LANDMARK UNIVERSITY, OMU-ARAN

COLLEGE: COLLEGE OF SCIENCE AND ENGINEERING
DEPARTMENT: MECHANICAL ENGINEERING
PROGRAMME: MECHANICAL ENGINEERING

Course

Course code: MCE 538
Course title: **AUTO SYSTEM AND VEHICLE DYNAMICS**
Course Units: 3 UNITS.
Course status: OPTIONAL.

LECTURE NOTE 1

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MCE 538 Auto System and Vehicle Dynamics (3 Units)

Friction forces in Automobile systems; Drag and propelling forces; Effect of body shape on vehicles. Production, assembly line and power systems control techniques. Principles of automation in mechanized systems. Application of thermal, pneumatic, hydraulic and fluidic systems to automatic control in plant processes and machinery.

Vehicle Dynamics.

Fundamental Definitions

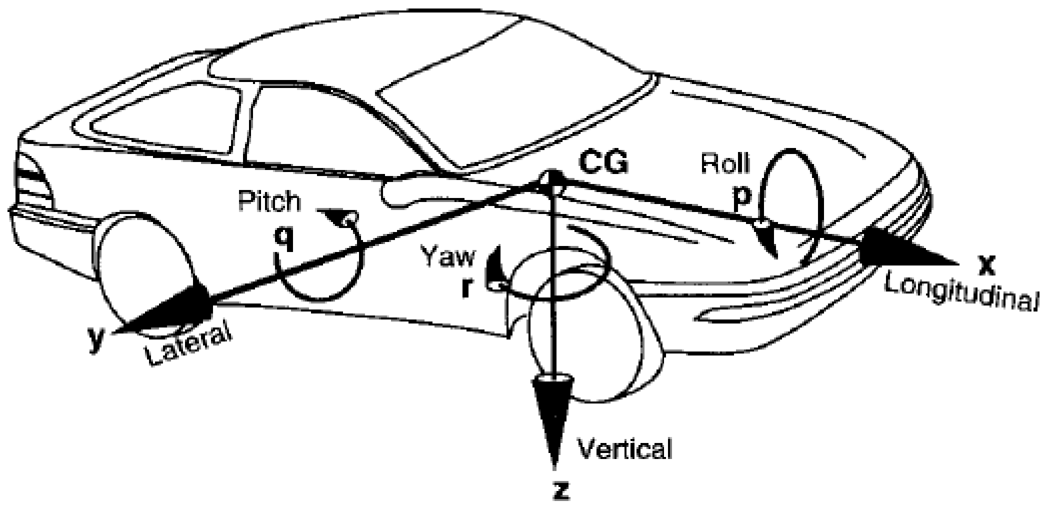
Vehicle Dynamics: It concerns with the movements of vehicles on a road surface

Physical condition: Acceleration and braking, ride, and turning

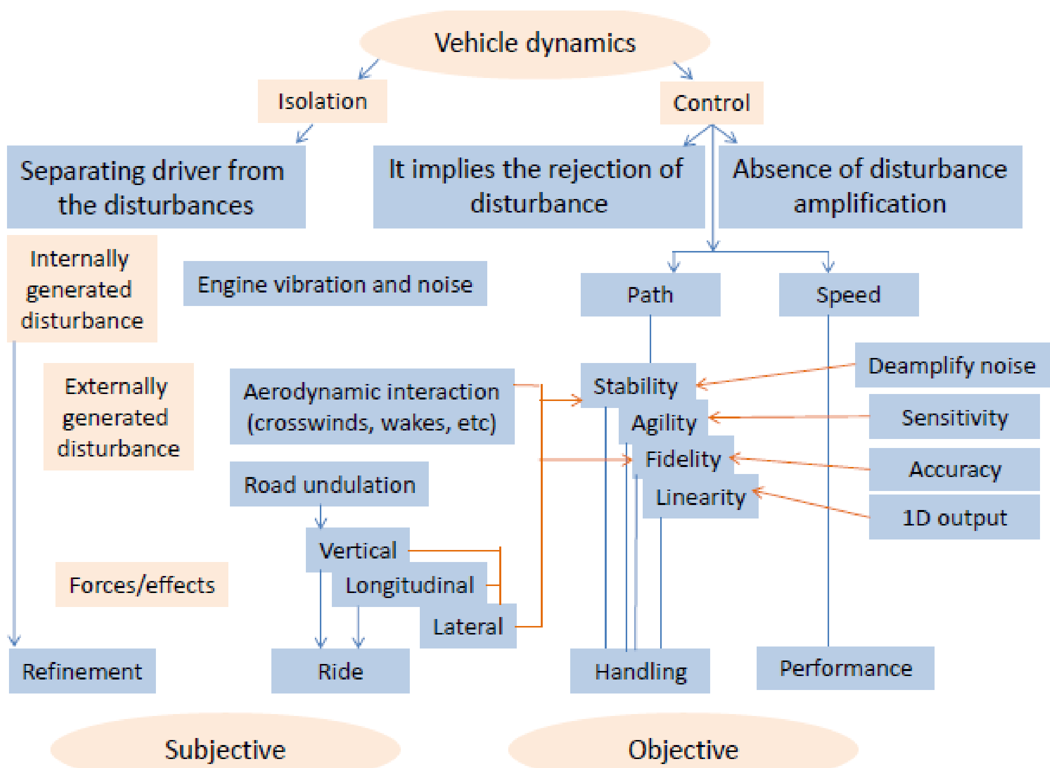
Dynamic behavior: Forces on the vehicle due to tires, gravity, and aerodynamics.

