Chapter 1
Freeway Traffic Systems

1.1 Sustainable Mobility

Transportation systems have always played a relevant role in the social and economical development of all the countries, but only in recent years the need for traffic mobility systems has grown considerably. Although this increase surely provides positive effects on the human progress, at the same time, the increase in traffic mobility is the source of several negative externalities such as pollutant emissions, congestion, safety reduction and environmental deterioration.

These phenomena have been observed for both the advanced economies and the developing countries, where the significant growth in the number of vehicles has generated a negative impact on the quality of people's life. In particular, the increased number of vehicles has caused both an increment of pollution and an intensification of congestion phenomena, due to the inefficiency of the existing infrastructures that are often unable to handle the growth of traffic demand. Indeed, it is not always possible, both for physical and economic constraints, to modify the existing infrastructure to meet the current traffic demand.

In order to address all these problems, it is required to implement management and control tools which allow to improve the system performance and the quality of drivers' life, without requiring significant infrastructural changes to the present traffic network. In addition, the present mobility systems must be designed to be sustainable, i.e. they must pursue the economic development, the social welfare, and the environmental safeguard, guaranteeing the needs of the current society and the future one.

The concept of *sustainable development* has been recently introduced in the international legislation, in order to overcome the limited logic of simply pursuing economic benefits in the short term without considering the consequences of political actions in the long period. The case of road transport systems is particularly interesting, since the road represents the most widespread option to move passengers and to supply goods (see Fig. 1.1), though being one of the most critical choices, since it produces several negative effects with implications for the entire society.

A. Ferrara et al., *Freeway Traffic Modelling and Control*, Advances in Industrial Control, https://doi.org/10.1007/978-3-319-75961-6_1

Fig. 1.1 A road stretch in A1 freeway, close to Rome, Italy (courtesy of Autostrade per l'Italia SpA, photo from Archivio Videofotografico Autostrade per l'Italia)

The importance of these issues emerges also from the actions taken by the European Commission which has promoted, in recent years, several studies [1–3] and the White Paper on Transport [4]. Analogously, in the U.S., following the Clean Air Act, different regulations have been introduced since the 60s in order to limit the emissions of pollutants. A recent comparative study focusing on the main differences between the European and the U.S. legislations about emissions in the automotive sector is reported in [5].

All the countries all over the world, according to their legislation, have developed guidelines and regulations in the area of sustainable development, by highlighting the possible actions to be implemented in order to reduce emissions. In particular, the main common priorities are referred to the reduction of energy consumptions, emissions of greenhouse gases and pollutants, the containment of noise and network congestion, the compliance with minimum standards of safety and minimum standards of functionality.

1.2 Criticalities of Freeway Traffic Systems

Among the negative impacts associated with the growth of freeway traffic systems, a major issue is surely related to recurrent and non-recurrent congestion phenomena (see Fig. 1.2) which, in turns, cause an increase of the time spent by travellers in

Fig. 1.2 A freeway stretch in I-405, city of Los Angeles, U.S. (courtesy of Michael Ballard)

the network, of fuel consumption, of environmental impact, as well as a higher probability of accidents. The main critical factors connected with freeway traffic systems are analysed in detail in the following subsections.

1.2.1 Congestion Phenomena

Traffic congestion is a major criticality in modern freeway systems, causing serious infrastructure degradation in and around metropolitan areas. Despite the significant advances in the area of *Information and Communication Technology* (ICT), it seems that the full exploitation of such innovative technologies to mitigate motorway traffic congestion has not been completely achieved yet. Urban and interurban freeways were originally conceived so as to provide virtually unlimited mobility to road users. However, the dramatic expansion of car ownership has led to daily recurrent and non-recurrent freeway congestions of thousands of kilometres in length around the world. Such congestions substantially reduce the available infrastructure capacity at the rush hours, i.e. at the time in which this capacity is most urgently needed, causing delays, increased environmental pollution and reduced traffic safety. Similar effects are observed in the frequent case of non-recurrent congestions caused by incidents, road works (see Fig. 1.3), and so on.

Traffic jams occur whenever a high number of vehicles attempt to use a common roadway with limited capacity (Fig. 1.4). Such events may have various effects on the

Fig. 1.3 Road works for deep renovation of asphalt pavement on A1 freeway, Italy (courtesy of Autostrade per l'Italia SpA, photo from Archivio Videofotografico Autostrade per l'Italia)

Fig. 1.4 Congestion forming in I-5 North at State Route 55 in Santa Ana, U.S. (courtesy of Michael Ballard)

performance and the quality of the system, causing the formation of queues and the consequent increase of travel times. In some cases, the consequences of traffic jams are even worse, leading to deadlock states characterised by excessive delays in travel times, high reductions of the safety level and a consequent strong increase of fuel consumptions. Moreover, in the literature several studies recognise that, in addition to the economic disadvantage caused by the loss of time and the increase of fuel consumption, it is possible to observe a further social damage due to the increasing level of stress of the drivers, which suffer the frustration produced by the frequent exposure to congestion phenomena. Indeed, users lose confidence on the reliability of the system considering the higher time spent to reach their destination as a *wasted time*, which could have been used for other activities [6, 7].

