UNIVERSITY OF TRENTO

Formula SAE
Driverless

Academic Year 2022-2023

Contents

Introduction

Driverless

The autonomous car has generally three sub systems:

1. Applications
2. Computational Platform $\Longrightarrow$ extremely important part of an autonomous car to integrate and control the whole system. The applications are controlled by the processing platform by the inputs given by the sensors and feedback data from the actuators

   > **Note:** The inputs to the actuators and the pneumatic systems are sent from the computational platform

3. Mechanical Control $\Longrightarrow$ done by using pneumatic actuators in this system. Feedback systems are attached to the systems so as to get a continuous feedback to the computational platform

The mechanical framework of the vehicle is divided into 5 parts:

1. Gear
2. Clutch (frizione)
3. **Brake**
4. Steering
5. Accelerator

Regenerative Braking

Regenerative braking enables the vehicle's kinetic energy to be converted back to electrical energy during braking. The converted electrical energy is stored in energy storage devices such as batteries to extend the driving range by up to 10%. By taking a measure of the initial and final vehicle velocity, the amount of kinetic energy that is lost to braking can be calculated

> **Note:** In addition to improving the overall efficiency of the vehicle, regeneration can significantly extend the life of the braking system as the mechanical parts will not wear out quickly

In an Electric Vehicle (EV), the power source is the battery that supplies electric energy to operate the motor. The motor supplies energy to rotate the vehicle wheels producing kinetic energy. The motor can operate in reverse. When a motor operates in reverse it acts as a generator. When the vehicle slows down, the generator converts the kinetic energy into electrical energy to charge the vehicle's battery

> **Observation:** The efficiency of capturing this energy is reported to vary from 16% to 70%. The reason for this significant difference in efficiency will depend on the driver's style of driving whether they brake gradually or severely $\Rightarrow$ **NOT A PROBLEM IF DRIVERLESS**
> Furthermore, temperature of the system and outside ambient temperature affect the efficiency greatly

There are various energy capturing devices that are suitable to be used in regenerative braking systems:

- FLYWHEEL (VOLANO) $\Longrightarrow$ device that when rotated, can store kinetic energy during braking (using the conservation of angular momentum): a form of kinetic energy proportional to the product of its moment of inertia and the square of its rotational speed
- ULTRACAPACITOR $\Longrightarrow$ device that temporarily stores electrical charge. This short charge and discharge period is cheaper than the flywheel system and additionally has a higher energy density

The ultracapacitor is the most commonly adopted device in regenerative braking systems

Chapter 1

Parameters - FENICE

1.1 Braking system

Table 1.1 displays the most relevant parameters which characterise the braking system.

Variable Name	**Description**	**Value**
brakeRatio	brake balance (front)	0.74
max_brake_torque_front	max front braking torque that the hydraulic system can provide	750 [Nm]
max_brake_torque_rear	max rear braking torque that the hydraulic system can provide	750 [Nm]
totBrakeTorque	max total brake torque that the braking system can develop (it is then split btween front/rear axles)	750 [Nm]
tau_br	time constant for brake actuation dynamics	0.03 [s]
prop_valve_cut_torque	rear braking torque corresponding to proportioning valve cut-off	130 [Nm]
prop_valve_cut_factor	cut-off strength factor	4
regularSignScale	scale parameter for the regularized sign function	1 [rad/s]

Table 1.1: *Brake Parameters*

1.2 Electric Motor

Table 1.2 displays the most relevant parameters which characterise the motor.