Vehicle and its components are studied to determine forces produced by the sources at particular maneuver and trim condition

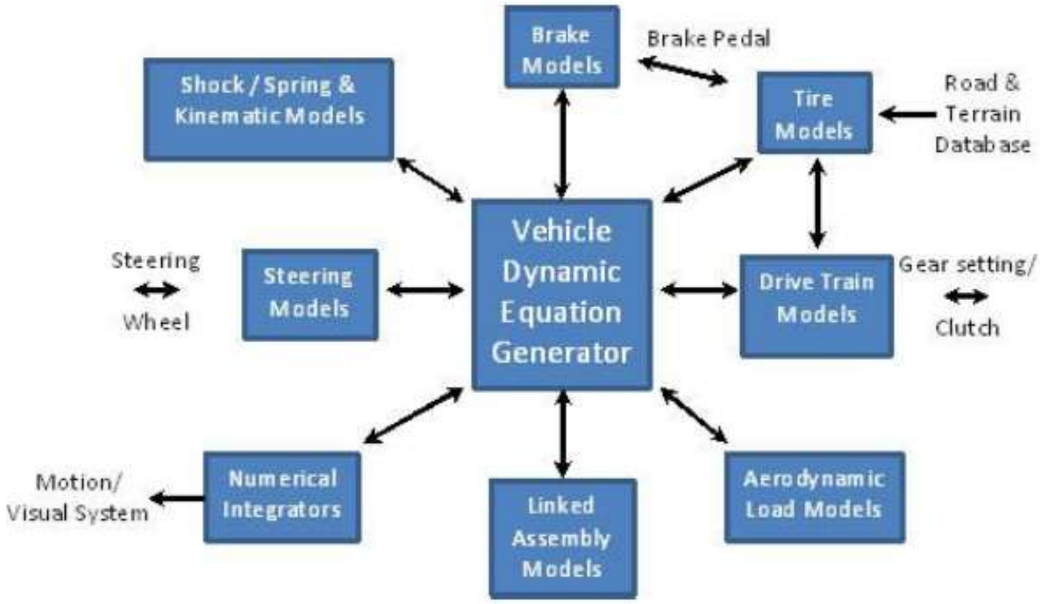
Objective: How the vehicle responds to these forces.



Vehicle Dynamics Interaction



Vehicle Dynamics Model



Operating conditions

The operating conditions of a vehicle lend expressions from general dynamics, as listed below.

• (***Static*** conditions, meaning that vehicle is standing still, are seldom relevant to analysis. Static means that the all velocities are zero, i.e. that all positions are constant.)

• ***Steady State*** operation means that time history is irrelevant for the quantities studied. Seen as a manoeuvre over time, the studied quantities are constant.

• ***Transient*** manoeuvres means that time history is relevant; i.e. there are delays, represented by "state variables" when simulated.

