- this graph give us the idea of what to do in different driving condition to obtain the best force from our tyre!

ALIGNING TORQUE slide 19

M_z, describe a tire's tendency to steer about a vertical axis through the center of the print

- At low and medium slip angles the tire tends to align its heading with its path

THIS torque is important because is what we ~~f~~ feel in our steering wheel!

⇒ after a certain ~~s~~ slip angle this torque goes to zero and the felling is like you loose the steer!

ROLLING RESISTANCE TORQUE

$\downarrow$

M_y is caused by : - hysteresis

- dirt road

- brushing effect in tire threads

Some dissipative effect!

$$\underset{\text{NORMAL FORCE}}{} \quad \underset{\text{ROLLING PARAMETER}}{}$$

$$M_y = F_z X_R$$

X_R is few mm length and tells that the contact point is moved in front of the tire

$$X_R = f_R R$$

ROLLING COEFFICIENT

RADIUS of TIRE

TIRE MODEL

We can't go outside the FRICTION CIRCLE DIAGRAM (remember)

→ the goal is to implement a formula that give 6 values ~~with its 2 state~~
↓
depending on the state (α, SR)
ex.

3 type of models : - LUT

	F_x	F_y	F_z	
α_1				
α_2				
α_3				

very expensive!

- SEMI-EMPIRICAL ex → (PACEJKA)

able to build some plot starting from limited number of experimental data

- PHYSICAL METHOD videogames based on this!

↓
used by the manufacturer that want to improve the tyres

- high frequency vibration → NOISE!

use FINITE ELEMENT APPROACH

COULOMB MODEL

require only one μ (friction coefficient)

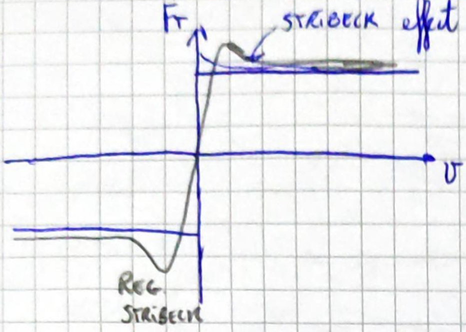
$$\|F_T\| \le \mu_S F_N \longrightarrow \text{in case of STATIC friction } (v=0)$$

the sum between F_N and F_T must stay inside a cone, obtaining a φ angle.

$$\|F_T\| = \mu_D F_N \longrightarrow \text{in case of dynamic friction } (v\neq 0)$$

if $v \neq 0$ the F_T is opposite of the v $\xleftarrow[F_T]{}$ $\longrightarrow v$

the model is described by μ_s and μ_0 or μ in simplified model



FTIRE

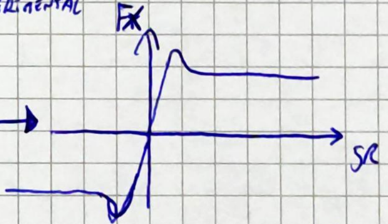
simple formula and need only 9 parameters (easy to find)

→ it doesn't consider the CAMBER

PACEJKA

→ FEW EXPERIMENTAL DATA

magic formula →



STORY → create this curve in matlab

↓

the formula ~~that~~ on the slide give this shape

need only → peak, and other

SH, SV → how much is shifted from the origin ⇒ for example with the camber

- different version of PACEJKA FORMULA
- use of other formula to MIX the longitudinal and lateral force plots

MF_TIRE

based on PACEJKA, introduce also the inflation, the model of the road.

MF - SWIFT

- the tyre is composed by multiple slices and each slice is represented by few DOF (6) that represent a RING able to move up and down respect to the ring thanks to "damper and spring"

TM easy

allow parking and stand still!

presence of spring and dampers in "horizontal and tangential" direction

FTire

PHYSICAL MODEL

represent also the deformation of the tyre!

CD tire

→ one of the most advanced model

- good results of simulation when the tyre is in resonance
- simulation of the different layers present in a tire!
- temperature model! → link to the friction coefficient!
  ↓
  useful for racing car tire...
- Cavity model → air trapped inside the tyre

AERODYNAMICS

relevant in high speed!

→ Why we have to study it?

DRAG → LESS AUTONOMY

NOISE → COMFORT

DOWFORCE → higher performance in lateral dynamics.

→ it is a NON LINEAR effects, difficult to study

APPROACHES
- → ANALYTICAL → only for simple shapes
- → EXPERIMENTAL → change the scale, need to change also other ~~the~~ condition
- → NUMERICAL → CFD software

BASIC CONCEPTS

- STATIC PRESSURE p → measured with a U-PIPE
  in a wing there is a pressure tap
- DYNAMIC PRESSURE q → also called stag pressure
- TOTAL PRESSURE

$$H = p + \overbrace{\left(\frac{1}{2}\rho V^2\right)}^{q}$$

- PITOT TUBE

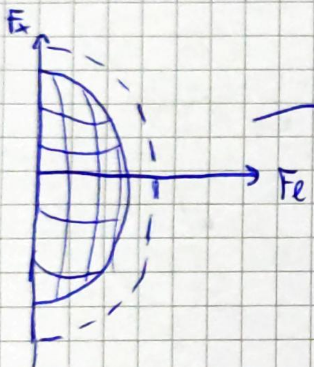
↳ compute airspeed (V) → compute ~~same~~ $q = H - p$

given q is easy to find V

→ the pressure can be controlled by the SHAPE to generate lift or downforce!