Variable Name	Description	Value
maxTorque	max torque that the motor can provide	55 [Nm]
speedForTorqueCut	motor rotational speed at which torque is decreased a lot	5000 [rpm]
maxRotSpeed	maximum rotational speed	6500 [rpm]
k_torque	motor torque constant	0.39
I_max	max motor current	150 [A]
maxMotPower	max motor power	52e3 [W]
tau_mot	time constant for motor actuation dynamics	0.024 [s]

Table 1.2: *Electric Motor Parameters*

> **Observation:** **The maximum delivered power by the motor is about 80 KW**

Chapter 2

Braking Performance

General equation for braking performance:

$$M \cdot a_x = -\frac{W}{g} \cdot D_x = -F_{xf} - F_{xr} - D_A - W \sin\Theta \tag{2.1}$$

where:

- W $\Longrightarrow$ vehicle weight
- $D_x \Longrightarrow$ linear deceleration
- $F_{xf} \Longrightarrow$ front axle braking force
- $F_{xr} \Longrightarrow$ rear axle braking force
- $D_A \Longrightarrow$ aerodynamic drag
- $\Theta \Longrightarrow$ uphill grade

Definition 2.1 **Axle $\Rightarrow$ *Assale***

Steel rod that connects the rear and front wheels of the car to the transmission. In this way it transfers the driving force of the engine from the transmission to the wheels allowing traction. It also serves to support the weight of the vehicle

Constant deceleration

Simple relationships can be derived for the case where it is reasonable to assume that the forces acting on the vehicle will be constant throughout a brake application:

$$\begin{cases} SD = \frac{{V_o}^2}{2\frac{F_{xt}}{M}} = \frac{{V_o}^2}{2 \cdot D_x} & \text{stopping distance} \\ t_s = \frac{V_o}{\frac{F_{xt}}{M}} = \frac{V_o}{D_x} & \text{time to stop} \end{cases} \tag{2.2}$$

where:

- $V_o \Longrightarrow$ initial velocity
- $F_{xt} \Longrightarrow$ total of all longitudinal deceleration forces on the vehicle

Observation:
SD proportional to the velocity squared
t_s proportional to the velocity

Deceleration with wind resistance

More complicated expressions are necessary when the aerodynamic drag is considered:

$$SD = \frac{M}{2C} \cdot \ln \frac{F_b + C \cdot {V_o}^2}{F_b} \tag{2.3}$$

where:

- C $\Longrightarrow$ aerodynamic drag factor
- $F_b \Longrightarrow$ total brake force of front and rear wheels

Energy/Power absorbed by a brake system

The **Energy** absorbed is the kinetic energy of motion of the vehicle:

$$\text{Energy} = \frac{M}{2} \cdot \left({V_o}^2 - {V_f}^2 \right) \tag{2.4}$$

where V_f is the final velocity.
The **Average Power** absorption is the energy divided by the time to stop:

$$\text{Power} = \frac{M}{2} \cdot \frac{{V_o}^2}{t_s} \tag{2.5}$$

> **Observation:** The power absorption varies with the speed and is equivalent to the braking force times the speed at any instant of time. Thus, the power dissipation is greatest at the beginning of the stop when the speed is highest

Braking Forces

Rolling resistance

Rolling resistance always opposes vehcile motion; hence, it aids the brakes:

$$R_{xf} + R_{xr} = f_r \cdot \left(W_f + W_r \right) = f_r \cdot W \tag{2.6}$$

where:

- $f_r \Longrightarrow$ rolling resistance
- $W_f \Longrightarrow$ dynamic weight on the front axle
- $W_r \Longrightarrow$ dynamic weight on the rear axle

> **Note:** Rolling resistance is nominally equivalent to about 0.01 g deceleration

Aerodynamic drag

The drag from air resistance is proportional to the square of the speed. At low speed it is negligible. At normal highway speeds, it may contribute a force equivalent to about 0.03 g.

Driveline (*linea di trasmissione*) drag

The engine, transmission, and final drive contribute both drag and inertia effects to the braking action. The inertia of these components adds to the effective mass of the vehicle. The drag, instead, arises from bearing and gear friction in the transmission and differential, and engine braking (*freno motore*).

Observation: Engine braking disappears when an engine over-revs excessively (*va eccessivamente fuori giri*).

