Steering

Mechanism: Tires set at slip angle to course (direction of travel) generate lateral force necessary to hold vehicle in turn \( (mV^2/R) \)

Turn-in (turn initiation): slip angle only on front wheels (due to steering input). Unbalanced forces (front/rear) cause both lateral force and angular acceleration (yaw – sets vehicle into turn). Yaw acceleration limited by yaw moment of inertia.

Steady turning: angle of vehicle relative to course builds slip angle at rear wheels, also generating lateral force, balancing vehicle front/rear, yaw acceleration → 0

Ackermann angle:
\[
\delta = \tan^{-1}\left( \frac{l}{R} \right) \approx \frac{l}{R}
\]
where \( l \) is wheelbase, \( R \) is turn radius. Ackermann angle is angle between front wheel and vehicle centerline when both front and rear wheels are pointed tangent to the circular path of the turn (tangent to vehicle course). Note:

\[
\delta_i = \tan^{-1}\left( \frac{l}{R - \frac{t_f}{2}} \right) \approx \frac{l}{R - \frac{t_f}{2}}
\]
\[
\delta_o = \tan^{-1}\left( \frac{l}{R + \frac{t_f}{2}} \right) \approx \frac{l}{R + \frac{t_f}{2}}
\]
for the inside and outside wheels. Since \( \delta_i > \delta_o \), the steering mechanism must provide more steer angle to the inside than the outside wheel. This is known as Ackermann steering, or 100% Ackermann. 0% Ackermann would be when \( \delta_i = \delta_o \), and some other percentage implies either outside wheel steered a little more than it would be for 100% Ackermann (>100%), or a little less (<100%). Reverse Ackermann is when \( \delta_i > \delta_o \).

Vehicles with a lot of lateral load transfer (high angular acceleration or soft roll stiffness) often use low Ackermann since most of the lateral force is on the outside wheel.

Steering mechanism:
Simply a mechanism for rotating the front wheels about a vertical axis. Rotating rear wheels gets tried from time to time, but since car pitches forward (dive – see text) when braking into a turn, the front wheels have more vertical load on turn-in, and so are more effective. The vertical axis (“kingpin axis”) can be inclined longitudinally (creating “castor”) or laterally (creating “camber”).

Usually mechanism is a lever (steering arm) pushed by bars (tie rods) pivoted from a lateral bar (e.g., steering rack) driven from side to side (e.g., by steering wheel rotating steering column rotating steering pinion engaging steering rack, or by one of many equivalent arrangements). Degree of Ackermann is set by:
Length of steering arm (measured from kingpin axis)
Angle of steering arm (relative to vehicle axis)
Length of steering rack (or equivalent lateral slider)
Front/rear placement of steering rack relative to kingpin
Track width

The more lateral acceleration desired, the more slip angle necessary, so that the whole vehicle points inside the direction of travel (tangent to the turn) to give the rear wheels a slip angle, and the front wheels are turned even more inside than this (i.e., rear wheels track outside front wheels at high lateral acceleration; at low acceleration the rears track inside the fronts, and the rear crossing the track often upsets cars that make this transition too rapidly). Low lateral force is a coefficient times the slip angle (“lateral force coefficient”, $C_\alpha$). At higher slip angles, $C_\alpha$ is reduced. At higher vertical wheel loads, $C_\alpha$ is reduced. $C_\alpha$ is a tire property.

“It can be shown” that steer angle (neglecting differences inside/outside) to maintain a turn is:

$$\delta = \frac{l}{R} + \alpha_f - \alpha_r$$

where:

$$\alpha_f = \frac{mg\left(b/l\right)}{C_{\alpha,f}}\left(v^2/R\right)$$

$$\alpha_r = \frac{mg\left(a/l\right)}{C_{\alpha,r}}\left(v^2/R\right)$$

or:

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

$$a_y = \frac{v^2}{R}$$

$$K = \frac{mg\left(b/l\right)}{C_{\alpha,f}} - \frac{mg\left(a/l\right)}{C_{\alpha,r}}$$

$K$ is the understeer gradient. If $K=0$ (“neutral steer”), steer angle is not dependent on speed. If $K>0$, steer angle must increase with speed. This is stable and controllable. The car tends to understeer, and at high lateral acceleration tends to plow out of a turn (the front end hits the wall). If $K<0$, steer angle to hold a lateral acceleration decreases with lateral acceleration. This is unstable. The car tends to oversteer, and at high lateral accelerations wants to spin (the rear end hits the wall).

Corrections to understeer gradient:
Lateral load transfer – if the front tires lose $C_\alpha$ less with increasing lateral acceleration, then this increases $K$. If the rear tires hold up better, then $K$ is decreased. Better to have a rear tire in which the tire patch is more resistant to twist.

Camber – similar effect to lateral load transfer. A little more camber gain in front increases $K$.

Compliance – lack of rigidity in the wheel placement mechanism (i.e., bushings) increases $K$ for front compliance and decreases $K$ for rear compliance.

Aligning torque – this is due mainly to mechanical trail, the distance of the center of the tire patch behind the intersection of the kingpin axis with the ground (not exactly “castor”). Mechanical trail increases $K$ by:

$$mg \frac{p}{l} \frac{C_{a,f} + C_{a,r}}{C_{a,f} C_{a,r}}$$

where $p$ is mechanical trail

Steering design:
Set maximum steer angle to suit maximum lateral acceleration turn. 100 lbs./deg. is reasonable for $C_\alpha$. Slip angles should not exceed about 10 degrees.

Choose about 50% Ackermann, and design rack travel and placement to achieve.

Assume same tire (and tire coefficients front/rear)

Assure that understeer gradient is either neutral or slightly positive, and adjust vehicle characteristics to maintain (can make slightly negative and then bring back with aligning torque, but be careful about increasing steering effort!)

Bump Steer:
- Suspension deflection causes:
- Lateral movement (scrubbing) of the wheels (unsprung mass)
- Change in the steering arm lateral position (due to roll of tierod as inboard end stays fixed to sprung mass and outboard end stays fixed to unsprung mass)
- Change in the steer angle if the suspension scrub is not equal to the steering arm lateral movement. Called Bump steer.
- Bump steer at zero steer angle is a design fault.
- Bump steer at nonzero steer angle is usually unavoidable.