Module 11: Regenerative braking

Lecture 38: Fundamentals of Regenerative Braking

Fundamentals of Regenerative Braking

The topics covered in this chapter are as follows:

- Introduction.
- Energy Consumption in Braking
- Braking Power and Energy on Front and Rear Wheels

Introduction

The electric motors in EVs and HEVs can be controlled to operate as generators to convert the kinetic or potential energy of the vehicle mass into electric energy that can be stored in the energy storage and reused. A successfully designed braking system for a vehicle must always meet two distinct demands:

i.   In emergency braking, the braking system must bring the vehicle to rest in the shortest possible distance.

ii. The braking system must maintain control over the vehicle's direction, which requires braking force to be distributed equally on all the wheels.

Energy Consumption in Braking

A significant amount of energy is consumed by braking. Braking a 1500 kg vehicle from 100 km/h to zero speed consumes about 0.16 kWh of energy ($0.5 \times M_v \times V^2$) in a few tens of meters. If this amount of energy is consumed in coasting by only overcoming the drags (rolling resistance and aerodynamic drag) without braking, the vehicle will travel about 2 km, as shown in **Figure 1.** When vehicles are driving with a stop-and-go pattern in urban areas, a significant amount of energy is consumed by frequent braking, which results in high fuel consumption.

The braking energy in typical urban areas may reach up to more than 25% of the total traction energy. In large cities, such as New York, it may reach up to 70%. It is concluded that effective regenerative braking can significantly improve the fuel economy of EVs and HEVs.

Braking Power and Energy on Front and Rear Wheels

Braking power and braking energy consumed by the front and rear wheels are closely related to the braking forces on the front and rear wheels. A full understanding of the braking force, braking power, and braking energy consumed by the front and rear wheels in typical drive cycles is helpful in the design of regenerative braking systems.
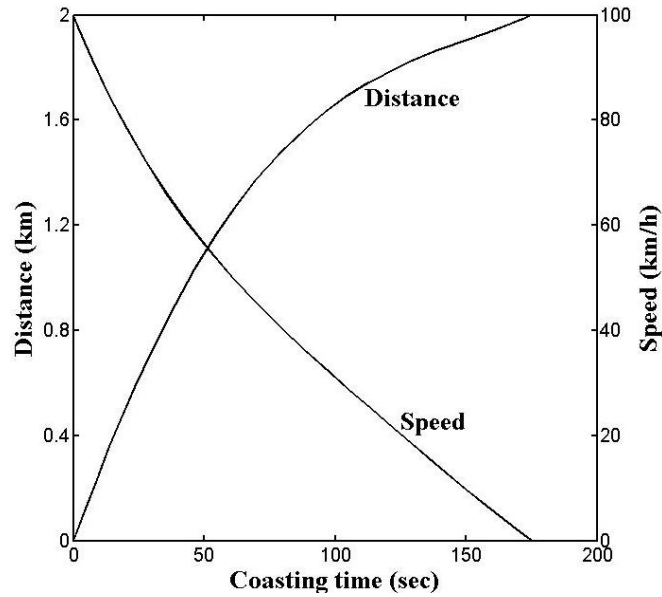

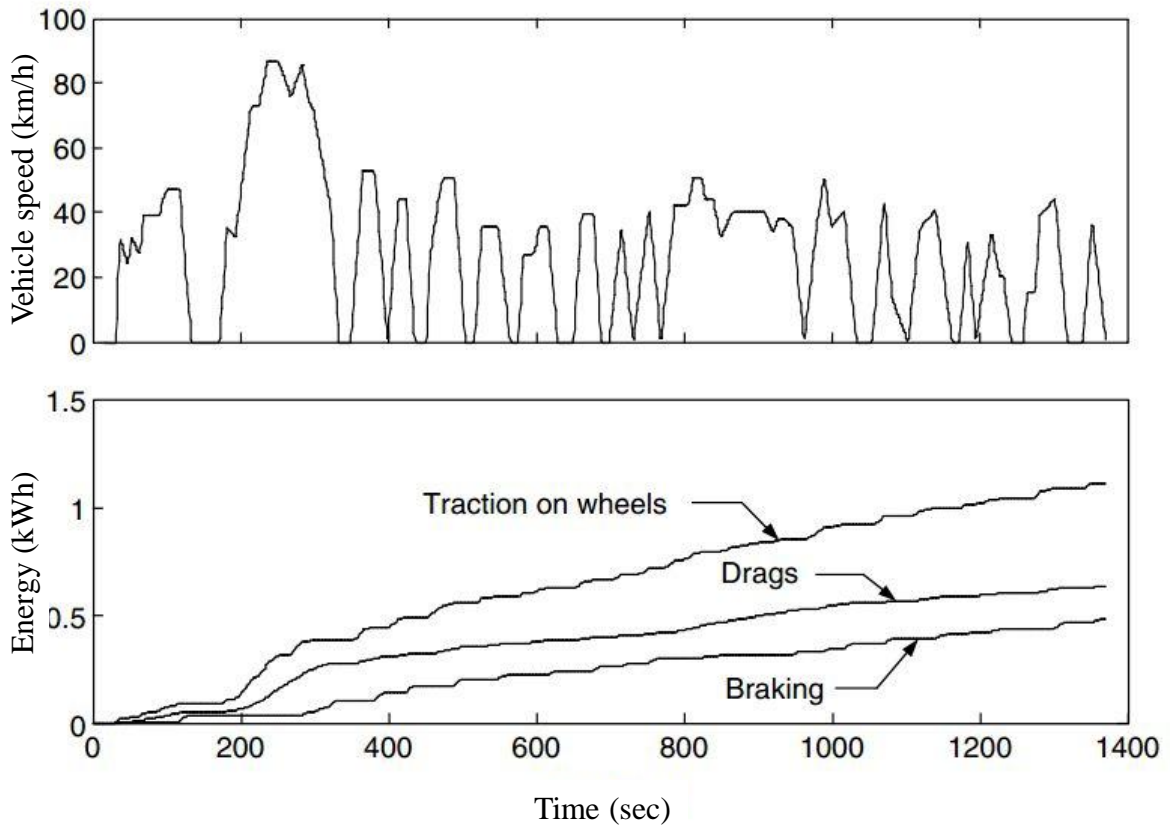Figure 1: Coasting time, Speed and Distance [1]