Driveline drag aids in braking depending on the rate of deceleration:

- if the vehicle is slowing down faster than the driveline components would slow down under their own friction, the drive wheel brakes must pick up the extra load of decelerating the driveline during the braking
- during low-level decelerations the driveline drag may be sufficient to decelerate the rotating driveline components and contribute to the braking effort on the drive wheels as well

Road grade

Road grade - defined as the vertical distance over the horizontal one (rise over the run) - will contribute directly to the braking effort, either in a positive (uphill) or negative (downhill). Additional force on the vehicle arising from grade:

$$R_g = W \cdot \sin\Theta \tag{2.7}$$

For small angles:

$$R_g = W \cdot \Theta \tag{2.8}$$

Observation: A grade of 4% will be equivalent to a deceleration of $\pm$ 0.04 g

Brakes

Types of brakes

Automotive brakes in common usage today are of two types: **Drum** and **Disc**. Historically, drum brakes have seen common usage because of their high brake factor. On the other hand they are may not be as consistent in torque performance as disc brakes. The lower brake factors of disk brakes require higher actuation effort.

Definition 2.2 Brake Factor

Mechanical advantage that can be utilized in drum brakes to minimize the actuation effort required

On drum brakes, there is an actuation force which pushes the lining (*rivestimento*) against the drum generating a friction force. The moment generated by the friction force w.r.t. the pivot acts to rotate the shoe against the drum, thus increasing the friction force developed $\Longrightarrow$ self-actuation
Disc brakes lacks this self-actuation effect, but they have a better torque consistency, although at the cost of requiring more actuation effort. On drum brakes, the torque will often exhibit a "sag" (*abbassamento*) in the intermediate portion of the stop. Disc brakes normally show less torque variation in the course of a stop.

Observation: With an excess of these variations during a brake application, it can be difficult to maintain a the proper balance between front and rear braking effort during a maximum-effort stop

General equation of torque at the brakes:

$$T_b = f\left(P_a, \text{Velocity}, \text{Temperature}\right) \tag{2.9}$$

> **Note:** Because the equation depends on the brake temperature, which increases during a brake application, it is necessary to incorporate a thermal model of the brake in the calculation process

The torque produced by the brake acts to generate a **Braking force** at the ground and to decelerate the wheels and the driveline components:

$$F_b = \frac{(T_b - I_w \cdot \alpha_w)}{r} \tag{2.10}$$

where:

- r $\Longrightarrow$ rolling radius of the tires
- $I_w \Longrightarrow$ Rotational inertia of wheels
- $\alpha_w \Longrightarrow$ Rotational deceleration of wheels

Generally it holds:

$$F_b = \frac{T_b}{r} \tag{2.11}$$

> **Observation:** As long as all wheels are rolling, the braking forces on a vehicle can be predicted using Equation 2.11. However, the brake force can only increase to the limit of the frictional coupling between the tire and road $\Longrightarrow$ **Tire-road friction**

Figure 2.1 shows how the braking coefficient changes with the wheel slip, which is defined as:

$$Slip = \frac{V - w \cdot r}{V} \tag{2.12}$$

where:

- V $\Longrightarrow$ vehicle forward velocity
- w $\Longrightarrow$ tire rotational speed

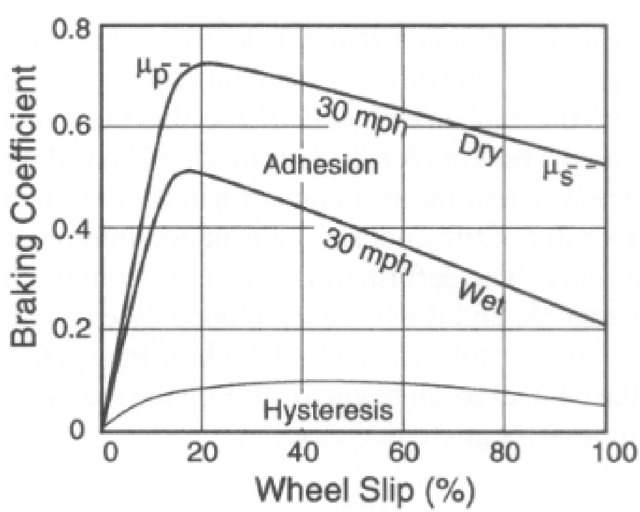

Figure 2.1: *Braking coefficient vs slip*

Brake Proportioning

Definition 2.3 Brake Proportioning

It describes the relationship between front and rear brake forces determined by the pressure applied to each brake and the gain of each