Congestion phenomena are mainly classified as recurring and non-recurring congestions, the main difference being related to the predictability of the occurrence of the congestion [8]. *Recurrent congestion* is predictable since it is a direct consequence of the traffic daily routine. This is generally caused by a traffic demand close or greater than the one for which the saturation of the infrastructure occurs, and in freeway contexts it is often associated with the movement of commuters during rush hours. It is worth noting that drivers acquire some experience about recurrent congestion phenomena and they plan their travel choices accordingly.

Non-recurrent congestion is instead connected with random events which are not predictable by users. For such reason, non-recurrent congestion leads to a greater frustration of road users compared with recurrent congestion. Non-recurrent congestion is normally generated by the following causes:

- *traffic accidents*, which interrupt the normal flow of traffic and block one or more lanes. Besides vehicle crashes, traffic incidents include all the events that cause traffic disturbances such as vehicle malfunctions on roadways. In this case, the congestion happens, primarily, for the capacity reduction caused by the interruption of one or more lanes and, secondarily, by the slowdowns caused by drivers that decrease their speed to observe the accident or the rescue operations. The severity of the congestion depends both on the number of lanes which have been obstructed and on the duration of the event;
- *adverse weather conditions*, which have a negative influence on the driving behaviour. Events such as rain or snow reduce the pavement adherence, as well as fog or intense rain phenomena produce a considerable reduction of visibility. These aspects generate a strong decrease of the mean speed and a high increase in the frequency of traffic incidents;
- *demand fluctuations*, i.e. the variability of traffic flows due to demand peaks that happen daily, weekly and seasonally, with particular reference to the holiday periods and the emergency evacuations;
- *work zones*, implying a reduction of the road capacity due to activities of construction and maintenance. The impact of the works on the reliability of the infrastructure depends on their extension and duration; especially the short term activities have a greater effect on non-recurrent congestion, since the drivers are not able to reschedule their choices taking into consideration the suffered delay;

- *special events*, which normally generate a high traffic demand in a limited time period, with consequent creation of non-recurrent congestion in the vicinity of stadiums, sports centres, shopping centres and others.

In addition to delays, another important aspect that must be taken into account as a negative effect of congestion is related to the *reliability* of the roadway [9]. The reliability of a roadway is related to the variance of the travel times experienced by the drivers: reliable roadways have travel times with low variability, whereas high variabilities in travel times make a road unreliable. The reduction of reliability of a freeway is normally due to non-recurrent congestion phenomena, while delays derived from recurrent congestion do not affect reliability as much, because they are rather constant and predictable. Only recently, the concept of reliability has become an important measure for roadway performance. One of the main reasons for the importance of measuring and managing freeway reliability is that drivers have less tolerance for unexpected delays than for expected ones. Many drivers prefer to choose a path with reliable congestion than a path with unreliable travel times, even if the reliable path is characterised by longer expected travel times.

1.2.2 Pollutant Emissions

Despite the significant technological progress, the levels of pollutant emissions generated by road transport are surely a major cause of risks for the human health and for the environment, especially in urban areas (Fig. 1.5). This is specifically due to the increase of traffic flows and the almost exclusive use of fossil fuels [4, 10].

In particular, the process of air degradation may be caused by three different sources:

- *chemical pollution*, generated by the adoption of heat engines and strictly related to the process of combustion in which several toxic substances are produced, such as carbon monoxide, hydrocarbons, nitrogen oxides, sulphur oxides and particulate matter;
- *thermal pollution*, caused by the exposure of the ecosystem to heat sources and greenhouse gases, such as nitrous oxide, methane, sulphur hexafluoride and especially carbon dioxide;
- *noise pollution*, connected with excessive noise, with effects on the psychological state and physical health of the exposed population.

The previously cited pollutants, besides providing significant environmental damages, involve serious repercussions on human health [11]. *Carbon monoxide* is produced by an inefficient fuel combustion basically caused by a lack of oxygen. The risk derived from the presence of carbon monoxide in the air is due to its high affinity with the haemoglobin in the human blood, which provokes the formation of carboxyhemoglobin causing inadequate oxygenation of the blood cells. The presence of *hydrocarbons* in the air is instead due to the presence of phenomena leading to the

Fig. 1.5 A freeway stretch in Villeneuve d'Ascq, close to Lille, France

incomplete combustion of hydrocarbons. These hydrocarbons, when introduced into the environment, cause chemical reactions in the air, contributing to the formation of photochemical smog and greenhouse effect. Among the substances produced in the regular combustion process, there are also *nitrogen oxides*. Most of them are constituted by nitrogen monoxide, while the formation of nitrogen dioxide occurs in a secondary reaction and is not strictly linked with the phase of combustion. Finally, the *particulate matter* is constituted by microscopic solid particles suspended in the air and produced mainly in the phase of combustion in diesel engines. The harmfulness of these powders is related to their small dimension, since this particulate matter can penetrate deeply in the pulmonary alveoli causing a severe damage.