Figure 2: Total traction energy and energies consumed by drags and braking in an FTP 75 urban drive cycle [2]

Initially, assuming that the braking distribution on the front and rear wheels follow the curve I (refer to Chapter 2), ignoring vehicle drags, the braking forces on the front and rear wheels can be expressed as:

$$F_{bf} = \frac{jM_v}{L}(L_b + \frac{h_g}{g} j)$$

and
$$F_{br} = \frac{jM_v}{L}(L_a + \frac{h_g}{g} j)$$

where j is the deceleration of the vehicle in m/s^2, L is the wheel base of the vehicle, L_a and L_b are the horizontal distances between the vehicle gravity center to the center of the front and rear wheels, respectively, and h_g is the height of the gravity center of the vehicle to the ground. **Figure 3** shows vehicle speed and acceleration/deceleration in an FTP 75 urban drive cycle.

Figures 4 - 6 show the braking force, braking power, and braking energy of a 1500 kg passenger car in an FTP 75 urban drive cycle. This example has parameters of $L=2.7\,m$, $L_a=0.4\,L$, $L_b=0.6\,L$, and $h_g=0.55\,m$.

Figures 4 - 6 indicate that:

i. The front wheels consume about 65% of the total braking power and energy. Thus, regenerative braking on front wheels, if available only on one axle, is more effective than on rear wheels.