The preferred design is to bring both axles up to the lockup point simultaneously. Yet, this is not possible over the complete range of operating conditions to which a vehicle will be exposed. Balancing the brake outputs on both the front and rear axles is achieved by "proportioning" the pressure appropriately for the foundation brakes installed on the vehicle. The maximum brake force on each axle is given by:

$$\begin{cases} F_{xmf} = \mu_p \cdot \left(W_{fs} + W_d\right) = \mu_p \left(W_{fs} + \frac{h}{L}\frac{W}{g}D_x\right) & \text{front axle} \\ F_{xmr} = \mu_p \cdot \left(W_{rs} - W_d\right) = \mu_p \left(W_{rs} - \frac{h}{L}\frac{W}{g}D_x\right) & \text{rear axle} \end{cases} \tag{2.13}$$

where:

- $\mu_p \Longrightarrow$ peak coefficient of friction
- $W_{fs} \Longrightarrow$ front axle static load
- $W_{rs} \Longrightarrow$ rear axle static load

From the above equation and from Figure 2.2 it can be seen that the maximum brake force is dependent on the deceleration, varying differently at each axle.

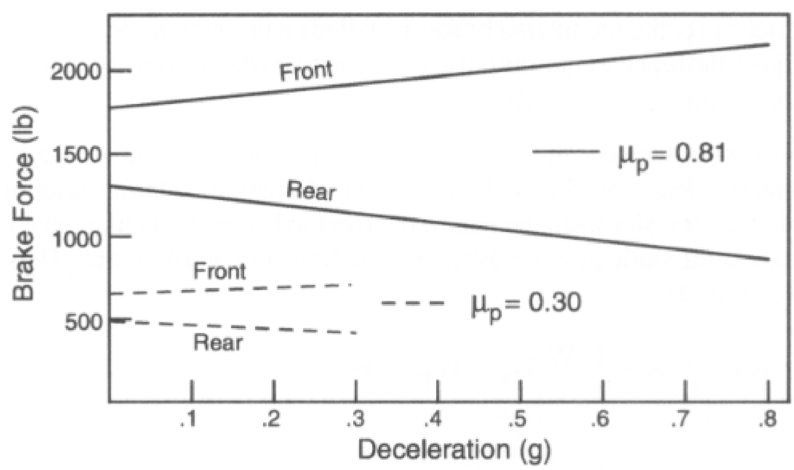

Figure 2.2: *Maximum brake forces as a function of deceleration*

Equations 2.13 do not provide an explicit solution for the maximum braking forces on an axle. It is possible to find an explicit solution with the following equations:

$$\begin{cases} F_{xmf} = \frac{\mu_p \cdot \left(W_{fs} + \frac{h}{L}F_{xr}\right)}{1 - \mu_p \cdot \frac{h}{L}} \\ F_{xmr} = \frac{\mu_p \cdot \left(W_{rs} - \frac{h}{L}F_{xf}\right)}{1 + \mu_p \cdot \frac{h}{L}} \end{cases} \tag{2.14}$$

Thus the maximum braking force on the front axle is dependent on that present on the rear axle. Conversely, the same effect is evident on the rear axle. Figure 2.3 shows the proportionality between the front and rear forces.