Particular attention must also be paid to the production of *carbon dioxide*. Although it is not toxic nor harmful, its accumulation in the atmosphere is one of the major causes of the *greenhouse effect* and the resulting *global warming*. Carbon dioxide is a thermal pollutant resulting from the complete combustion of the carbon present in the fuel. The transport sector represents a significant source in the production of carbon dioxide, which has highly increased in the last decades [12]. For these reasons, stricter standards have been progressively adopted to limit vehicle emissions in many countries. Nonetheless, nowadays the level of carbon dioxide detected in some areas (especially in urban districts) is still far from the normative limits and, therefore, further actions are required to improve air quality.

1.2.3 Safety Issues

If traffic congestion has a negative impact on the economy and the quality of citizens' life, its effects on traffic safety are less evident. For this reason, some studies have been carried out to analyse the relation between road safety and congestion in freeways, often leading to different outcomes. According to the classification reported in [13], the studies focused on the relationship between traffic conditions and safety (in terms of crash severity, frequency and type) can be divided in two categories. The former group compares congestion and safety levels at different locations or different time periods, on the basis of data obtained during long observation periods. The studies of the latter group use instead short observation periods in order to analyse which traffic conditions lead to crashes. Hence, they are more suitable to capture short-term variations in traffic flows, which normally correspond to the formation or recovering phase of congestion.

Some studies in the literature aim to find quantitative relations between crashes and variables specifically referred to traffic conditions, such as traffic flow or traffic density [14, 15]. A recent research on the relation between crashes and traffic density has been conducted on the freeways of some American countries [15], by distinguishing accidents into two categories according to their severity. The data collected in this research show a U-shaped relationship between crash rate and traffic density. As a matter of fact, at low traffic densities, *single-vehicle crashes* are more likely to happen, because the interactions among vehicles are rare and drivers are inattentive and travel at very high speeds. On the other hand, at high traffic densities, the interactions among vehicles highly increase so that *rear-end crashes* and *multiple-vehicle crashes* due to lane changing behaviours become more frequent.

1.2.4 Freight Transport Issues

All the negative effects associated with traffic and described before are much more critical and relevant when considering a particular typology of traffic, that is the transport of goods by road. Although European policies and similar rules in other countries have encouraged the *modal shift* towards more sustainable means of transport (such as the rail mode), the use of road still remains the preferred choice for short and medium-range freight transportation. This is due to many reasons, such as the higher flexibility of road transport, which is the most suitable mode to meet the requirements of the fragmentation of industrial production.

As aforementioned, freight transport by road, that is normally realised with trucks, has negative impacts both from the social point of view and from the point of view of safety and environmental safeguard (Fig. 1.6). Analogously to passenger traffic, greenhouse gas emissions and congestion phenomena are considered the most serious environmental and sustainability issues related to freight transport and logistics.

Fig. 1.6 High percentage of trucks in A10 freeway, in Savona, Italy

In this context, it is possible to state that sustainability of freight transport seems more difficult to be achieved than for passenger transport. This is due to a variety of factors, including the long time horizons necessary to implement major technological changes in heavy vehicles, the need for significant price changes to induce modal shift and the lack of innovation in freight transport modes. The main guidelines of the developed countries towards sustainability in freight transport and logistics are related to promote intermodal transportation, to improve efficiency and environmental performance of the existing modes, to develop alternative fuels technologies, and to exploit opportunities provided by ICT in order to find innovative and sustainable solutions [16, 17].

1.3 Actions to Improve Freeway Traffic Systems

Different possible actions and interventions in freeway traffic systems have been studied and implemented worldwide in order to improve traffic circulation and safety, and to mitigate the environmental impact. These solutions can be directly related to the design of the infrastructure or the development, in the current automotive sector, of new technologies for producing safer and more compatible vehicles. In addition, another possibility is to exploit the concepts of information technology and traffic engineering (electronic surveillance, vehicle communications systems, traffic analysis and control theory) to increase the efficient use of the present transport infrastructure.

Any type of action realised in a freeway traffic system should be developed taking into account that the mobility of people and goods is a complicated problem, since it affects a large number of actors with interests and objectives that are often incompatible and conflicting. The developed measures should address the needs of the main stakeholders, that are:

- government or local *authorities*, which plan to improve the quality of life in terms of environment safeguard, accessibility (both to areas and services) and decongestion of traffic, without compromising the socio-economic vitality of the country;
- *road users*, who are involved in the twofold role of drivers and citizens and require high standards of services and quality of life;
- *managers of road service* and *automotive industry*, whose main aim is the maximisation of profits and the minimisation of costs.

