

BACHELOR'S THESIS

International Literature Review on Congestion Mitigation Methods

Author:

Rai Edú Córdova Vidal

Mentoring:

M. Eng. Barbara Metzger (TUM)

Dipl.- Math. Lisa Kessler (TUM)

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Everyone who travels by car or truck, even if only rarely, is familiar with traffic jams. The question arises whether congestion could be prevented or solved by particular traffic management or traffic control measures. The focus of this bachelor thesis lies on smaller traffic jams such as jam waves or stop&go traffic. Large and long-lasting traffic jams are often caused by accidents and can therefore hardly be prevented.

The aim of the bachelor thesis is to obtain an overview of the possible avoidance strategies and methods for the mitigation of congestion on freeways, highways, and comparable road categories. This goal is achieved by a systematic literature research. The different methods and strategies against congestion are collected in this thesis and examined and evaluated according to their effectiveness.

The student will present intermediate results to the mentors (M.Eng. Barbara Metzger, Dipl.-Math. Lisa Kessler) in the fifth, tenth and 15th week.

The student must hold a 20-minute presentation with a subsequent discussion at the most two months after the submission of the thesis. The presentation will be considered in the final grade in cases where the thesis itself cannot be clearly evaluated.

Abstract

Every person who travels by car, especially those who live in or nearby dense urban areas, is well familiarized with traffic jams on the highway. With the aim of mitigating traffic congestion, several technologies have been developed over the years to design intelligent transportation systems capable of controlling traffic dynamically or statically. In other words, they are either programmed to adapt to current traffic conditions or have preset working modes saved in their system.

Other solutions to the congestion problem include the opening of part-time shoulders, high-occupancy vehicle lanes, congestion pricing, coordination between adjacent jurisdictions, transportation agencies temporarily taking control of traffic during heavy weather or at accident scenes, among others. Their implementation has resulted to be beneficial for the overall traffic flow by providing reliable travel times as well as by lowering environmental degradation, improving the quality of life of drivers and giving highway users, freight companies and even governments opportunities to save money and reduce unnecessary money expenses.

Keywords: intelligent transportation systems, congestion pricing, highway, part-time shoulder, high-occupancy vehicle lanes.

Kurzfassung

Jedem, der im Auto fährt, vor allem diejenigen, die in oder in der Nähe dicht besiedelten Stadtgebieten wohnen, sind die Staus auf der Autobahn sehr bekannt. Mit dem Ziel, Verkehrstaus zu entlasten, wurden im Laufe der Jahre verschiedene Technologien entwickelt, um intelligente Verkehrssysteme zu konzipieren, die die Fähigkeit haben, den Verkehr dynamisch oder statisch steuern zu können. Das heißt, sie sind entweder so programmiert, um sich an die aktuellen Verkehrsbedingungen anpassen zu können oder haben voreingestellte Arbeitsmodi, die in ihrem System gespeichert wurden.

Weitere Lösungen für das Stauprobblem sind u.a. die temporäre Freigabe von Seitenstreifen, Fahrspuren für stark belegte Fahrzeuge, Staugebühren, Koordination zwischen Behörden und die vorübergehende Übernahme der Verkehrskontrolle bei Unwetter oder Unfällen durch Straßenverkehrsämter. Ihre Umsetzung hat sich als vorteilhaft für den gesamten Verkehrsfluss erwiesen, indem sie kürzere Fahrzeiten bieten. Andere Vorteile sind, dass sie Umweltschäden verringern, die Lebensqualität der Autofahrer verbessern und Autobahnbenutzern, Spediteuren und sogar Regierungen die Möglichkeit bieten, Geld zu sparen, indem sie unnötige Geldausgaben reduzieren.

Schlusswörter: Intelligente Transportsysteme, Staugebühren, Autobahn, Teilzeitschulter, stark besetzte Fahrzeugspuren.