• ***Stationary (oscillation)*** manoeuvre is a special case of transient, where cyclic variations continues over long time with a constant pattern. This pattern is often assumed to be harmonic, meaning that the variable varies in sinus and cosine with constant amplitudes and phases. An example is sinusoidal steering, where also the vehicle response is harmonic if steering amplitude is small enough to assume the vehicle response is governed by a linear dynamic system.

• ***Quasi-static*** and ***Quasi-steady state*** are terms with a more diffuse meaning, which refers rather to analysis methods than the actual operation/manoeuvre. It is used when the analysis neglects the dynamics of a variable which normally is a state variable. An example is when constant non-zero deceleration is assumed, but speed is not changed; then the dynamics "der (speed)=acceleration" is neglected, and speed is instead prescribed.

Coordinate Systems

A vehicle's (motion) degrees of freedom are named as in marine and aerospace engineering, such as heave, roll, pitch and yaw, see Figure 1-5. Figure 1-5 also defines the 3 main geometrical planes, such as transversal plane and symmetry plane. For ground vehicles, the motion in ground plane is often treated as the primary motion, which is why longitudinal, lateral and yaw are called in-ground-plane degrees of freedom. The remaining degrees of freedom are referred to as out-of-ground-plane.

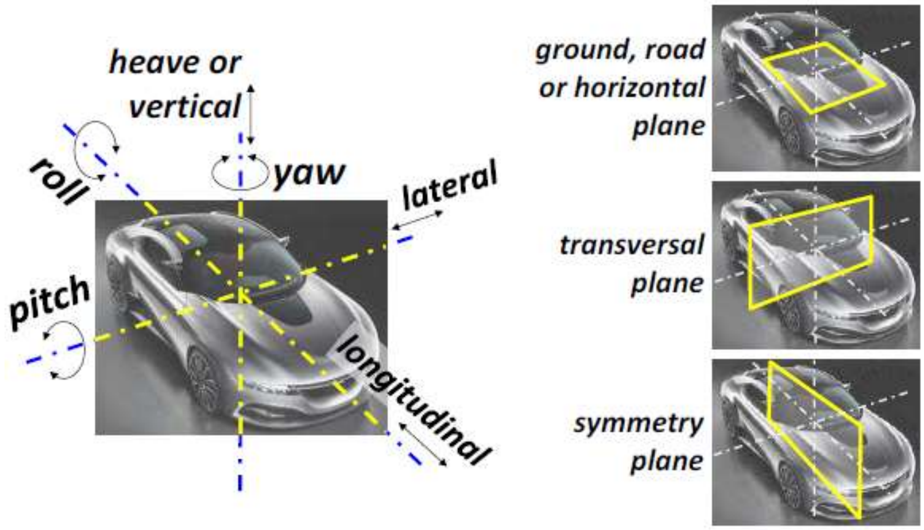


Figure 1-5: Vehicle (motion) degrees of freedom and important planes.

The consistent use of parameters that describe the relevant positions, velocities, accelerations, forces, and moments (torques) for the vehicle are critical. Unfortunately there are sometimes disparities between the nomenclature used in different text books, scientific articles, and technical reports. It is important to recognize which coordinate system is being applied and realize that all conventions will provide the same results as long as the system is used consistently. Two predominant approaches are encountered: the International Standards Organisation (ISO) and the Society of Automotive Engineers (SAE). Both ISO, (ISO8855), and SAE, (SAEJ670), are right handed systems. Figure 1-6 shows the vehicle fixed coordinate systems for these two standards. This compendium uses ISO, which also seems to be the trend globally. The new edition of (SAEJ670) now also recognises an optional use of z-up.

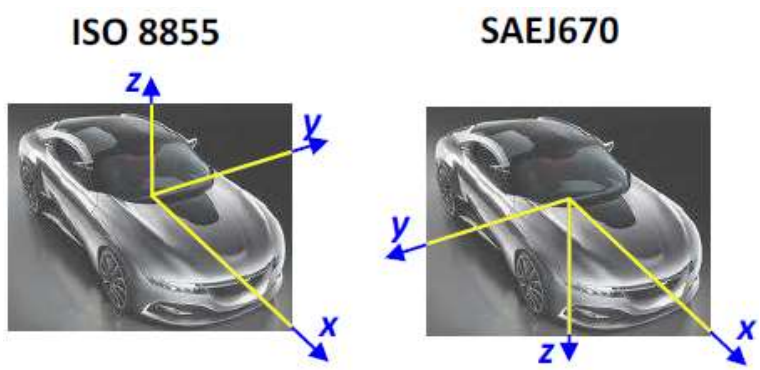


Figure 6: ISO and SAE coordinate systems

The distinction of vehicle fixed and inertial (= earth fixed = world fixed) coordinate systems is important. Figure 7 depicts the four most relevant reference frames in vehicle dynamics: the inertial, vehicle, wheel corner and wheel reference frames. All these different coordinate systems allow for the development of equations of motion in a convenient manner.

