Vehicle Dynamics

Suspension Tuning
Vehicle Dynamics
Goals

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- Reduce race time

How do we do that?

what you want from Big Rigs: Over the Road Racing

a game that you should never touch
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- High acceleration - speed on straights
- Fast cornering - fast through turns
- High deceleration - slowing for turns

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- Maximize tire grip!

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Let’s make some back-of-the-envelope estimates of tire grip and its effects on performance.

- Simple friction model \( F_f = \mu F_n \)
- How can we estimate the coefficient of friction?
Simple Friction Model

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- Simple friction model \( F_f = \mu F_n \)
- How can we estimate the coefficient of friction?
- Put your car on a ramp, tip until it slides. Do this! Measure the angle!
Back-of-the-envelope linear acceleration

- Car model: point mass $m$ on a straight track of length $d$ in gravity $g$
- Friction model: $F_f = \mu F_n$
- If the car starts and ends at rest, what is the shortest time to drive $d$? Discuss with your team mates or a partner.

1) What is its maximum acceleration?
   \[ a = \mu g \]
   - Depends on tire grip!

2) How can we express the time in terms of $a$ and $d$?
   \[ d^2 = \frac{1}{2} a t^2 \]
   \[ t = 2 \sqrt{\frac{d}{\mu g}} \]
Linear acceleration

Back-of-the-envelope linear acceleration

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- 2) How can we express the time in terms of $a$ and $d$?
  - $\frac{d}{2} = \frac{1}{2} a \left(\frac{t}{2}\right)^2$
  - $t = 2 \sqrt{\frac{d}{\mu g}}$
Now let’s look at a simple model for cornering

- Car model: point mass $m$ in constant-speed circular motion
- What are the acceleration and force vectors?

\[ \mathbf{a} = -\omega^2 \mathbf{r} \]
\[ \mathbf{F} = -m\omega^2 \mathbf{r} = -m v^2 r \hat{r} \]

What’s the maximum $v$ for $r = 1 \text{ m}$ and $\mu = 1$?

\[ \mu mg = m v^2 r \]
\[ v = \sqrt{\mu g r} \]
\[ v \approx 3.1 \text{ m/s} \]

Simple models aren’t perfect, but they’re a good start to figure out what’s possible.
Cornering

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Now let’s look at more detailed models:

**Tire Grip vs. Load Curve**
- Tire grip is nonlinear with load
- Diminishing returns with more pressure

So I have 4 tires - what’s the optimal distribution?

tire grip curve from (link)
Tire Grip Curves

Now let’s look at more detailed models:

Tire Grip vs. Load Curve

- Tire grip is nonlinear with load
- Diminishing returns with more pressure

So I have 4 tires - what’s the optimal distribution?

- Completely even
- Don’t trade a loss of larger amount of grip for a gain of smaller amount of grip

Tire grip curve from (link)
Lateral Weight Transfer

And a more detailed car model with four wheels:

What happens to my effective weight distribution when turning?
assume stiff suspension for simplicity
analysis with springs much more involved
Lateral Weight Transfer

And a more detailed car model with four wheels:

What happens to my effective weight distribution when turning?

- Assume stiff suspension for simplicity
- Analysis with springs much more involved
  - Inward turning force from wheels
  - Applies torque, rolling to outer side of turn
  - Increases pressure on outer wheel
  - Decreases pressure on inner wheel

So total grip reduced - how to fix?
Lateral Weight Transfer

And a more detailed car model with four wheels:

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▶ Inward turning force from wheels
▶ Applies torque, rolling to outer side of turn
▶ Increases pressure on outer wheel
▶ Decreases pressure on inner wheel

So total grip reduced - how to fix?

▶ Note lever effect of turning force
▶ Shorten height to reduce torque
What happens to my effective weight distribution when accelerating?
What happens to my effective weight distribution when accelerating?