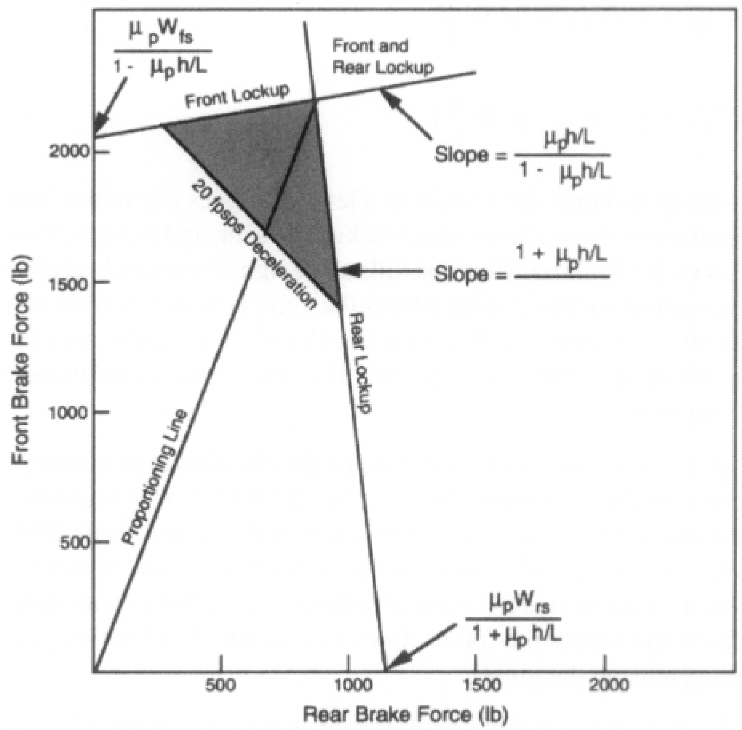

Figure 2.3: *Maximum braking forces on the front and rear axles*

An attempt to brake the vehicle to a level that goes above the front brake force boundary will cause front wheel lockup to occur, and steering control will be lost. Likewise, braking effort that falls to the right of the rear brake boundary causes rear wheel lockup, which places the vehicle in an unstable condition.

The primary challenge in brake system design is the task of selecting a proportioning ratio (the slope of a line on the graph in Figure 2.3) that will satisfy all design goals. The primary factor determining brake proportioning is the gain of the brakes used on the front and rear wheels. From Equation 2.11 it is possible to compute the brake gain as follows:

$$F_b = \frac{T_b}{r} = G \cdot \frac{P_a}{r} \tag{2.15}$$

where:

- $P_a \Longrightarrow$ application pressure
- G $\Longrightarrow$ brake gain [lb/psi]

Concetto 2.1: Use of a pressure proportioning valve

To achieve all performance goals, a proportioning design must be selected that passes through all of the triangles shown. This cannot be achieved with a straight line providing a constant relationship between front and rear brake force. A solution to this problem is to incorporate a valve in the hydraulic system that changes the pressure going to the rear brakes over some portion of the operating pressure range. Such a valve is known as a pressure proportioning valve

Concetto 2.2: Anti-lock brake systems (ABS)

Rather than attempt to adjust the proportioning directly, anti-lock systems sense when wheel lockup occurs, release the brakes momentarily on locked wheels, and reapply them when the wheel spins up again

Brake Balance (brake bias)

Figure 2.4 shows a simple model of the car for the analysis of braking performance.

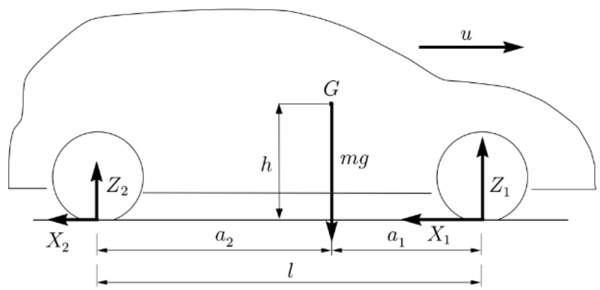

Figure 2.4: *Vehicle model for braking performance*

Assumptions:

- break on a flat and straight road $\Longrightarrow$ vehicle goes straight
- application of a constant force to the brake pedal $\Longrightarrow$ pitch oscillations are negligible
- vehicle as a single mass m which moves horizontally with velocity speed u and acceleration $\dot{u}$
- two vertical forces Z1 and Z2 for each axle as a reaction from the road
- longitudinal braking forces X1, X2 directed as in Figure

The brake balance is basically the ratio between the longitudinal brake forces when braking at the best braking performance, that is:

$$\beta_p = \frac{a_2 + \mu h}{a_1 - \mu h} \tag{2.16}$$

where μ is the global longitudinal friction coefficient.