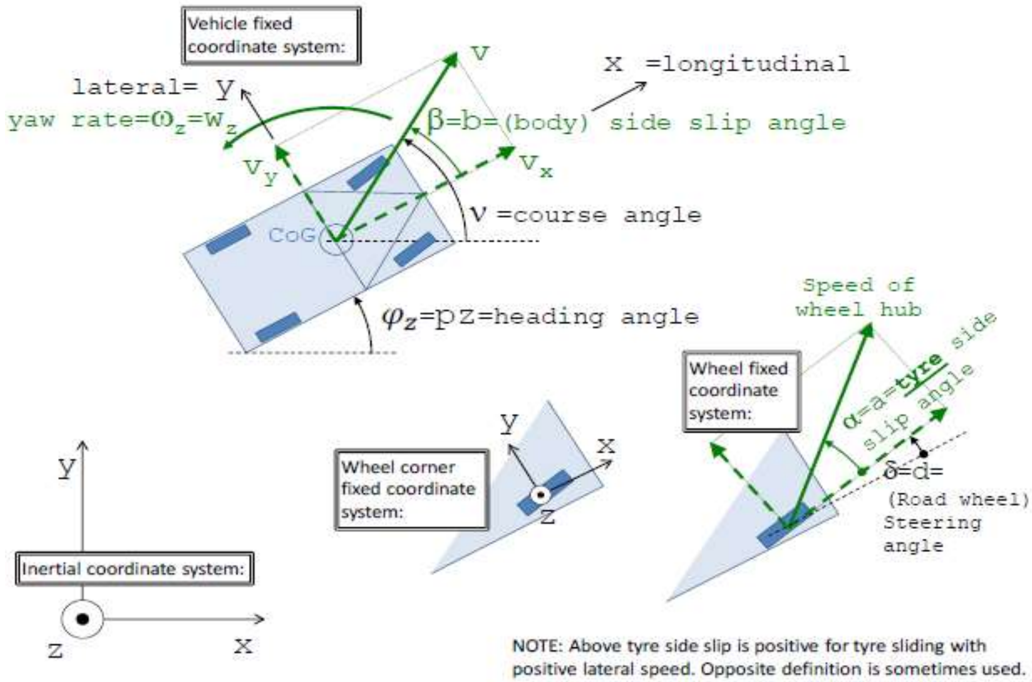


Figure 7: Coordinate systems and motion quantities in ground plane

The orientation of the axes of an inertial coordinate system is typically either along the vehicle direction at the beginning of a manoeuvre or directed along the road or lane. Road or lane can also be curved, which calls for curved longitudinal coordinate. Origin for a vehicle fixed coordinate system is often centre of gravity of the vehicle, but other points can be used, such as mid of front axle, mid of front bumper, outer edge of body with respect to certain obstacle, etc. Positions often need to be expressed for centre of lane, road edge, other moving vehicle, etc.

In ISO and Figure 7, tyre side-slip is defined so that it is positive for positive lateral speed. This means that lateral forces on the wheel will be negative for positive side-slip angles. Some would rather want to have positive force for positive angle. Therefore, one can sometimes see the opposite definition of tyre side-slip angles, as e.g. in (Pacejka, 2005). It is called the "modified SAE" or "modified ISO" sign convention. This compendium does not use the modified sign convention in equations, but some diagrams are drawn with force-slip-curve in first quadrant. Which is preferable is simply a matter of taste.

Often there is a need to number each unit/axle/wheel. The numbering in Figure 8 is proposed. It should be noted that non-numeric notations are sometimes used, especially for two axle vehicles without secondary units. Then front=f, rear=r. Also to differentiate between sides, l=left and r=right.