- Acceleration force produced at rear wheel
- Applies torque pitching up
- Increases traction on rear wheels
- Decreases grip on steering wheels
Ride height: distance between track surface to underside of chassis

We know lower center-of-gravity minimizes weight transfer. What are the limits?
Ride height: distance between track surface to underside of chassis

We know lower center-of-gravity minimizes weight transfer. What are the limits?

- Need to clear uneven surfaces
- Don’t drag your chassis
Ackermann Steering

Let’s look more closely at your car’s steering.

You may have noticed that your wheels aren’t parallel when turning. Why?
Ackermann Steering

Let’s look more closely at your car’s steering.

You may have noticed that your wheels aren’t parallel when turning. Why?

▶ Different turn radius for inner/outer wheels: it’s equivalent to two bicycle steering models glued side-by-side.
▶ Ackermann steering: angular difference between inner and outer wheels for different turn radius
▶ A result of the different lengths / angles of steering linkages
Slipping

Given the Ackermann steering geometry...

What happens if the front wheels slip?

- Understeer: turns less than intended
- Turning radius increased

What happens if the back wheels slip?

- Oversteer: turns more than intended
- Turning radius decreased

What sensors might you use to tell the car is slipping sideways? Accelerating/braking?
Slipping

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Vehicle Dynamics

Steering

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Suspension Tuning

Make sure your electronic hardware is working first. This suspension tuning is icing on the cake in comparison.
Disclaimer

- Justin’s research is with legs, not wheels
  - I’ve tuned exactly zero cars
- These slides were made in a previous year with information from various Internet sources, which hopefully is correct
  - (it passes the “smell test”)
- If it sounds wrong, it might really be...

I HAVE NO IDEA WHAT I'M DOING

not actually that bad
Camber

Camber: angle between wheel and vertical (from front)

- Positive if tilting outwards
- Negative if tilting inwards

What’s optimal to maximize contact area?

Positive camber

Negative camber
Camber

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What’s optimal to maximize contact area?

- 0 degree, ideally

But need to account for turning chassis roll
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  - Increases camber angle during turns
  - So slightly negative camber (-1° to -4°) to increase traction when cornering
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Caster: angle between steering axis and vertical

- Positive when steering axis line intersects road ahead of contact patch

What are the stability effects of positive caster?

think shopping cart “caster” wheels
Caster: angle between steering axis and vertical

- Positive when steering axis line intersects road ahead of contact patch

What are the stability effects of positive caster?

- Self-centering effect
  - Contact patch “trails” steering axis
  - Typically 3° to 5° recommended
  - Less may increase steering at stability cost
- Overall effect is fairly small

think shopping cart “caster” wheels
**Toe**

Toe: angle between wheels, viewed from top

- **Toe-in (positive):** inwards towards front
- **Toe-out (negative):** outwards towards front

**Effects of toe:**

- **Toe-in provides straight-line stability**
- **Toe-out provides better turn-in but amplifies disturbances**
- **Small changes produces noticable effect**
- **Recommended range (front):** -3° to 1°

**Why might toe be bad?**

- Wheels rub against road - reduces tire life
Suspension Tuning

Torque Tuning

Toe

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Effects of toe:

- Toe-in provides straight-line stability
- Toe-out provides better turn-in but amplifies disturbances
- Small changes produces noticeable effect
- Recommended range (front): -3° to 1°

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Benchmarking

Obviously, what matters in the end is measurable performance

So, what are some ways to measure success?
Benchmarks

Obviously, what matters in the end is measurable performance.

So, what are some ways to measure success?

- Straight-line acceleration
- Maximum cornering velocity
- Minimum cornering radius

We've typically had less experience with mechanical tuning

- Try to benchmark and measure results
- Have a known-good configuration
  - “The better is the enemy of the good”
- Sensor and control algorithms important
Summary

- Maximize grip to maximize acceleration to reduce track times
- Tune camber (slightly negative), caster (slightly positive), toe
- Lower center of gravity: minimize weight transfer
- Measure, measure, measure

- Many topics not covered: tires, springs, shocks, sprung roll

(Possibly) one more discussion section left
- Any topics people want to see?