1.3.1 Infrastructure Design

A first possibility to tackle the problems deriving from recurrent and non-recurrent congestion phenomena is related to changes of the freeway infrastructure. In particular, for events of recurrent congestion, some design solutions entail the extension of the existing infrastructure adding traffic lanes, introducing alternative routes and modifying the road geometry where bottlenecks occur. To address non-recurrent congestion, it is possible to define specific actions. For each cause of non-recurrent congestion, several possible solutions have been deeply examined in recent studies [9].

The main non-recurrent design treatments act on the *geometry* of the roadway, though not implying a massive intervention on the infrastructure. These strategies adopt technical solutions (such as insertion of emergency lanes, emergency crossovers, crash investigation sites, alternating shoulders, ramp widening, and so on), which improve the freeway accessibility both for road users and for road operators who are in charge of carrying out works and rescue operations in a quick and safe manner. Some of these interventions can be applied not only to deal with non-recurrent congestion but also to regulate the traffic flow in recurrent congestion situations. For instance, the *movable traffic barriers* (which are concrete barriers that can be shifted from one side of a lane to another one, to change the designated purpose or direction of travel flow for that lane) have potential benefits in case of non-recurrent congestion situations, such as work zones and major incidents, but their most common applications are to alleviate recurrent congestion due to an unbalanced flow during peak periods.

This wide range of geometric design treatments can actually reduce delays and improve travel time reliability, but they also imply negative consequences. First of all, the realisation of civil works necessarily provokes a loss of soil which could have instead an agricultural or ecosystem use and, also, it generates a territorial fragmentation interrupting the natural habitat. The construction of new infrastructures also produces a modification of the landscape and can have a strong hydrogeological impact, in terms of contamination of surface and ground water.

Finally, it is important to point out that all these measures for improving the freeway infrastructure have some indirect impacts [18]. For instance, the increased capacity of the infrastructure may actually improve the traffic performance in the short term, but may also attract a higher level of traffic demand, further worsening the current level of congestion and environmental pollution.

1.3.2 Technological Solutions on Vehicles

In addition to design actions on the infrastructure, the performance of the freeway traffic system can also be improved by exploiting new technological solutions in the design of vehicles. The two main directions of the technological development in the automotive industry are related to the reduction of fuel consumption and pollutant emissions, on the one hand, and to the increase of safety and comfort for passengers, on the other hand.

Considering fuel consumptions and pollutant emissions, different aspects have been developed, both related to vehicle technologies and devoted to the adopted fuels [19]. The main aim is to achieve a good compromise between energy efficient use and production costs, also considering aspects such as safety and reliability. In this context, the technologies already available or under development offer high potential for reducing pollutants in the long term, but many of them require a partial or total redesign of the vehicle, yielding high production costs that make these technologies difficult to be applied.

The introduction of vehicles with alternative propulsion is in the direction towards decarbonisation and replacement of fossil fuels [20, 21]. A first interesting technology is the *electric* propulsion system, mainly used in the urban context (Fig. 1.7). Although electric vehicles can recover energy during the braking phase, the battery performance severely limits their spread in the market on a larger scale at present, but the strong development in storage technologies allows to think that a larger diffusion of electric vehicles will happen in the near future. The *hybrid electric* propulsion system, i.e. an electric propulsion system combined with a conventional internal combustion engine, allows to overcome the limits of electric vehicles. A third possibility is given by the application of *fuel cells* for automotive field. According to this latter technology, the electricity for the electric motor is produced by an electrochemical device, where hydrogen is used as fuel and the oxygen present in the air is used as combustive agent.

As aforementioned, a further step towards green mobility is the progressive development of *alternative fuels* that in general allow a considerable abatement of carbon dioxide emissions. Specifically, the most promising alternatives are natural gas, liquefied petroleum gas, hydrogen, mixtures of hydrogen and natural gas and biofuels.

Fig. 1.7 Electric vehicle and charging station in Savona University Campus, Italy

It is worth noting that the urgency to limit the use of fossil fuels is not only due to the need of environmental protection, but is also encouraged by the increasing price of oil. Another contribution to alleviate fuel consumption is given by the enhancement of vehicles, due to the application of technological devices which allow the achievement of a better performance, for example the reduction of vehicle mass thanks to innovative materials, the increase of the efficiency of the transmission system, the improvement of vehicle aerodynamics and others.

Considering safety, security and comfort aspects, the most common systems developed to automate and enhance safety and driving conditions on vehicles are called *Advanced Driver Assistance Systems* (ADAS). For instance, in order to avoid collisions and accidents or to attenuate their effects, modern technologies are devoted to alert the driver about potential problems or to take over control of the vehicle. Other features are adaptive light control, adaptive cruise control, automatic parking, collision avoidance, intelligent speed adaptation, platooning systems, cooperative merging, and so on. These ADAS are either built into cars or available as add-on packages or aftermarket solutions. All these systems are based on multiple data sources, including automotive imaging, radar, image processing, computer vision, and in-car networking. These systems aiming at assisting, improving and easing the driving tasks are often called also *Vehicle Automation and Communication Systems* (VACS). The interested reader can find a very broad classification of VACS in [22], with specific attention to the freeway traffic management perspective.