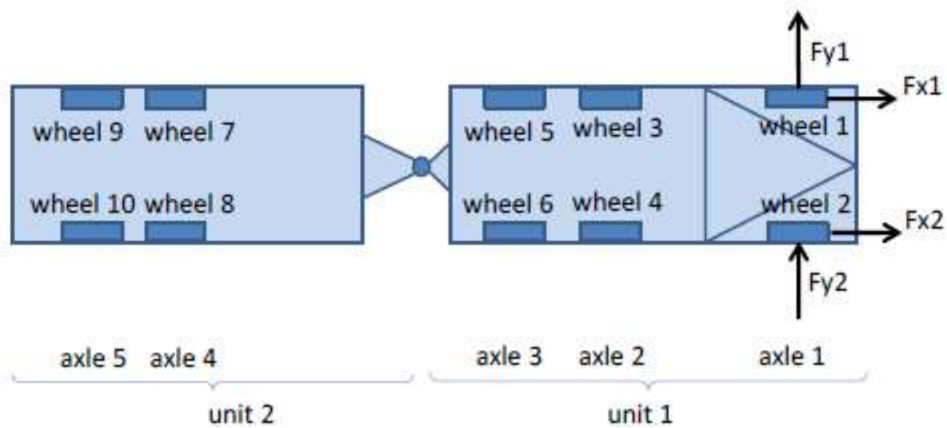


Figure 8: Proposed numbering of units, axles and wheels. Example shows a truck with trailer.

Terms with special meaning

Load levels

The weight of the vehicle varies through usage. For many vehicle dynamic functions it is important to specify the level, which is these definitions are important to know and use.

Kerb weight is the total weight of a vehicle with standard equipment, all necessary operating consumables (e.g., motor oil and coolant), a full tank of fuel, while not loaded with either passengers or cargo. Kerb weight definition differs between different governmental regulatory agencies and similar organizations. For example, many European Union manufacturers include a 75 kilogram driver to follow European Directive 95/48/EC.

Payload is the weight of carrying capacity of vehicle. Depending on the nature of the mission, the payload of a vehicle may include cargo, passengers or other equipment. In a commercial context, payload may refer only to revenue-generating cargo or paying passengers.

Gross Vehicle Mass (GVM) is the maximum operating weight/mass of a vehicle as specified by the manufacturer including the vehicle's chassis, body, engine, engine fluids, fuel, accessories, driver, passengers and cargo but excluding that of any trailers. Other load definitions exist, such as:

- *"**Design Weight**"* (typically Kerb with 1 driver and 1 passenger, 75 kg each, in front seats)
- *"**Instrumented Vehicle Weight**"* (includes equipment for testing, e.g. out-riggers)

For vehicle dynamics it is often also relevant to specify where in the vehicle the load is placed.

Path: Path with orientation and Trajectory

A ***path*** can be (y) or (x) for centre of gravity where x and y are coordinates in the road plane. To cope with all paths, it is often necessary to use a curved path coordinate instead, s, i.e. (s) and (s). The vehicle also has a varying orientation, (x) or $\varphi(s)$, which often is often relevant, but the term "path" does necessarily include this. In those cases, it might be good to use an expression "***path with orientation***" instead.

A ***trajectory*** is a more general term than a path and it brings in the dependence of time, t. One typical understanding is that trajectories can be $[(t); (t); \varphi(t)]$. But also other quantities, such as steering angle or vehicle propulsion force can be called trajectory: (t) and (t), respectively. The word "trace" is sometimes used interchangeably with trajectory.

Stable and Unstable

Often, in the automotive industry and vehicle dynamics, the words “stable” and “unstable” have a broad meaning, describing whether high lateral slip on any axle is present or not. In more strict physics/mathematical nomenclature, “unstable” would be more narrow, meaning only exponentially increasing solution, which one generally finds only at high rear axle side-slip.

It is useful to know about this confusion. An alternative expression for the wider meaning is “loss of control” or “loss of tracking”.

Subject and object vehicle

The ***subject vehicle*** is the vehicle that is studied. Often this is a relevant to have a name for it, since one often study one specific vehicle, but it may interact with other in a traffic situation. Alternative names are ***host vehicle***, ***ego vehicle*** or simply ***studied vehicle***.