ii. The braking force is almost constant in the speed range of less than 50 km/h and decreases when the speed is greater than $40\,km/h$. This characteristic naturally matches that of an electric motor that has a constant torque at the low-speed region and a constant power at the high-speed region. Further, **Figure 6** indicates that most braking energy is consumed in the speed range of 10 to $50\,km/h$.
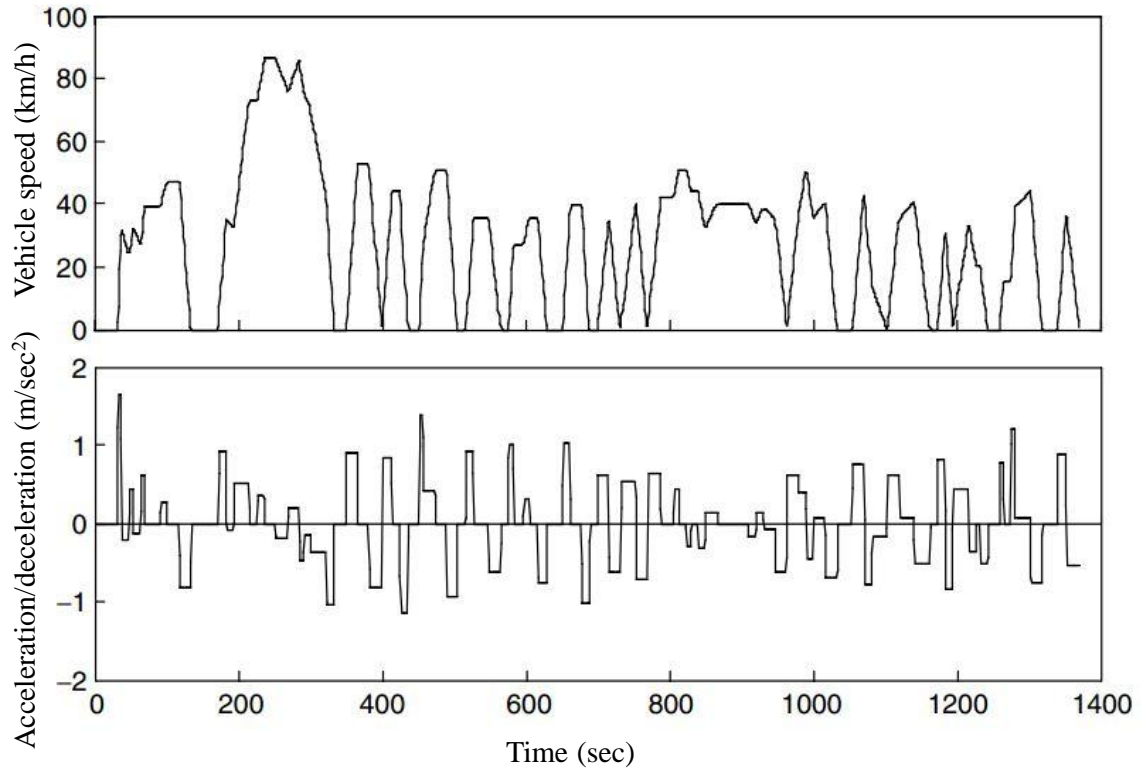
Figure 3: Vehicle speed and acceleration/deceleration in an FTP urban drive cycle [1]
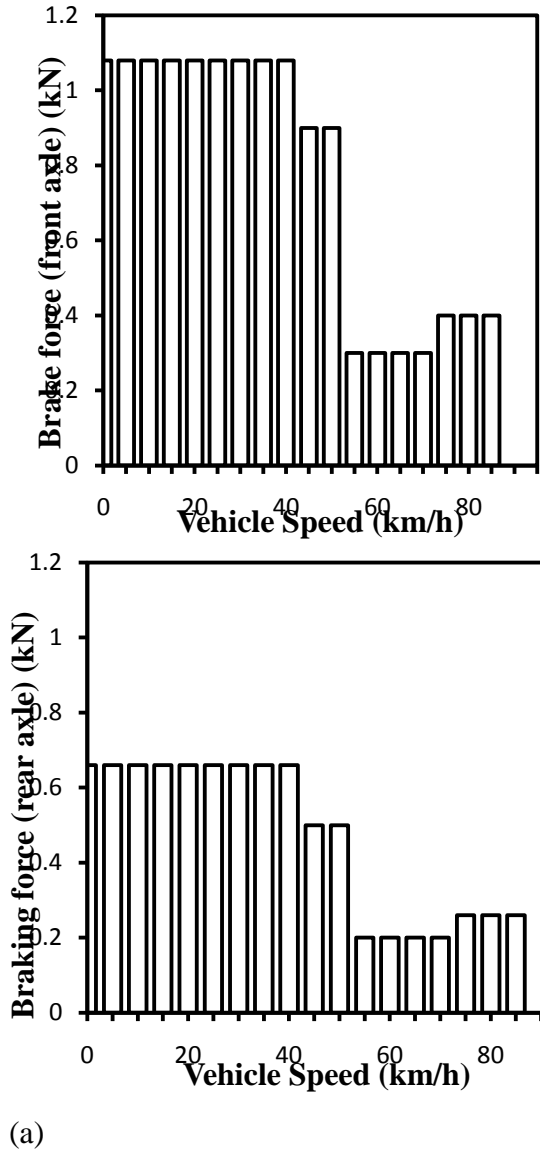
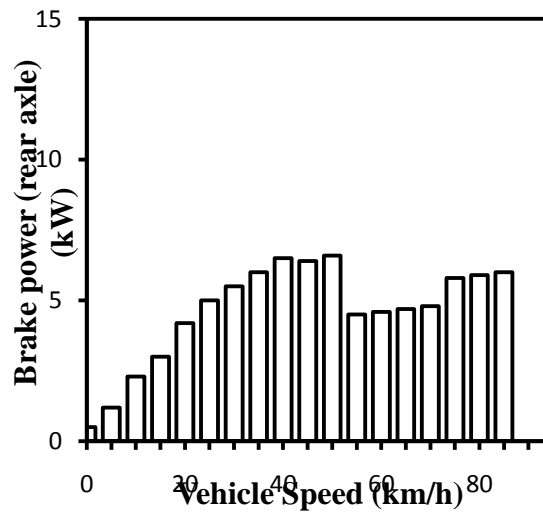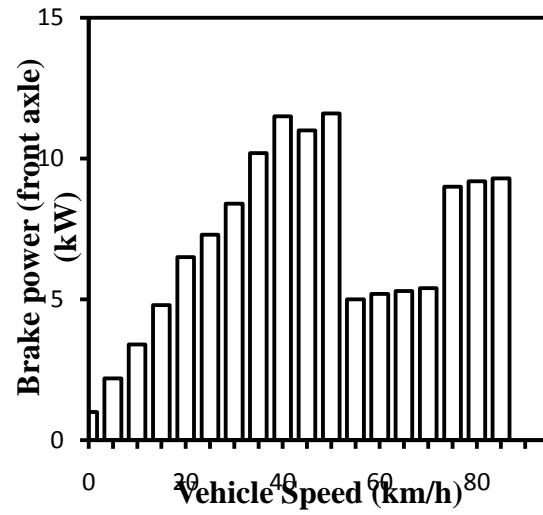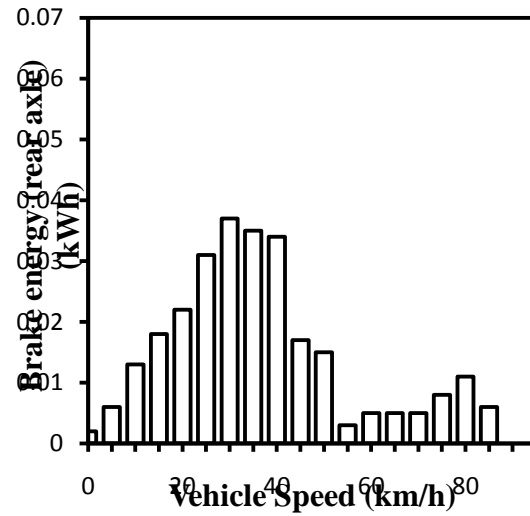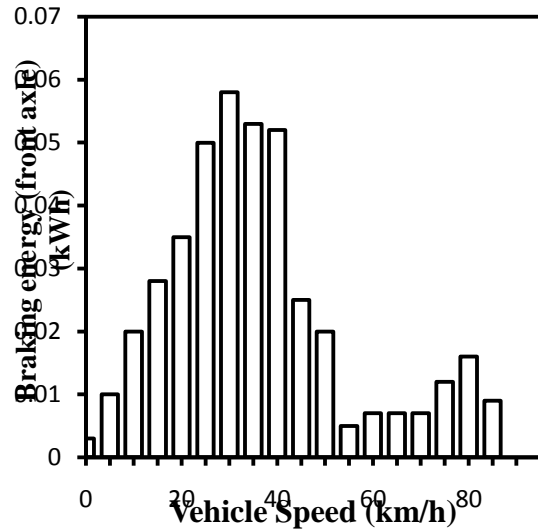(a)   (b)

Figure 4: Braking force vs. vehicle speed in an FTP 75 urban drive cycle: (a) on front wheels and (b) on rear wheels.[1]

Figure 5: Braking power vs. vehicle speed in an FTP 75 urban drive cycle: (a) on front wheels and (b) on rear wheels. [1]

Figure 6: Braking energy vs. vehicle speed in an FTP 75 urban drive cycle: (a) on front wheels and (b) on rear wheels. [1]

References:

[1]. M. Ehsani, *Modern Electric, Hybrid Electric and Fuel Cell Vehicles: Fundamentals, Theory and Design*, CRC Press, 2005

[2] A. E. Fuhs, *Hybrid Vehicles and the Future of Personal Transportation*, CRC Press, 2009

Lecture 39: Brake System of EVs and HEVs

Brake System of EVs and HEVs

The topics covered in this chapter are as follows:

- Brake System of EVs and HEVs
  - ➢ Series Brake — Optimal Feel
  - ➢ Series Brake — Optimal Energy Recovery
  - ➢ Parallel Brake
  - ➢ Antilock Brake System (ABS)

Brake System of EVs and HEVs

Two basic questions arise while considering regenerative braking in EVs and HEVs:

i. How to distribute the total braking forces required between the regenerative brake and the mechanical friction brake so as to recover the kinetic energy of the vehicle as much as possible.

ii. The other is how to distribute the total braking forces on the front and rear axles so as to achieve a steady-state braking.