Table of Contents

1. Introduction.....	1
2. Causes of Traffic Congestion	2
2.1 Influencing Events	2
2.1.1 Incidents	2
2.1.2 Work Zones	2
2.1.3 Weather	3
2.2 Demand.....	3
2.2.1 Fluctuations	3
2.2.2 Special Events.....	3
2.3 Physical Highway Features	3
2.3.1 Traffic Control Devices	3
2.3.2 Inadequate Base Capacity.....	4
3. Trends and Strategies for Mitigating Congestion	5
3.1 The Addition of More Physical Transit Capacity.....	5
3.1.1 Creating More Transportation Infrastructure	5
3.1.2 Part-Time Shoulders.....	6
3.2 Managing Highway Capacity More Effectively	9
3.2.1 Incident, Work Zone and Road Weather Management	9
3.2.2 Events Traffic Management	11
3.2.3 Reversible Lanes and Left Turn Restriction	12
3.2.4 Coordinated Timing of Traffic Signals	15
3.2.5 Traffic Signal Timing Optimization	16
3.2.6 Ramp Metering.....	19
3.2.7 Variable Speed Limits.....	20
3.3 Promoting Less-Congesting Travel Practices	21
3.3.1 High-Occupancy Vehicle Lanes.....	21
3.3.2 Congestion Pricing.....	23
3.3.3 Pico y Placa.....	25
4. Conclusion and Final Thoughts	27
List of References.....	29
List of Figures.....	36
List of Tables.....	37
List of Abbreviations	38

Table of Contents

Glossary	39
Appendix A: American Highway System	40
Appendix B: Highway Functional Classification	42

1. Introduction

Society is in constant movement. Hundreds of millions of people travel long distances every day, whether it is for a casual visit to friend, a ride to the airport or to their working places or educational institutions. However, the experience on the way may not be as expected and may be frustrating instead due to a phenomenon we are all familiar with. This is traffic congestion. Almost everyone has been stuck in traffic, moving at less than 10 km/h and sometimes not moving at all on a freeway where there may be a posted speed limit of 130 km/h. Given the growth in number of private vehicles to cover the needs of a non-stopping growing population [1], the limited capacity of roads and the driving behavior of motorists, the traffic congestion problem is getting bigger and more complicated to deal with, especially in and around major cities.

Planners and economic development experts acknowledge that this phenomenon has a direct impact on the environment and the economy because it not only frustrates business growth and attractiveness, but it also lowers the life quality of citizens affected by congestion. This economic impact like the waste in fuel and delays in the delivery of goods can in fact be estimated. In the European Union for example, the total delay costs in 2019 caused by traffic congestion ascend to over 270 billion € [2]. In the United States of America, congestion in 2013 was predicted to cost \$124 billion and by 2030, it was predicted to cost around \$186 billion [3].

For these and many other different reasons, numerous efforts have been made over the last decades to reduce traffic jams in number and size, and in this manner, provide reliable travel times, lower unnecessary extra costs, and minimize time waste for commuters, freight services and businesses in general [4]. Governments, transportation agencies, engineers and communities are all collaborating to promote, fund and execute plans to address traffic congestion in their locations.

This thesis will begin by explaining the various causes for traffic congestion and then focus on the many different strategies, trends, practices and methods to avoid, minimize and mitigate this problem on freeways and highways, where this phenomenon affects the vast majority of people. As many of the research papers compiled in this work are based in the U.S., it is strongly recommended to first understand the American highway system and its functionality hierarchy, which are explained in the appendixes at the end of this paper.

2. Causes of Traffic Congestion

In order to understand how the many different strategies and trends work to reduce traffic congestion, this thesis will briefly how this phenomenon originates.

According to previous research work [5], unreliable travel times due to congestion are produced by one or more of the seven different causes listed below, which are often correlated with one another. Cambridge Systematics, Inc. and the Texas Transportation Institute (2005) categorize these causes in the following three groups: traffic influencing events, demand and physical highway features.

2.1 Influencing Events

2.1.1 Incidents

These specific events affect the usual vehicle flow. At the same time, this source of traffic congestion can be classified into three types. The first one is when a travel lane is blocked directly, either by a car crash, a vehicle breakdown, rubble, or oil spills. These scenarios create physical struggle to the oncoming traffic directly and when they are being cleaned by the entity in charge [5].

The second kind are incidents that can occur on the shoulder, which affects traffic indirectly as drivers slow down to watch the accident scene [5]. The third form are events that could happen off the highway facility such as a close burning building, which can indeed be considered as a traffic incident if they have influence over the flow of vehicles [4].

2.1.2 Work Zones

These entail every construction work being executed on the road. They have a physical impact on the capacity of the highway in the form of lane shifts, diversions and closures of travel lanes or even of the entire road [5]. Fig. 1 shows a perfect example of how work zones look on a freeway and how they create traffic jams.



Fig. 1 [Traffic Congestion in Work Zone] [6]

2.1.3 Weather

Climate conditions influence driver behavior by forcing highway users to travel at lower speeds, for example, due to reduced visibility because of bright sun glare, a wet windshield, smoke or fog. Another common influencing factor is caused by precipitation, which can make the road surface to get icy, wet or snowy [5].

2.2 Demand

2.2.1 Fluctuations

It is the daily variation in traffic demand that cause inconvenient travel times due to the fixed capacity of roadways [5].