If one particular other vehicle is studied, it can be called ***object vehicle*** or ***opponent vehicle***. A special case of object vehicle is ***lead vehicle*** which is ahead of, and travels in same direction as, subject vehicle. Another special case is ***on-coming vehicle*** which is ahead of, and travels in opposite direction as, subject vehicle.

Active Safety and ADAS

The expression *Active Safety* is used a lot in Automotive Engineering. There are at least two different usages:

- Active Safety can refer to the vehicle’s ability to avoid accidents, including both functions where the driver is in control (such as ABS and ESC, but also steering response) and functions with automatic interventions based on sensing of the vehicle surroundings (such as AEB and LKA). See http://en.wikipedia.org/wiki/Active_safety. Active Safety can even include static design aspects, such as designing the wind shield and head light for good vision/visibility.
- Alternatively, Active Safety can refer to only the functions with automatic interventions based on sensing of the vehicle surroundings. In those cases it is probably more specific to use Advanced Driver Assistance Systems (ADAS) instead, see http://en.wikipedia.org/wiki/Advanced_Driver_Assistance_Systems. ADAS does not only contain safety functions, but also comfort functions like CC and ACC.

Heavy truck versus passenger cars

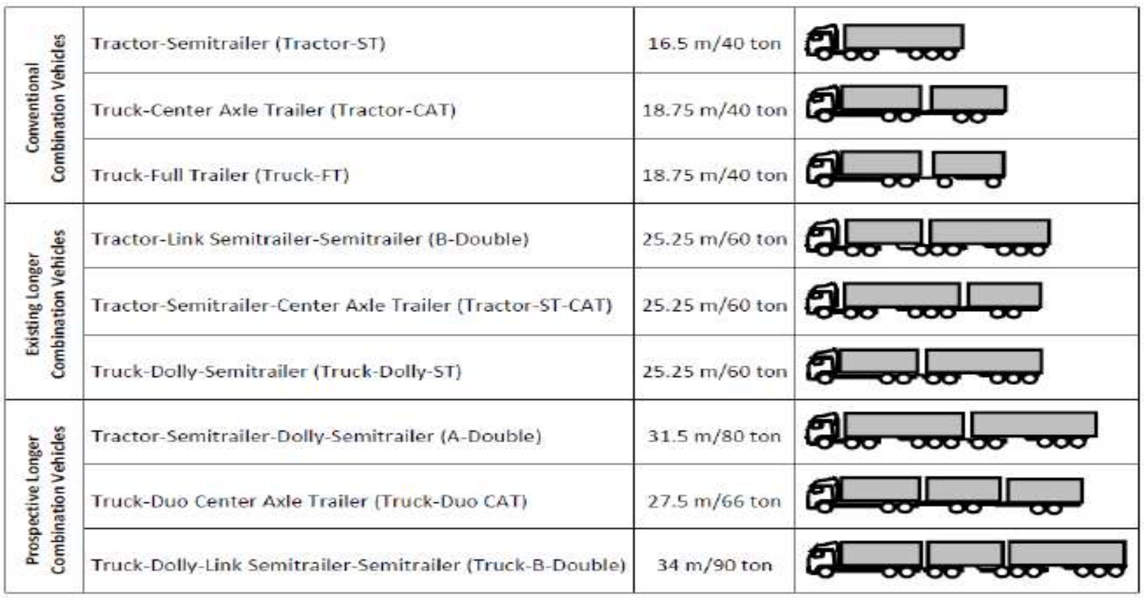
Passenger cars are relatively well known to most people and they seldom appear in very complex combinations. But heavy trucks are less well known and appear in vehicle combinations with many more units. Hence the following overview of the differences and most common units is given.

General differences

Trucks are normally bought by companies, not private persons. Each truck is bought for a specialized transport task. Life, counted in covered distance, for trucks is typically 10 times passenger cars. The life time cost of fuel is normally 5 times the vehicle cost, compared to passenger car where these costs are about equal. The cost for driver salary is a part of mileage cost, typically same magnitude as fuel cost. If investment cost for vehicle and repairs are distributed over travelled distance, these are typically also of same magnitude. So, the cost for a transport typically comes from one third fuel, one third driver salary and one third vehicle investment and repairs.