Basically, there are three different brake control strategies: series braking with optimal braking feel; series braking with optimal energy recovery; and parallel braking.

Series Brake -- Optimal Feel

The control objective is to minimize the stopping distance and optimize the driver's feel.

Figure 1 illustrates the principle of this braking control strategy. When the commanded deceleration (represented by the braking pedal position) is less than $0.2\,g$, only the regenerative braking on the front wheels is applied, which emulates the engine retarding function in conventional vehicles. When the commanded deceleration is greater than 0.2 g, the braking forces on the front and rear wheels follow the ideal braking forces distribution curve I, as shown in **Figure 1** by the thick solid line.

The braking force on the front wheels (driven axle) is divided into two parts: regenerative braking force and mechanically frictional braking force. When the braking force demanded is less than the maximum braking force that the electric motor can produce, only electrically regenerative braking will apply. When the commanded braking force is greater than the available regenerative braking force, the electric motor will operate to

produce its maximum braking torque, and the remaining braking force is met by the mechanical brake system.

It should be noted that the maximum regenerative braking force produced by an electric motor is closely related to the electric motor's speed. At low speed (lower than its base speed), the maximum torque is constant. However, at high speed (higher than its base speed), the maximum torque decreases hyperbolically with its speed. Therefore, the mechanical brake torque at a given vehicle deceleration varies with vehicle speed.
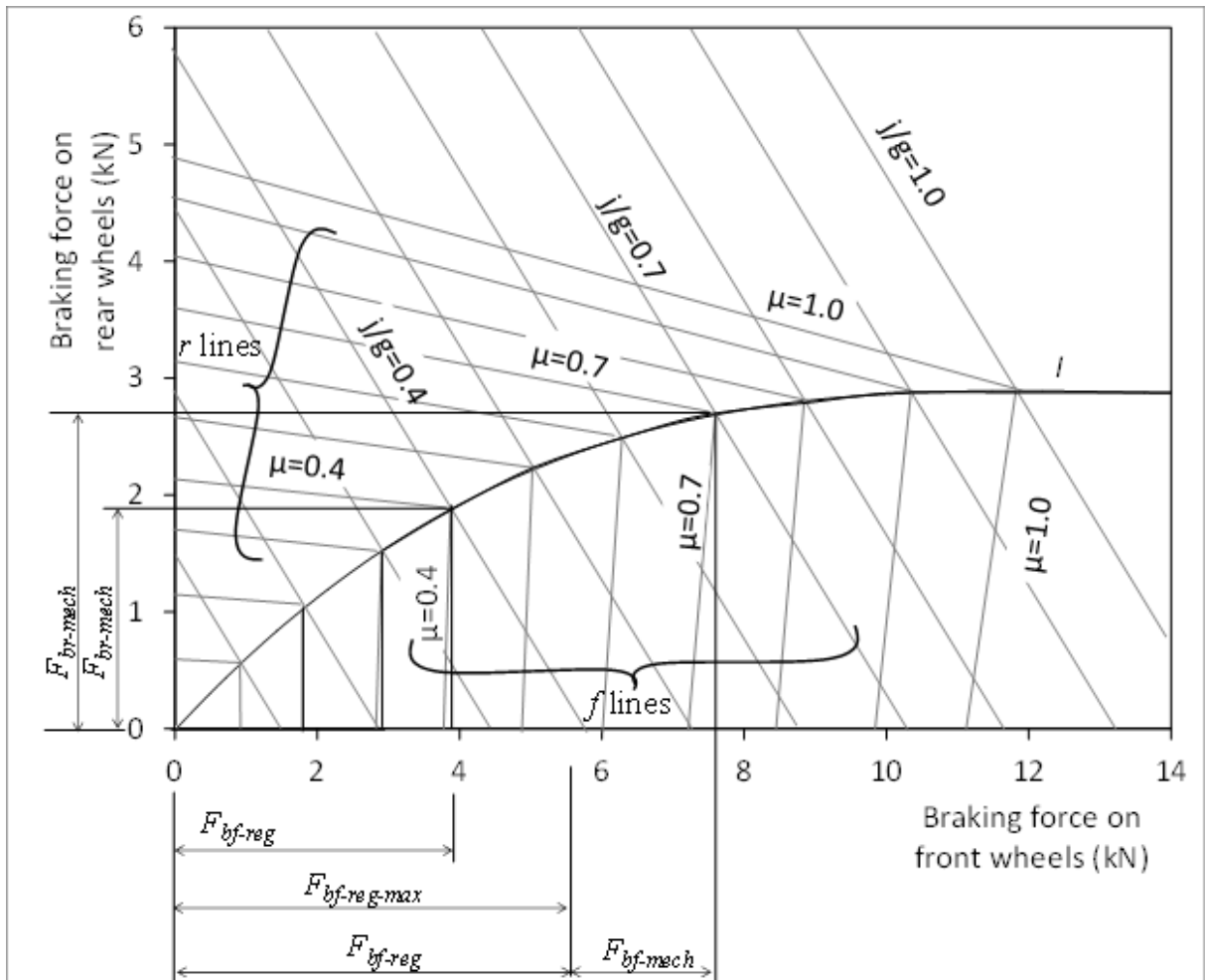

Figure 1: Illustration of braking forces on the front and rear axle for series braking - optimal feel [1]

Series Brake - Optimal Energy Recovery

The principle of the series braking system with optimal energy recovery is to recover the braking energy as much as possible in the condition of meeting the total braking force demanded for the given deceleration. This principle is illustrated in **Figure 2**.