- airplane net results of the pressure ↑
- for a racecar ↓

ex. a car taking a curve



for a certain load applied to the tire

increasing the load we change the plot

OTHER EFFECT

sharp corners cause separation and turbulence!

DRAG COEFFICIENT

measure how well we cut the air! we want to reduce it (always)

$$C_D = \frac{DRAG}{A q} \qquad F_x = \frac{1}{2} A C_D \rho V^2$$

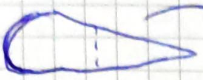
"FRONTAL DRAG"

theoretical

paying attention on both C_D and A

C_D of a F1 car is very bad ! $C_D = 1,7 \sim$

- need of very high downforce!

 optimal shape!   use of long tail

TEARDROP

→ create downforce to improve the contact force between ~~the~~ the tire and the ground.
↓
with wing / spoiler!

→ to evaluate the vertical force $F_Z = \frac{1}{2} C_L A \rho V^2$

C_L change with h → height of spoiler! without spoiler we can have some lift effect ("dangerous")

NB in some cases the introduction of a spoiler doesn't ~~affect~~ increase the DRAG, even improving!

FIRST SPOILER used in AL FERRARI DINO, Chaparral strange idea to Connect the wing to the suspension bracket and NOT in the FRAME

REGARDING the FLAP, if the angle of attack is too high we get a SEPARATION. for high angle we can attach a SLAT in the front of the wing and a FLAP in the rear (with a gap)

→ use of side FINS ("end plate") improve the flow of the air which touches the wing.

Use of the ground effect! → use of the VENTURI EFFECT

↳ under the car the flow is very high, so we have a LOW PRESSURE

so we obtain a different of pressure between the different part (TOP and BOTTOM)

↳ WITH SKIRTS to exploit this effect!

REAR DIFFUSER → create downforce

↓

the diverging effect will create additional downforce!

POWERTRAIN

engine + driveline

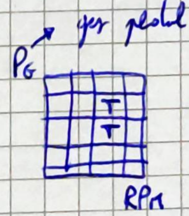
↓

pay attention on the definition!

transmission include:
- clutch
- torque converter
- gears

FREE SOFTWARE → OPEN MODELICA

ENGINE → use of LUT



torque converter → presents of OIL (need to watch a youtube video)

↳ to design it, just 2 numbers K^* and R_T

sequential gearbox → you can pass from I to II to III

H-type → synchronizer to match the speed of the gears!

$$\tau = \frac{\omega_o}{\omega_i}$$ → output; → input

DIFFERENTIAL

↓

to obtain different angular velocity!

$\tau_0 = -1$

↑ ordinary

$$\Omega_P = \frac{\omega_L + \omega_R}{2}$$

enter with speed in a direction and in output we have another direction

in case of a tire in contact with ICE we lose torque because the engine increase the speed due to the incr of speed of the wheel!
(DA RISENTIRE)

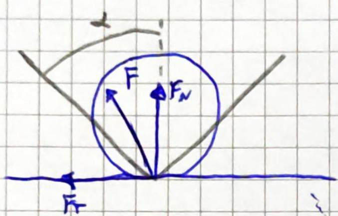
→ avoid this with SELF-LOCKING DIFFERENTIAL

LONGITUDINAL DYNAMICS | used at the very beginning of the design process!

Why ? predict : acceleration, braking, steady state ~~[illegible]~~

constant speed → evaluation of different aspect of a car

used of tire model simplified



F must stay inside the friction cone (in this case the ~~[illegible]~~ friction angle)

How to model? → analytical formulas
→ numerical methods → more complex

DYNAMIC WHEEL LOADS

- we have horizontal, vertical forces acting on both tires.

and we write the ~~[illegible]~~ equation of motion! → $\begin{cases} \Sigma H = 0 \\ \Sigma V = 0 \\ \Sigma M_o = 0 \end{cases}$

assumed NO SPRING (so NO BAMBING ??)

- the vertical loads are governed by 3 geometrical parameter!

$(a_1 + a_2) =$ wheel_base

- we can notice that increasing the ~~[illegible]~~ acceleration we decrease the F_{z1}! (lift of the front wheel)

h → have an impact on this!

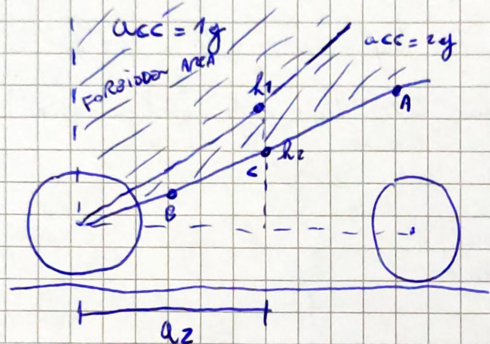
Slide 9

~~Stat~~ I - dynamic system → multiplied and divided by g

LOAD TRANSFER

When we accelerate a lot! rear tire pressed to the ground, front ~~b~~ lift!