In the most advanced solutions, additional inputs can come from sources which are external from the vehicle, such as other vehicles or the infrastructure, known respectively as *Vehicle-to-Vehicle* (V2V) or *Vehicle-to-Infrastructure* (V2I) systems. Vehicles equipped with V2V technology can wirelessly broadcast information and receive messages from other vehicles in the proximity, for instance about their position and speed. The communication among vehicles and with the infrastructure raises important issues about the cooperation among drivers, in order to follow objectives that can refer to a system perspective more that an individual logic. These next-generation vehicles including a high level of wireless connectivity and automated driving capability are sometimes known as *Connected and Automated Vehicles* (CAV).

A final issue that has become more and more relevant in the last years for ADAS is related to vehicle *cybersecurity*. Analogously to computers, modern vehicles must be protected from hacking, malicious cyber-attacks, and any other unauthorised access to retrieve driver data or to manipulate vehicle functionality. Vulnerabilities may exist for example within the wireless communication functions of a vehicle, within a mobile device connected to the vehicle via USB, Bluetooth, or Wi-Fi, or within a third-party device connected through a vehicle diagnostic port, so that a hacker could remotely exploit these vulnerabilities and gain access to the controller or to possible data stored in the vehicle.

1.3.3 Application of ICT

Even though infrastructure interventions and technological advances on vehicles can allow to improve the performance of road traffic systems, they cannot provide a complete solution to traffic problems. In particular, the delay in the adoption of appropriate infrastructures can be the result of many factors such as the high investment costs, the excessive duration of design and construction phases, the environmental incompatibility and the lack of space. At the same time, technological solutions on vehicles, such as VACS, can ameliorate comfort and traffic conditions for drivers, but the maximum exploitation of such technologies can be obtained by introducing management and control tools, which act according to a system perspective.

Indeed, the effective utilisation and exploitation of the road infrastructure is possible only if suitable management systems exploiting ICT are applied. The ICT-based applications are a valid opportunity to enhance the system efficiency at operational, economical and environmental level, by exploiting the present infrastructure and the available technologies in order to improve the performance of the whole traffic system.

The advanced applications which aim to provide innovative services for transport and traffic management, by enabling the users to be better informed, safer and more coordinated, are often known with the name of *Intelligent Transportation Systems* (ITS). The main applications of ITS are related to public and private transport management through optimisation and control tools, information to travellers, improvement and control of vehicle safety, emergency management, promotion of environmentally efficient use of the road network. The development of ITS represents a real opportunity to effectively address the forecasted growth in traffic demand and the inability to meet the mobility needs only through infrastructure investments. Thanks to these applications, road users can benefit from the information and directions provided by such systems and, meanwhile, the managers of road service and local authorities can take advantage of the increased capabilities of collecting, monitoring, and disseminating data.

ITS tools for managing and controlling freeway traffic systems (see Sect. 1.4) are first of all devoted to the reduction of traffic congestion. Recurrent congestion may be managed by smoothing peak demands through techniques such as ramp metering, mainstream traffic control, driver information and guidance systems that inform motorists about congestion situations ahead or about alternative routes. The management of non-recurring congestion is more difficult, because of its unpredictable nature; however, the control techniques adopted to manage recurrent congestion may also be beneficial in reducing the effects of non-recurrent congestion.

More sophisticated ITS applications encourage the use of the road network in an environmentally sustainable way. This can be achieved by adopting appropriate tools to regulate the traffic flow and, at the same time, to obtain a lower level of fuel consumption and pollutant emissions. Some strategies are based on the communication of the optimal speed to minimise the energy effort, the indication of alternative paths which are more efficient from the energetic point of view, the introduction of dedicated lanes for particular categories of traffic (heavy vehicles, public transport, and so on), or the implementation of strategies such as vehicle platooning to reduce fuel consumption.

1.4 Management and Control of Freeway Traffic

In order to manage, operate, and maintain freeway facilities in an efficient way, surveillance and control methods are often integrated with ICT tools into suitable freeway traffic management programs (Fig. 1.8). These systems are often referred to as *Advanced Traffic Management Systems* (ATMS). ATMS can be classified in different ways but, for the purposes of this book, it seems useful to distinguish them between road-based and vehicle-based traffic control systems.