When the vehicle is braked with an acceleration rate of $j/g < \mu$, the braking forces on the front and rear wheels can be varied in a certain range, as long as the $F_{bf} + F_{br} = M_v j$ is satisfied. This variation range of the front and rear axles is shown in **Figure 2** by the thick solid line ab, where $\mu = 0.9$ and $j/g = 0.7$. In this case, regenerative braking should be used in priority. If the available regenerative braking force (maximum braking force produced by the electric motor) is in this range (point c in **Figure 2**, for example), the braking force on the front wheels should be developed only by regenerative braking without mechanical braking. The braking force on the rear wheels, represented by point e, should be developed in order to meet the total braking force requirement. If, on the same road, the available regenerative braking force is less than the value corresponding to point a (e.g.
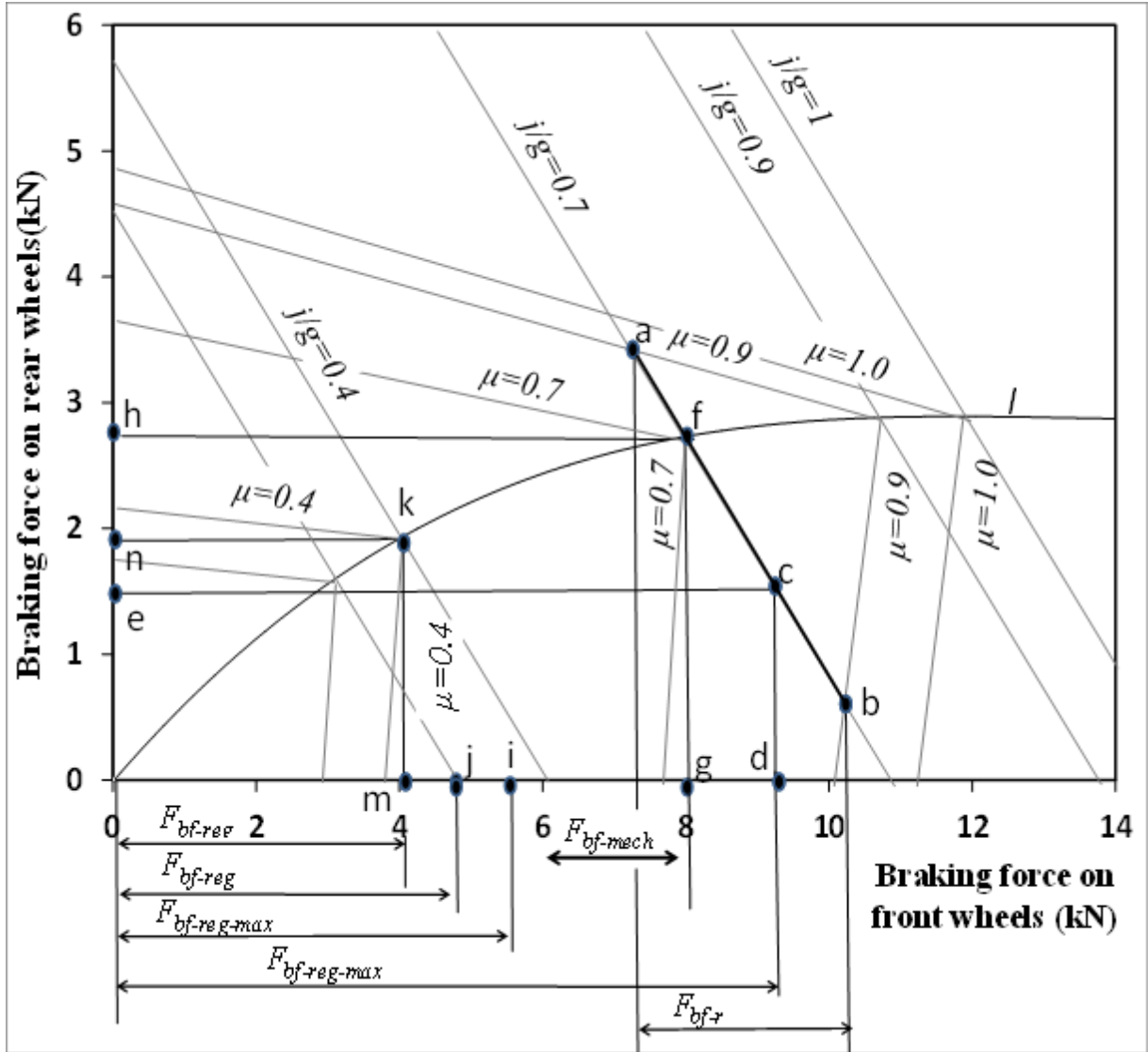
Figure 2: Demonstration of series braking — optimal energy recovery [1]

point i in **Figure 2**), the electric motor should be controlled to produce its maximum regenerative braking force. The front and rear braking forces should be controlled at point f so as to optimize the driver feel and reduce braking distance. In this case, additional braking force on the front wheels must be developed by mechanical braking by the amount represented by $F_{bf-mech}$, and the braking force on the rear axle is represented by point h.

When the commanded deceleration rate, j/g, is much smaller than the road adhesive coefficient ($j/g = 0.3$ in **Figure 2** for example), and the regenerative braking force can meet the total braking force demand, only regenerative braking is used without mechanical braking on the front and rear wheels (point j in **Figure 2**).

When the commanded deceleration rate, j/g, is equal to the road adhesive coefficient μ, the operating point of the front and rear braking forces must be on the curve I. On a road with a high adhesive coefficient ($\mu = 0.7$, operating point f, in **Figure 2**, for example), the maximum regenerative braking force is applied and the remaining is supplied by the mechanical brake. On a road with a low adhesive coefficient ($\mu = 0.4$, operating point k, in **Figure 2**, for example), regenerative braking alone is used to develop the front braking force.

When the commanded deceleration rate, j/g, is greater than the road adhesive coefficient μ, this commanded deceleration rate will never be reached due to the limitation of the road adhesion. The maximum deceleration that the vehicle can obtain is $(a/g)_{max} = \mu$. The operating point of the front and rear braking forces is on the curve I, corresponding to $\mu(\mu = 0.4$ and $j/g > 0.4$ in **Figure 2**, for example); the operating point is point k and the maximum deceleration rate is $j/g = 0.4$.