Vehicle dynamics differences

A truck has 5 to 10 times less power installed per vehicle weight. Trucks have their centre of gravity much higher, meaning that roll-over occurs at typically 4 m/s^2 lateral acceleration, as compared to around 10 m/s^2 for passenger cars. Trucks have centre of gravity far behind mid-point between axles, where passenger cars have it approximately symmetrical between the axles. Trucks are often driven with more units after, see Figure 9. The weight of the load in a truck can be up to 2 to 4 times the weight of the empty vehicle, while the maximum payload in passenger cars normally are significantly lower than the empty car weight. Trucks often have many steered axles, while passenger cars normally are only steered at front axle.



Conventional Combination Vehicles	Tractor-Semitrailer (Tractor-ST)	16.5 m/40 ton	
	Truck-Center Axle Trailer (Tractor-CAT)	18.75 m/40 ton	
	Truck-Full Trailer (Truck-FT)	18.75 m/40 ton	
Existing Longer Combination Vehicles	Tractor-Link Semitrailer-Semitrailer (B-Double)	25.25 m/60 ton	
	Tractor-Semitrailer-Center Axle Trailer (Tractor-ST-CAT)	25.25 m/60 ton	
	Truck-Dolly-Semitrailer (Truck-Dolly-ST)	25.25 m/60 ton	
Prospective Longer Combination Vehicles	Tractor-Semitrailer-Dolly-Semitrailer (A-Double)	31.5 m/80 ton	
	Truck-Duo Center Axle Trailer (Truck-Duo CAT)	27.5 m/66 ton	
	Truck-Dolly-Link Semitrailer-Semitrailer (Truck-B-Double)	34 m/90 ton	

Figure 9: An overview over conventional and longer combinations. From (Kharrazi , 2012).

Smaller vehicles

This section is about smaller vehicles, meaning bicycles, electric bicycles, motorcycles and 1-2 person car-like vehicles. The latter group refers to vehicles which are rare today, but there is a logic reasoning why they could become more common in the future: Increasing focus on energy consumption and congestion in cities can be partly solved with such small car-like vehicles, of which the Twizy in Figure 10 is a good example. All vehicles in Figure 10 can be referred to as Urban Personal Vehicle (UPVs), because they enable personalised transport in urban environments. The transport can be done with low energy consumption per travelled person and distance, compared to today's passenger cars. The transport can be done with high level of flexibility and privacy for the travelling persons, compared to today's public transportation.