2.2.2 Special Events

These include from parades to conventions or sporting events that may occur on a regular basis and at a fixed place but do still saturate the traffic system due to the large number of attendees.

2.3 Physical Highway Features

2.3.1 Traffic Control Devices

Level crossings or poor programmed signals are some examples that constantly disturb the traffic flow, which results in jams and irregular journey times [5].

2.3.2 Inadequate Base Capacity

Base capacity does not affect by itself the trip time reliability. Nevertheless, a highway with low vehicle capacity and high demand produces inconvenient variations in travel time when combined with the other cited causes of congestion. As explained in [5], roads with high base capacity are less susceptible to disruptions than roads with low base capacity.

3. Trends and Strategies for Mitigating Congestion

As a means to address the aforementioned causes of traffic congestion, it is more effective to combine various mitigation methods rather than single strategies, claimed Cambridge Systematics, Inc. and the Texas Transportation Institute (2005) in their report [4]. The same paper also alleges that formation of traffic jams can be prevented by adding more physical capacity to the road, managing it in a more effective manner and by promoting less-congesting travel practices. These main solutions encompass a variety of single strategies that can be implemented in highways and comparable road categories.

3.1 The Addition of More Physical Transit Capacity

3.1.1 Creating More Transportation Infrastructure

This first method is substantially the most traditional response to heavy traffic problems. Nevertheless, these are getting each time more complicated to implement due to the enormous construction costs that it involves and the social opposition from local and national detractors [4].

This solution consists in implementing more freight rail supply, building new roadways, or new lanes for existing roads [4], especially for highways as some of them were planned to be expanded breadthways in the future and therefore, have space reserved to that same purpose on each side.

A remarkable example of this strategy is the Alameda Corridor, a 32-km freight railway opened in 2002 [7] that connects downtown Los Angeles, CA, with the Port of Long Beach and the Port of Los Angeles [8], two of the busiest container terminals in the world [9].

To significantly mitigate the severe congestion on the rail routes and most importantly on the adjacent highways, the National Cooperative Highway Research Program (NCHRP) (2002) claimed that the construction of this project would reduce waiting times at these crossings by 90% and that "over 15,000 hours of vehicle delay [would] be eliminated every day" [10, p. 105].

Furthermore, this project was not only a solution for the traffic jams caused in the area, but it was also an improvement in safety for road users and nearby communities by removing over 200 at-grade rail crossings. This means that emergency vehicles would travel with less stops, and road accidents and toxic spills would be addressed more

effectively. Finally, the environmental impact would be significantly reduced, and the economic development in the region would grow thanks to the Alameda Corridor [10].

As the project also incorporates bridges, tunnels and other grade separated railroad-highway crossings [8], the total cost summed up to 2.4 billion US dollars in 2003 [10], which is currently approx. 4 billion U.S. dollars if adjusted to inflation. This reaffirms the fact that building new transportation infrastructure to address traffic congestion is highly expensive, which is a big disadvantage for developing countries that do not have the budget to execute roadworks of such magnitude.

Furthermore, construction of new roads or lanes are not always the right response against traffic congestion. As explained by the transportation engineer James Brownley (2020), people tend to use public transportation means when congestion levels on roads are high because it gives the impression of arriving earlier to their planned destination. Hence, when new roads are built, this new "roadway capacity encourages more people to drive, thus failing to improve congestion" [11].

3.1.2 Part-Time Shoulders

According to Jenior et al. (2016), this other practice "may be [one of the] most appropriate for cost-effectively reducing delays and improving travel-time reliability for addressing traffic congestion" [12, p. 1]. This strategy consists in temporarily allowing vehicles to use the left or right shoulder of a freeway or highway during certain times of the day, otherwise the shoulder remains prohibited for private transportation. It is important that the road in question meets specific pavement, geometric and visibility requirements before a part-time shoulder policy comes into force. Aside from alleviating recurring peak-hour congestion, the other main purpose of opening a highway shoulder is to avoid the loss of general purpose lane capacity in case the shoulder were adapted to operate as a high-occupancy vehicle (HOV) lane instead. This method became very popular in the U.S., in such a way that already by 2016, there were already part-time shoulders in over 16 states [12].

As seen in fig. 2, an open part-time shoulder is indicated by a variable-message sign and a green arrow above it.