It should be noted that the series brake with both optimal feel and energy recovery needed active control of both electric regenerative braking and mechanical braking forces on the front and rear wheels. At present, such a braking system is under research and development.

Parallel Brake

The parallel brake system includes both an electrical (regenerative) brake and a mechanical brake, which produce braking forces is parallel and simultaneously. The operating principle is illustrated in **Figure 3**, in which regenerative braking is applied only to the front wheels.

The parallel brake system has a conventional mechanical brake which has a fixed ratio of braking force distribution on the front and rear wheels. Regenerative braking adds additional braking force to the front wheels, resulting in the total braking force distribution curve. The mechanical braking forces on the front and rear axles are

proportional to the hydraulic pressure in the master cylinder. The regenerative braking force developed by the electric motor is a function of the hydraulic pressure of the master cylinder, and therefore a function of vehicle deceleration. Because the regenerative braking force available is a function of motor speed and because almost no kinetic energy can be recovered at low motor speed, the regenerative braking force at high vehicle deceleration (e.g., $a/g = 0.9$) is designed to be zero so as to maintain braking balance. When the demanded deceleration is less than this deceleration, regenerative braking is effective. When the braking deceleration commanded is less than a given value, say $0.15g$, only regenerative braking is applied. This emulates the engine retarding in a conventional vehicle. In **Figure 3**, the regenerative braking force, $F_{bf-regen}$, and mechanical braking forces on the front and rear wheels, $F_{bf-mech}$ and F_{br}, are illustrated.

Figure 4 shows the total braking force, regenerative braking force, and mechanical braking force on the front wheels as well as the braking force on the rear wheels in the parallel braking system of a passenger car.

The parallel braking system does not need an electronically controlled mechanical brake system. A pressure sensor senses the hydraulic pressure in the master cylinder, which represents the deceleration
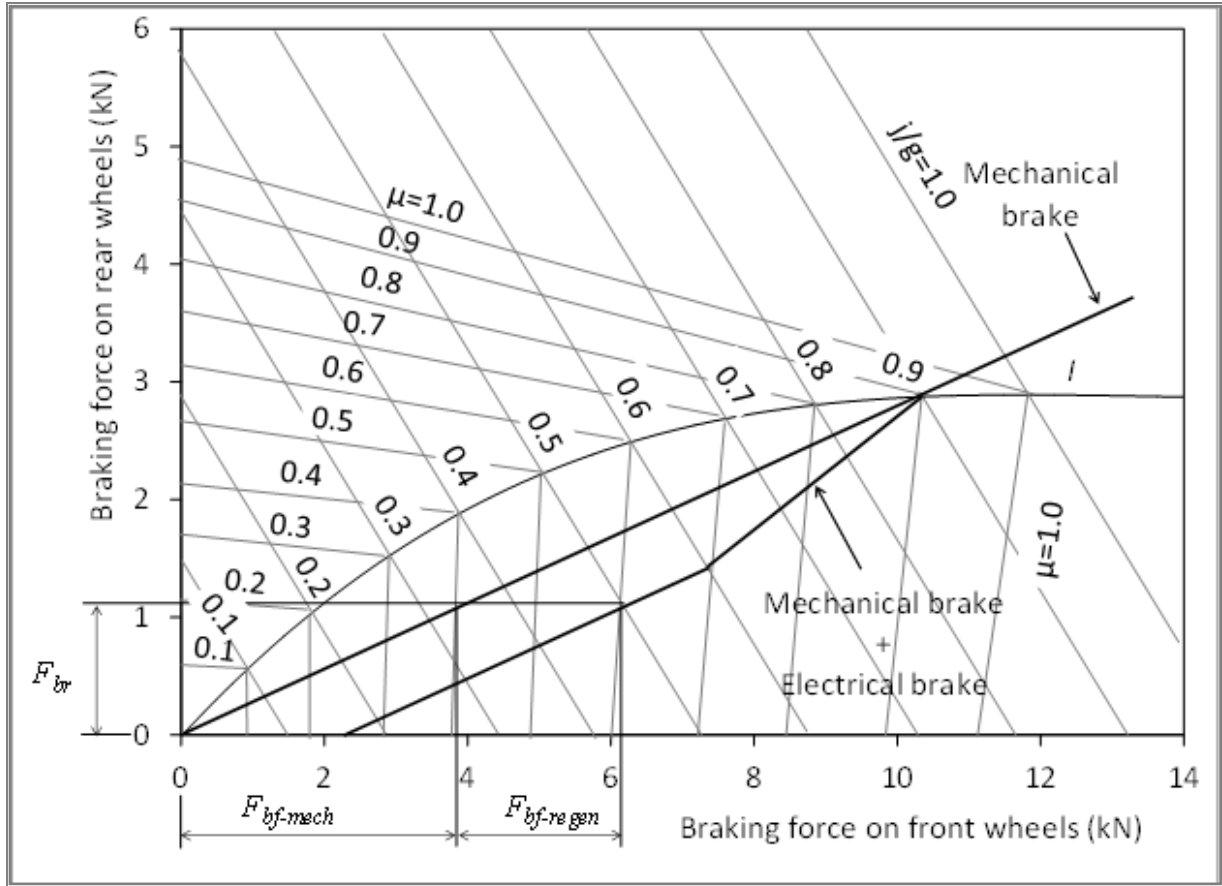
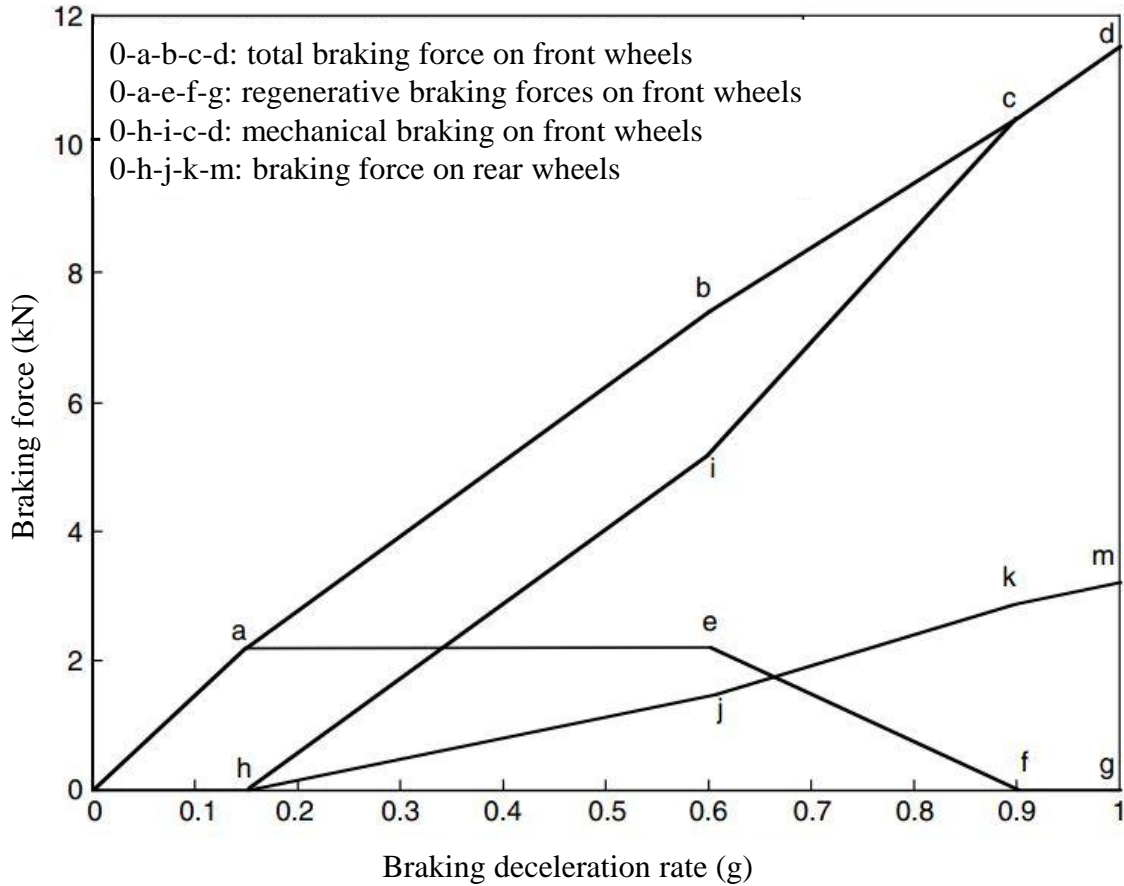**Figure 3: Illustration of parallel braking strategy [1]**