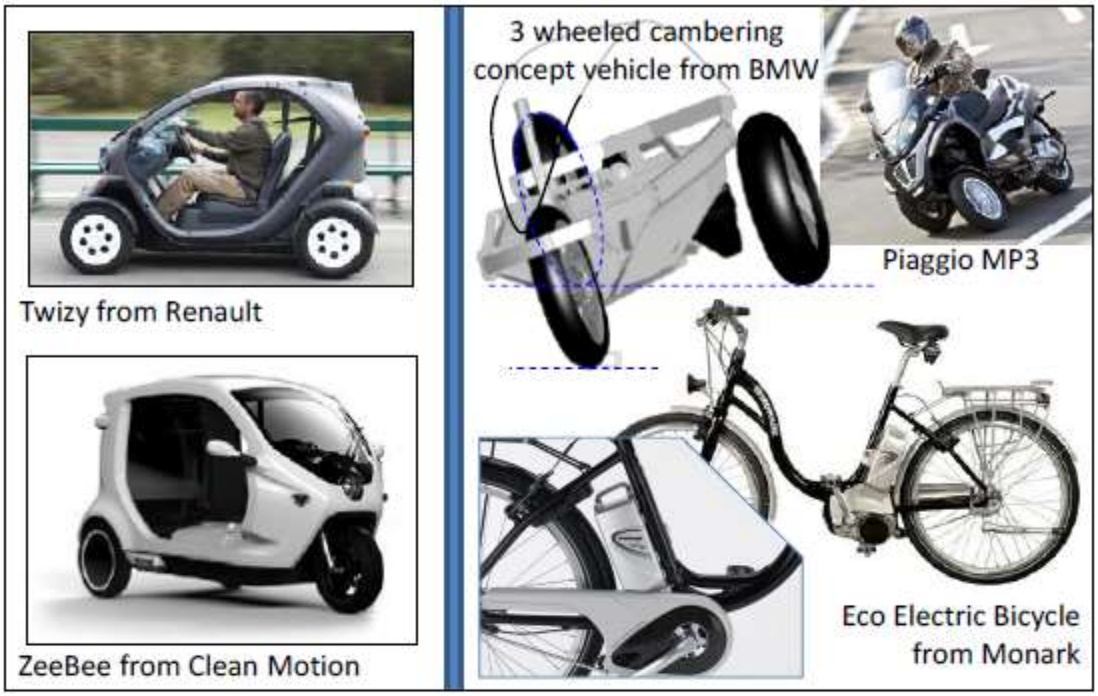


Figure 10: Examples of Urban Personal Vehicles. Left: “Roll-stiff”. Right: “Cambering“. *From www.motorstown.com, www.cleanmotion.se, www.monarkexercise.se, www.nycscootering.com.*

New solutions as in Figure 10 may require some categorization.

• Climate and user type: Sheltered **or** open.

• Transport and user type: Short travels (typically urban, 5-10 km, 50 km/h) or long travels (typically inter-urban, 10-30 km, 100 km/h).

• Chassis concept: o Narrow (e.g. normal bicycles and motorcycles) **or** wide (at least one axle with 2 wheels, resulting in 3-4 wheels on the vehicle). Note that UPVs in both categories are typically still less wide than passenger cars.

o Roll moment during cornering carried by suspension roll stiffness or roll moment during cornering avoided by vehicle cambering. The first concept can be called “Roll-stiff vehicle”. The second concept can be called “Cambering vehicle” or “Leaning vehicle”. 1-tracked are always Cambering vehicles. 2-tracked are normally Roll-stiff, but there are examples of Cambering such (see upper right in Figure 10).

o (This compendium does only consider vehicles which are “Pitch-stiff”, i.e. such that can take the pitch moment during acceleration and braking. Examples of vehicles not considered, “Pitching vehicles”, are: one-wheeled vehicles as used at circuses and two-wheeled vehicles with one axle, such as Segways.)

Note that also Roll-stiff Vehicles camber while cornering, but only **slightly** and **outwards** in curve, while Cambering Vehicles above refer to **significant** cambering and **inwards** in curve.

Cambering Vehicles is more intricate to understand when it comes to how wheel steering is used. As a reference: In Roll-stiff Vehicles, the wheel suspension takes the roll-moment (keeps the roll balance), which means that driver can use wheel steering solely for making the vehicle steer (follow an intended path). In Cambering Vehicles, the driver has to use the wheel steering for both keeping the roll balance and follow the intended path. This means one control for two purposes, which calls for one more control. The additional control used comes from that the driver can move the CoG of the vehicle (including driver) laterally. So, the driver of a

Cambering Vehicle has to use a combination of wheel steering and CoG moving for a combination of maintaining roll balance and following the intended path.
Smaller vehicles might have significantly different vehicle dynamics in many ways:

• Influence of driver weight is larger than for other vehicle types. This especially goes for bicycles, where driver weight can be typically 5 times larger than the vehicles own weight. Drivers not only change the total inertia properties, but they can also actively use their weight and move it during driving.

• Ratio between CoG height and wheel base is likely to be larger than passenger cars and trucks. This gives a larger longitudinal load transfer during acceleration and braking. Some concepts might even have the risk of “pitch-over”.

• For 2-tracked UPVs, the ratio between CoG height and track width is likely to be larger than passenger cars, rather like trucks, because it is likely that one want to keep swept area low for UPVs. o If Roll-stiff, this gives a larger lateral load transfer and roll angles during cornering. The risk for roll-over is also likely to be larger than passenger cars.

o If Cambering, this opens for the risk for slide (“roll-over inwards in curve”, so called “low-sider”), which is known from motorcycles.

• For future UPVs it is possible that the part costs need to be kept low, as compared to passenger cars. This, and the fact that new inexperienced OEMs might show up on market, might lead to low-cost and/or unproven solutions appear for the vehicle design. This might be a challenge for driving experience and (driver and automated) active safety.

• Positive, for safety, is that future UPVs can have significantly lower top speed than passenger cars. However, the acceleration performance up to this top speed might be high, e.g. due to electric propulsion, which might cause new concerns for city traffic with surrounding.