Road-based traffic control systems are nowadays the most commonly utilised: such systems allow to regulate the traffic flow in a freeway system by controlling all the vehicles together, i.e. by acting at a macroscopic level. These systems for dynamic traffic control intervene in traffic in order to improve the performance of the traffic networks, i.e. to increase safety, to improve traffic flows, to reduce travel times, to make travel times more reliable, or to reduce emissions and noise production [23]. The control measures that are normally employed in freeway networks are *ramp management* (in particular ramp metering, applied with traffic lights at the on-ramps), *mainstream control* (including variable speed limits, lane control, congestion warning, keep-lane instructions, and so on), and *route guidance* (normally displaying specific indications at intersections) [24].

On the other hand, *vehicle-based* traffic control systems are the most modern alternative which will become more and more relevant in the near future, but the real

Fig. 1.8 The radio room located in the Bologna regional freeway management centre, Italy (courtesy of Autostrade per l'Italia SpA, photo from Archivio Videofotografico Autostrade per l'Italia)

application of which still is only at prototype levels. Vehicle-based control systems will shift the macroscopic control to specific control actions imposed to each vehicle. This type of control is based on the development of *Intelligent Vehicles* (IV), which are equipped with sensors to make measurements and try to achieve more efficient vehicle operation, either by assisting the driver or by taking partial or complete control of the vehicle [25].

This section presents the most widely used road-based freeway control actions i.e. ramp management, mainstream control, and route guidance, and an overview of vehicle-based traffic control systems.

1.4.1 Ramp Management

Ramp management can be defined as the application of control devices, such as traffic signals, signs and gates, to regulate the number of vehicles entering or leaving the freeway. Ramp management strategies may be used to control the access at the on-ramps or to regulate the rate of vehicles entering the freeway, but they can also be applied to off-ramps.

The most widespread strategy belonging to this category is *ramp metering* (Fig. 1.9), which has been used in the U.S. since the early 1960s. Ramp metering is realised by placing traffic signals at on-ramps to control the rate at which vehi-

Fig. 1.9 A ramp metering installation in downtown San Diego to State Highway 94, U.S. (courtesy of Michael Ballard)

cles enter the freeway. The ramp metering controller, through suitable algorithms, computes the metering rate to be applied; such metering rate is implemented by appropriately setting the phase lengths of the traffic signals present at the on-ramps. According to the adopted ramp metering policy, it is possible to distinguish different types of ramp metering, e.g. single-lane with one vehicle per green, single-lane with multiple vehicles per green, and dual-lane.

Ramp metering can be implemented with different purposes. A first use is related to regulate the merging process of the on-ramp traffic by breaking the platoons and by spreading the on-ramp traffic demand over time, in order to mitigate shock waves. Another important use of ramp metering strategies is to prevent breakdowns. When traffic density is high, it is possible to prevent traffic breakdowns on the freeway via ramp metering by properly adjusting the metering rate in order to maintain the mainstream density below a critical value. More in general, ramp metering systems can be used to increase the throughput of vehicles, to increase the average speed along the freeways, to reduce the total number of crashes, to reduce vehicle emissions and fuel consumption. Some of the ramp metering benefits, in terms of safety, mobility and productivity, as well as in terms of environmental effects, are reported in [26] for some cities in the U.S., where very high improvements have been revealed.

Besides all these benefits, the application of ramp metering strategies can have some disadvantages. Among them, it can be cited the fact that drivers may use parallel facilities to avoid ramp meters, sometimes corresponding to longer trips. Moreover, ramp metering strategies may result in unfair policies, in which the users of specific on-ramps are highly penalised compared with others, or can lead to the shift of traffic congestion from one location to another. Also, it is highly relevant to consider that the on-ramp queues have a storage upper bound, due to practical space limitations. If the queue storage capacity is low, the potential of ramp metering can be strongly limited.

1.4.2 Mainstream Control

While ramp metering acts on the freeway ramps in order to regulate traffic, it is possible to control traffic conditions also through strategies acting on the mainstream. These strategies have been applied in many European countries, such as in Germany, in the Netherlands, and in the United Kingdom, and in some U.S. states, with the common objective of homogenising the traffic flow in order to reduce congestion phenomena and to fully exploit the freeway capacity.

Fig. 1.10 Variable speed limits at the junction Kleinpolderplein of the A13 and A20 freeways, the Netherlands (courtesy of Rijkswaterstaat, Photo: Essencia Communication/Rob de Voogd)

Such strategies can be of different types, the most common one being the definition of *variable speed limits* to be displayed on Variable Message Signs (VMSs) (Fig. 1.10). A first obvious scope of speed limits is related to the increase of safety, since it is well known that speed reduction leads to improved safety conditions on freeways, and also because it has been shown that speed limits reduce the frequency of lane changes. With this scope, speed limits are applied in potentially dangerous situations, such as upstream the congested areas or during adverse weather conditions. Variable speed limits can also be applied to homogenise the traffic behaviour, i.e. to reduce the speed differences. Another important objective of variable speed limits is the prevention of traffic breakdowns, by avoiding high densities in the mainstream.