Figure 4: Braking forces varying with deceleration rate [1]

demand. The pressure signal is regulated and sent to the electric motor controller to control the electric motor to produce the demanded braking torque. Compared with the series braking of both optimal feel and energy recovery, the parallel braking system has a much simpler construction and control system. However, the driver's feeling, and amount of energy recovered are compromised.

Antilock Brake System (ABS)

Active control of the braking force (torque) of the electric motor is easier than the control of the mechanical braking force. Thus, antilock in braking with an electric brake in EVs and HEVs is another inherent advantage, especially for a vehicle with an electric motor on four wheels. **Figure 5** conceptually illustrates a scheme of regenerative braking, which can potentially function as an ABS.

The main components of this braking system are the brake pedal, master cylinder, electrically powered and electronically controlled brake actuators, electronically controlled three-port switches (common mode: port 1 open, port 2 close, and port 3 open), fluid accumulator, pressure sensor, and an overall controller unit. The pressure sensor measures the fluid pressure, which represents the driver's desirable braking strength. The fluid is discharged into the fluid accumulator through the electronically controlled three-port switches. This emulates the braking feeling of a conventional braking system. After receiving a braking pressure signal, the overall controller unit determines the braking torques of the front and rear wheels, regenerative braking torque, and mechanical braking torque, according to the traction motor characteristics and control rule. The motor controller (not shown in **Figure 5**) commands the motor to produce correct braking torque, and the mechanical braking controller commands the electrically powered braking actuator to produce correct braking torques for each wheel. The braking actuators are also controlled to function as an antilock system to prevent the wheels from being locked completely. If an electrically powered braking actuator is detected to be a failure, the corresponding three-port switch closes port 3 and opens port 2, and then fluid is directly discharged to the wheel cylinder to produce braking torque. The control strategy is crucial for energy recovery and braking performance.