TILTING LIMIT CASE → to avoid ~~the~~ flips area



the COG can stay in the limit line, the optimal point depend on different situation

B → better for brake

C → better for steering

A → big mistake for braking

at the end probably C is the best option!

A, B, C → good for load transfer and obtaining the best acceleration!

GRADE EFFECT

mg split in two components, one in vertical and one in horizontal direction!

→ the static component change a little due to the grade

AERODYNAMICS

in vertical direction we introduce the F_D, in horizontal we have the aerodynamical resistance!

F_D and F_{AR} depend on speed!

MAX ACCELERATION

work in friction limits

for normal tire $\mu = 1$ ... at a certain point the power doesn't change the acceleration, we reach the limit of the tire!

(NB) the limit depend on the FRICTION COEFFICIENT

$\Rightarrow$ $\boxed{\text{MAX ACCELERATION is limited by tires!}}$

what happen for a (2WD) ? different! slide → (17)

↓

the results is worse compared to 4WD

regarding the PLOT → For a FWD better to have the engine in the front
↓
slide 18

For a RWD better in the back
(paying attention to the tilting limits)

MAX DECELERATION

better to brake with the FRONT BRAKE

BRAKING TORQUE higher at the front!

NO SLIPPING ACCELERATION ~~[illegible]~~ exercise live ?!

LATERAL DYNAMICS

Why ? predict : - max cornering speed for a given radius
- understeering / oversteering
- stability

How ? → similar to the longitudinal dynamics!

Coordinate use the standard from SAE

→ NORMAL VELOCITY not used in lateral dynamics (same for roll and pitch velocity)

We only care about YAW angle!

STEADY STATE STEERING

Cornering at constant speed

the ideal steering ⇒ ACKERMAN steering

→ the hubs face in front of the rotation AXIS → that should stay on the line that connect the rear wheels

Real ~~[illegible]~~ life → difficult to turn the two wheels in order to have the hubs that point the ROTATION AXIS

→ with 2 the we can achieve an approximation of the ideal steering!

or obtain the PARALLEL or the reverse ackerman

long to achieve

- definition of ACKERMANN STEERING ANGLE based on the BYCICLE MODEL

$$\delta = \frac{l}{R}$$

for the same l, if l is higher we get an higher δ

- SPACE REQUIREMENTS → important for BUS, TRUCK

BYCICLE CAR MODEL

+ r yaw velocity

+ N torque applied to the vehicle

+ β sliping angle

+ δ angle given by the users to the steering wheel

slide 15

α_r → sliping angle of the rear wheel

α_f → for the front tire

- LONGITUDAL FORCE applied to the tire is neglected, so the force is perpendicular to the tires (only the lateral force is present)

Y_F, Y_R

for balance of forces

centripetal force: $CF = Y_F + Y_R$

Changing the position of the CG we can obtain a NEUTRAL STEER, UNDERSTEERING, OVERSTEERING CAR

SLIDE 18 → for an understeering car we need to increase the δ at the increase of the centripetal acceleration! (is the opposite for UNDERSTEERING CAR)

- for a TILTED Road a NEUTRAL STEERING vehicle Keep the trajectory!

STABILITY

Considering a vehicle that goes ~~the~~ straight with a ~~[illegible]~~ speed V, there is a value of V that if we have a disturbance in the ride the vehicle start to oscillatory (possible flipping)

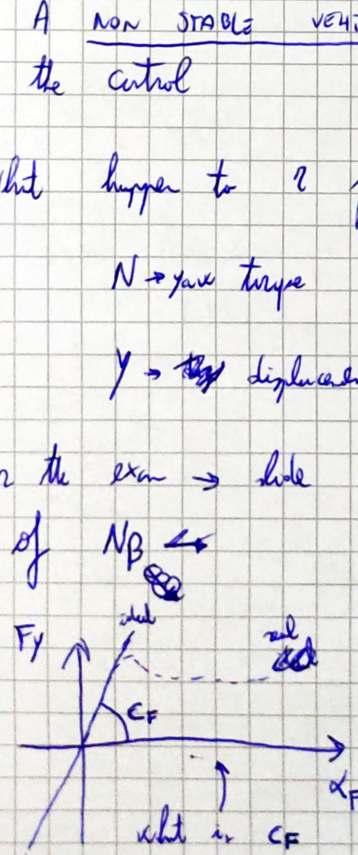
A NON STABLE VEHICLE is the one that receive the disturbance and lose the control

What happen to r for the stability?

N → yaw torque I_z → inertia in z axis

Y → ~~[illegible]~~ displacement

for the exam → slide 26 → remember the 2 ~~[illegible]~~ ODE and the equation of N_β ←



$N_\beta = 0$ for a NEUTRAL STEER CAR

> 0 understeer

< 0 oversteer