Note: Typical values of β_p:

- β_p = 2 on dry asphalt
- β_p = 1.5 on wet asphalt

Maximum braking performance occurs just before brake lockup, as a sliding tire has less grip than a rolling tire, thus tuning brake balance is all about controlling when the brakes lockup.

Observation: An ideal brake bias is one that locks the front and rear brakes at the same time

Brake balance is very important because too much rear brakes will tend to cause the car to spin; too much front and the car will not turn in. The goal is to adjust the proportion of the braking forces between front and rear (brake bias) in order to maximize overall braking efficiency.

Braking Efficiency

Useful concept as a design tool for the designer to access success in optimizing the vehicle braking system and it is a useful method to evaluate the performance of the brake system. It may be defined as the ratio of actual deceleration achieved to the "best" performance possible on the given road surface. The best performance any vehicle can achieve is a braking deceleration equivalent to the coefficient of friction between the tires and the road surface (μ_p), that is:

$$\eta_b = \frac{D_{act}}{\mu_p} \tag{2.17}$$

Observation: Implementation of braking standards using the braking efficiency approach has been unsuccessful. The main problem has been the difficulty of defining an effective friction level for a tire-road surface pair because of the variations in friction with velocity, wheel load, tire type and other factors.

Braking efficiency is determined by calculating the brake forces, deceleration, axle loads, and braking coefficient on each axles a function of application pressure. The braking coefficient is defined as the ratio of brake force to lead on a wheel or axle.

Chapter 3

Regenerative Braking

Only way to charge the battery without another mechanical connection between the motor and engine

Introduction

Regenerative braking enables the vehicle's kinetic energy to be converted back to electrical energy during braking, which is stored inside devices such as batteries. By taking a measure of the initial and final vehicle velocity, the amount of kinetic energy that is lost to braking can be calculated. In electric vehicles the motor can operate in reverse acting as a generator. In this way, when the vehicle slows down, the generator converts the kinetic energy into electrical energy to charge the vehicle's battery. The efficiency of capturing back this energy, which otherwise would have been lost, is reported to vary from 16% to 70%. This difference is due to:

- the driving technique of the driver
- the temperature of the system
- the temperature of the outside ambient

Note: There are various energy capturing devices that are suitable to be used in regenerative braking systems:

- flywheel
- ultracapacitor $\Longrightarrow$ most commonly used
- electrical battery

The ultracapacitor is a better alternative to an electrical battery for short journey times thanks to very high associated efficiencies

Observation: When the vehicle is driven at low speed the motor efficiency is low $\Longrightarrow$ the car will not capture recovered kinetic energy at speeds below a threshold value set in the control algorithm

In general, electric vehicles are equipped with the regenerative-hydraulic hybrid braking system. Whenever the regenerative braking torque is insufficient to offer the same deceleration rate as available in conventional vehicles, the hydraulic braking torque is applied.

Observation: During low brake pedal force, only the regenerative braking torque is applied on the driving wheels, and is proportional to the pedal pressing force

Note: To measure the efficiency of a regenerative braking system $\Longrightarrow$ hub-mounted chassis dynamometer

Two main **strategic models of regenerative braking**:

1. Parallel regenerative braking control strategy
2. One-pedal driving control strategy

With the **one-pedal driving control strategy** the accelerator pedal is usually used. The algorithm uses the deceleration from the accelerator pedal itself and not the braking pedal.