Besides variable speed limits, mainstream control includes also other strategies, such as *mainline metering* adopting traffic lights along the mainline in order to reduce breakdown phenomena. In addition, *lane control* can be applied to prevent the use of lanes upstream critical areas, such as accident locations or highly congested on-ramps. Another possibility is to give "keep your lane" indications to the drivers, so that they are not allowed to change lanes, leading to lower disturbances in the freeway traffic flow. The use of *peak lanes* is also common in many cases: the hard shoulder lane of a freeway (which is normally used only by vehicles in emergency) is opened to traffic during peak hours. In this way, the capacity of the road is increased, but safety may be reduced. In some situations, the shoulder lane is opened only to dedicated vehicles, such as public transport, freight transport, or high occupancy vehicles. Another popular strategy is the use of *reversible lanes* (also called tidal flow lanes): a freeway lane can be used in both directions and the current direction is determined dynamically on the basis of the highest traffic demand.

1.4.3 Route Guidance

Another possibility to control freeway traffic is to efficiently distribute the traffic demand over the network, by properly routing traffic flows on alternative paths. A traffic network can include many origins and destinations with multiple paths connecting each origin-destination pair. During peak hours, the travel time on many paths increases and alternative routes (which imply longer times in absence of congestion) may become competitive.

Even though the past experience can be helpful for regular drivers (who are familiar with the traffic conditions in the network) to take routing decisions, daily varying demands, changing environmental conditions, exceptional events and accidents make the traffic conditions very difficult to be predicted and, consequently, the routing decisions very difficult to be taken. This results in situations in which some road links are very congested and, at the same time, other links on alternative paths are rather under-utilised. The use of VMSs to provide en-route information to motorists or to explicitly give them route recommendations can improve the overall network efficiency (Fig. 1.11). The information systems which disseminate to drivers messages

Fig. 1.11 Routing indications in A20 freeway, close to Rotterdam, the Netherlands (courtesy of Rijkswaterstaat, Photo: Essencia Communication/Rob de Voogd)

with information and recommendations to assist them in their route choice decisions are called *Route Guidance and Information Systems* (RGIS).

In many cases, freeway managers prefer to provide real-time information rather than to give explicit route indications. RGIS typically display traffic information such as congestion length, delay on the alternative routes, or travel time to the next common point on the alternative routes. Simply displaying real-time information has the advantage that drivers can make their own routing decisions and do not feel compelled by the controller, but there are many disadvantages. First of all, given the real-time information, it is not easy for drivers to take a routing decision in few seconds, and this decision is much harder for those drivers who are not familiar with the network. Besides, the VMSs have limited space to display the traffic information that must be strongly summarised and can become ineffective in many cases.

1.4.4 Vehicle-Based Traffic Control

In recent years, the fast development of technology in the automotive industry has led to the diffusion of many VACS, as previously introduced in Sect. 1.3.3. These systems are expected to change the features and capabilities of individual vehicles in the next decades, so that a scenario with self-driving vehicles moving in a completely connected road-vehicle infrastructure does not seem completely unrealistic any more. Nevertheless, the most likely scenario for the next future is the one in which freeway systems will be characterised by a *mixed traffic* flow, in which both traditional cars and vehicles provided with VACS of different advancement levels will share the same infrastructure. The mixed-traffic case is not only the most probable framework of the next future but also the most interesting and difficult challenge for researchers and scientists.

At present, many vehicles are equipped with *human-machine interfaces* through which the drivers can receive advice or warnings (e.g. blind spot warning, parking assistance, and so on). There are also *semi-autonomous* systems which can take partial control of vehicle manoeuvres (e.g. avoidance systems which initially warn the driver via seat vibrations and, in case of no reactions by the driver, start to brake). Finally, *fully autonomous* systems can take complete control of vehicle operations (e.g. fully automated adaptive cruise control and anti-lock braking systems).

The vehicles of today and surely those of the future are provided with many sensors, so that they are able to collect lots of data. These types of vehicles are often called *probe vehicles* or *floating cars*, since they are capable to make measurements of the traffic state along their trajectories by adopting suitable technologies, such as Global Positioning System (GPS) devices, radar systems, cameras, and so on.

Hence, the vehicles of the future will easily include sensors and control devices, since they will be able to collect and transmit information, as well as they will easily actuate specific control actions and, consequently, actively interfere with traffic. This will surely change the architecture of traffic management systems, that will require an adaptation of the present traffic management actions and strategies in order to be able to exploit the potential of VACS to further improve traffic conditions in road networks [27].

The possible future impacts of VACS on freeway traffic, as well as the effects of autonomous vehicles provided with high connectivity potentials are analysed in the two recent papers [22, 28], which can provide the reader with an interesting overview of current and future trends for freeway traffic management systems.