Figure 6 shows the simulation results of a passenger car, which is experiencing a sudden strong braking on a road with varying road adhesive coefficients. When the commanded braking force is less than the maximum braking force that the ground surface can support without the wheel being locked, the actual braking force follows the commanded braking force. However, when the commanded braking force is greater than the maximum braking force that the ground can support, the actual braking force follows the maximum ground braking force (in a period of 0.5 to 1.5 sec in **Figure 6**). Then, the wheel slip ratios can be controlled in a proper range (usually $< 25\%$). The vehicle will have directional stability and short braking distance.
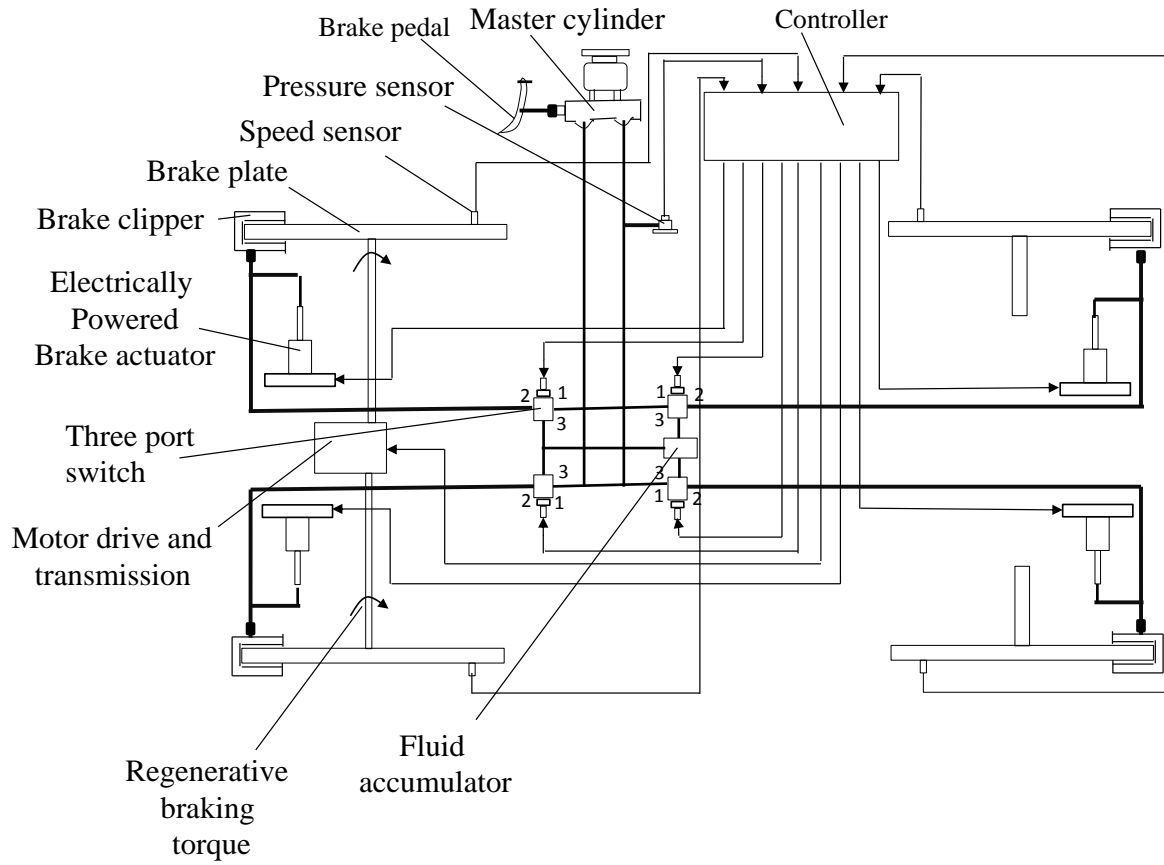
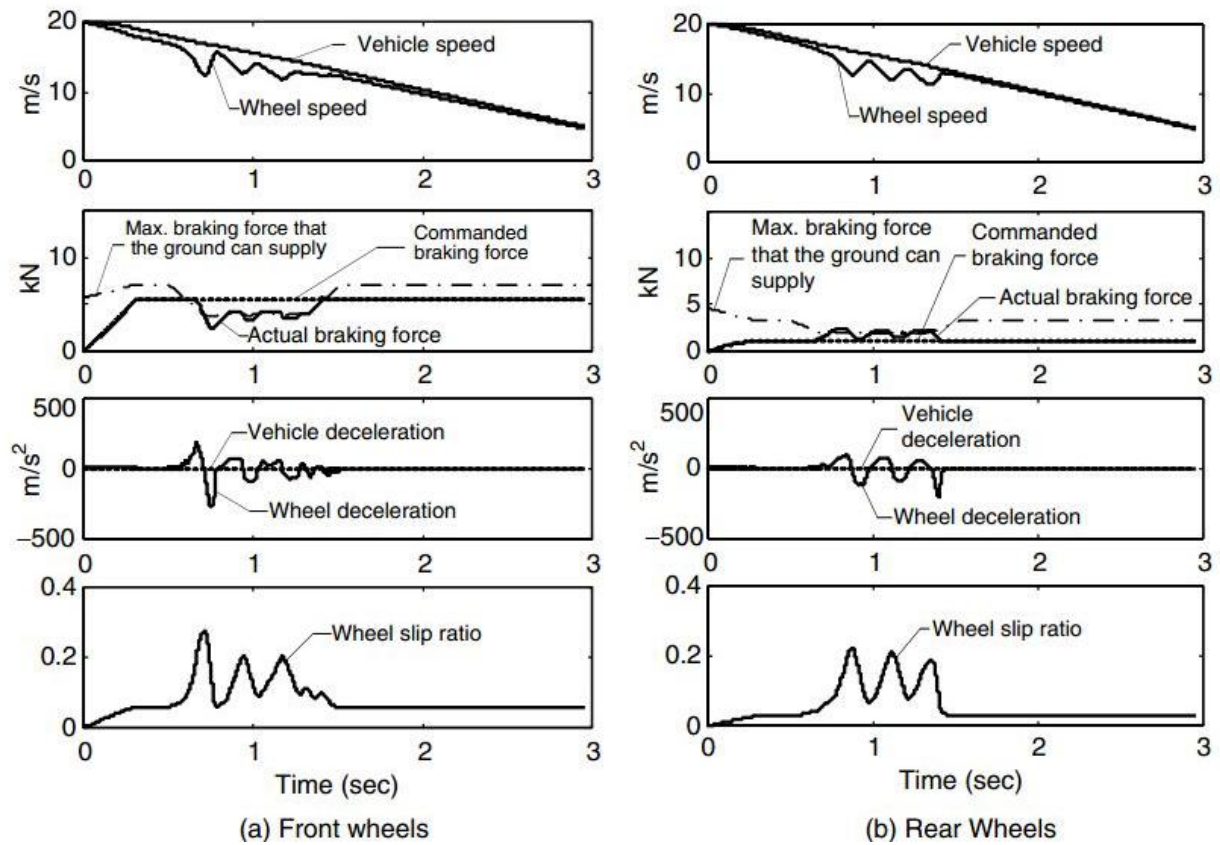**Figure 5: Electronically controlled regenerative braking system functioning as an ABS [1]**

Figure 6: Braking with ABS [1]

References:

[1]. M. Ehsani, *Modern Electric, Hybrid Electric and Fuel Cell Vehicles: Fundamentals, Theory and Design*, CRC Press, 2005