Types and Properties of Regenerative Braking and Energy Recovery

In their most fundamental form regenerative braking systems are basically bi-directional power transmission systems, with a power source and sink at one end, and an energy storage device on the other. This type of systems are typically mechanical, electrical or hydraulic.

Electrical regeneration properties

The power source generates electricity which charges a battery which feds the electricity back to the motor in the acceleration phase.

Note: The specific power of electrical energy recovery systems is very highly dependent on the size and chemistry of the battery, but is typically much poorer than both hydraulic and mechanical systems. However, the specific energy storage is much better than hydraulic systems

Vehicle Optimisation for Regenerative Brake Energy Maximisation

Regenerative braking efficiency is a measure of how effective the individual components are in recapturing braking energy. Hence, it is the percentage of how much energy is recaptured from the energy consumption. It can also be defined as the ratio of regenerated energy to required brake energy.

Power-Electronic for Electrical Machine Drives

Chopper-controlled d.c. machine

One of the simplest power-electronic/machine circuits that can be seen in Figure 3.1. With a battery, it is currently the most common electric road vehicle controller.

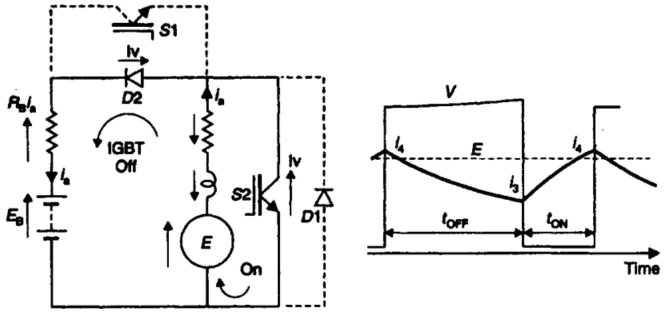

Figure 3.1: *Chopper-controlled d.c. machine - Generating conventions*

Electronic Braking System

For electrical regenerative braking systems. high battery current demands during acceleration and braking limit the amount of regenerative braking that can be used, and energy conversion rates are a challenge for all regenerative braking system technologies.

Concetto 3.1: The retarding torque generated by most motor/generator technologies is speed dependent: the torque decreases with speed, and thus no system of regenerative braking is effective at low speeds and therefore friction brakes are likely to remain essential in order to provide full road vehicle braking capability. Additional, no current form of regenerative braking is able to generate sufficiently high braking force for emergency braking from relatively high speed because of the high power dissipation and the rate of energy transfer required

Friction braking is the only retardation technology that can be practically implemented on road vehicles to provide reliable braking at all road speeds, and dissipate large amounts of energy very quickly $\Longrightarrow$ A combination of friction brakes and regenerative braking is likely to be required, and this presents a challenge for the management of braking effort generated by each system

Some form of motor/generator augments the friction braking where possible; as the driver applies the brake through a conventional pedal, the motor/generator creates braking torque that may provide sufficient retarding force to meet the driver demand, or may supplement the friction braking

The **design and implementation of regenerative braking system control** is quite difficult; the basic strategy can be to split the braking energy between both systems, prioritising the use of the regenerative braking over the use of the friction brakes, which are used to complete the braking demand. The operation of the regenerative braking system has to be "blended" with that of the friction braking system to avoid braking balance and vehicle stability problems, and to provide an acceptable control interface for the driver.

There are mainly **two categories of regenerative braking systems**:

1. Category A: regenerative braking system not part of service braking system $\Longrightarrow$ typically regenerative braking is introduced when the accelerator pedal is released

2. Category B: regenerative braking system that is part of service braking system

For vehicles with category B regenerative braking systems the service braking system can only have one control device. Vehicles fitted with both categories of regenerative braking must not cause the action of the service braking control to reduce the electric regenerative braking effect generated by the release of accelerator control $\Longrightarrow$ this represents an important control strategy consideration: whether to apply regenerative braking on lift-off of the accelerator pedal to simulate or augment engine braking, or apply it all on the brake pedal, or a combination of the two