References

1. Maibach M, Schreyer C, Sutter D, Van Essen HP, Boon BH, Smokers R, Schroten A, Doll C, Pawlowska B, Bak M (2008) Handbook on estimation of external costs in the transport sector. Report for the European Commission, CE Delft
2. Martino A, Maffii S, Sitran A, Giglio M (2009) The calculation of external costs in the transport sector. Report for the European Parliament's Committee on Transport and Tourism, Brussels
3. Korzhenevych A, Dehnen N, Bröcker J, Holtkamp M, Meier H, Gibson G, Varma A, Cox V (2014) Update of the handbook on external costs on transport. DG MOVE Ricardo-AEA/R/ED57769, Report for the European Commission
4. (2011) White paper: roadmap to a single European transport area - towards a competitive and resource efficient transport system. COM, Brussels
5. Nesbit M, Fergusson M, Colsa A, Ohlendorf J, Hayes C, Paquel K, Schweitzer J-P (2016) Comparative study on the differences between the EU and US legislation on emissions in the automotive sector. European Union

6. Hennessy DA, Wiesenthal DL (1999) Traffic congestion, driver stress and driver aggression. Aggress Behav 25:409–423
7. Lajunen T, Parker D, Summala H (1999) Does traffic congestion increase driver aggression? Trans Res Part F 2:225–236
8. Potts IB, Harwood DW, Hutton JM, Fees CA, Bauer KM, Lucas LM, Kinzel CS, Frazier RJ (2014) Identification and evaluation of the cost-effectiveness of highway design features to reduce nonrecurrent congestion. Transportation Research Board, Washington
9. Potts IB, Harwood DW, Hutton JM, Fees CA, Bauer KM, Lucas LM, Kinzel C, Frazier RJ (2014) Design guide for addressing nonrecurrent congestion. Transportation Research Board, Strategic Highway Research Program 2, Washington
10. Maddison D, Pearce D, Johansson O, Calthrop E, Litman T, Verhoef E (2014) Blueprint 5: true costs of road transport. Routledge
11. Hoek G, Brunekreef B, Goldbohm S, Fischer P, Van Den Brandt PA (2002) Association between mortality and indicators of traffic-related air pollution in the Netherlands: a Cohort study. The Lancet 360:1203–1209
12. IEA (2015) CO_2 emissions from fuel combustion. International Energy Agency, Paris
13. Marchesini P, Weijermars W (2010) The relationship between road safety and congestion on motorways. SWOV Institute for Road Safety Research, Leidschendam
14. Golob TF, Recker WW, Alvarez VM (2004) Freeway safety as a function of traffic flow. Accid Anal Prev 36:933–946
15. Potts IB, Harwood DW, Fees CA, Bauer KM, Kinzel CS (2015) Further development of the safety and congestion relationship for urban freeways. Transportation Research Board, Strategic Highway Research Program 2, Washington
16. The future of sustainable freight transport and logistics. (2010) European Parliament, Brussels
17. Systems sustainable freight transport: opportunities for developing countries. (2015) United Nations, Trade and Development Board, Geneva
18. Noland RB (2001) Relationships between highway capacity and induced vehicle travel. Trans Res Part A 35:47–72
19. Romm J (2006) The car and fuel of the future. Energy Policy 34:2609–2614
20. Chan CC (2007) The state of the art of electric, hybrid, and fuel cell vehicles. Proceedings of the IEEE 95:704–718
21. Ehsani M, Gao Y, Emadi A (2009) Modern electric, hybrid electric, and fuel cell vehicles: fundamentals, theory, and design. CRC Press, Taylor and Francis Group, Boca Raton
22. Diakaki C, Papageorgiou M, Papamichail I, Nikolos I (2015) Overview and analysis of vehicle automation and communication systems from a motorway traffic management perspective. Trans Res Part A 75:147–165
23. Hegyi A, Bellemans T, De Schutter B (2009) Freeway traffic management and control, In: Meyers RA (ed) Encyclopedia of complexity and systems science. Springer, Berlin, pp 3943–3964
24. Papageorgiou M, Diakaki C, Dinopoulou V, Kotsialos A, Wang Y (2003) Review of road traffic control strategies. Proc. IEEE 91:2043–2067
25. Baskar LD, De Schutter B, Hellendoorn J, Papp Z (2011) Traffic control and intelligent vehicle highway systems: a survey. IET Intell Trans Syst 5:38–52
26. Jacobson L, Stribiak J, Nelson L, Sallman D (2006) Ramp management and control handbook. U.S. Department of Transportation, Federal Highway Administration, Washington
27. Papageorgiou M, Diakaki C, Nikolos I, Ntousakis I, Papamichail I, Roncoli C (2015) Freeway traffic management in presence of vehicle automation and communication systems (VACS). In: Meyer G, Beikerin S (eds) Road vehicle automation, vol 2. Springer, Berlin, pp 205–214
28. Mahmassani HS (2016) Autonomous vehicles and connected vehicle systems: flow and operations considerations. Transp Sci 50:1140–1162