Fig. 2 Interstate 405 northbound shoulder bypass near Bothell, WA [13]

As mentioned in [12], part-time shoulders have two different layout configurations, i.e. a left and a right shoulder option that should not be used simultaneously. There are many different advantages and disadvantages in opening a right or left shoulder to freeway users. For example, on the one hand, left shoulder users will not have to slow down to let a driver exit the freeway through a ramp. On the other hand, right shoulders are generally wider than left shoulders and are therefore easier to adapt to a part-time shoulder. A complete list of these advantages and disadvantages are shown in table 1.

Design Alternatives	Advantages	Disadvantages
Use of left shoulder	<ul style="list-style-type: none"> • Left shoulder not used as much for emergency stops or law enforcement stops. • Least expensive if width is available. • Further from most large vehicles – trucks often restricted from left lane. • No conflicts with ramps (unless left exits/entrances present). 	<ul style="list-style-type: none"> • Usually requires restriping. • Potential sight distance problems with some median treatments. • Less likely to provide a 12 foot shoulder.
Use of right shoulder	<ul style="list-style-type: none"> • Often the easiest to implement because right shoulders are generally wider than left shoulders. • More likely to have large adjacent areas for turnouts 	<ul style="list-style-type: none"> • Right shoulder is preferred area for emergency stops and enforcement. • Conflicts and sight distance challenges at merge and diverge areas of ramps.

Tab. 1 Advantages and disadvantages of left and right part-time shoulder use (adapted from [12])

The report also includes vehicle-use options like implementing the shoulder as a high-occupancy toll lane or like opening the shoulder either to high-occupancy vehicles only, to only public transport, to only slow moving trucks, to all vehicles except trucks or to all vehicle classes [12].

The types of operations explained in the same guide [12] include a dynamic and a static shoulder use. The first alternative consists in allowing traffic on the shoulder only when specific traffic congestion limits are reached. The latter consists in opening the shoulder only at common peak hours. Part-time shoulders can also be differentiated by the posted speed limits. Shoulders can either have the same speed limit as other general-purpose lanes of the highway or lower.

There are some infrastructure requirements to take into consideration before opening shoulder lanes to motorists. For instance, the shoulder should have the legal width to carry traffic, and if not, evaluate if by setting a lower speed limit or excluding trucks from shoulder usage would maintain safety standards. The shoulder is also required to have a highway drainage system with a superelevation rate that is compatible for carrying vehicles and with a pavement thickness adequate for vehicle travel [12].

Moreover, the design specifications of a part-time shoulder determine the size of the benefits that it provides. For example, Jenior et al. (2016) claimed in their report, that the 3.6-meter-wide shoulder of the Interstate 66 could carry the same lane capacity as the adjacent general purpose lanes, whereas the narrower part-time shoulder of the I-93 in Massachusetts carried only about 50% to 67% of the lane capacity of the other general purpose lanes [12].

In conformity with a simulation run by Sisiopiku, Sullivan and Fadel (2009), the opening of the shoulder lane of a 19-kilometer stretch of the Interstate 65 corridor from 5:30 a.m. until 9:30 a.m. brought down the total travel time from 6790 hours to 3963 hours, which translates to a reduction in travel time of 42%. Furthermore, the average speed increased from 48 km/h to 85 km/h. Taking also into consideration the reduction of delay times thanks to the part-time shoulder lane, the total travel time improved from 1.25 min/km to 0.7 min/km [14].

Another study was conducted on the US 2 in Washington. The direction heading east was restriped from a layout of two lanes and four relatively narrow shoulders to a layout of two narrower general-purpose lanes, a narrower left shoulder and a 3-meter wide part-time shoulder. Thanks to this, average speeds on the I-5 northbound that connects to the US 2 have increased from 16 km/h to 60 km/h during the most congested period in the afternoon. Moreover, the part-time shoulder could carry about 1400 vehicles per

hour, whereas the general purpose lanes could carry approx. 2000 vehicles per hour per lane at a speed of around 80 km/h [15].

3.2 Managing Highway Capacity More Effectively

This second category of strategies for alleviating traffic congestion can be notably cost-effective, specially where solutions like building new transportation infrastructure, e.g., adding new lanes or designing new roads, are undesirable, prohibited or unfeasible, not only because of high construction costs, but also because they include costs of operation and maintenance [4].

Cambridge Systematics, Inc. and the Texas Transportation Institute affirm that in the last years, engineers have been adopting strategies for the operational improvement of existing highways, rather than just spending public funds for building new infrastructure [4]. "[I]t is operations strategies that have the most dramatic effect on reliability because they target the sources of unreliable travel directly" [4, ES-12].

Intelligent transportation systems (ITS) monitor highway operations in real-time through a transportation management center. These systems use advanced technologies to recognize issues and regulate traffic flow [4]. ITS include portable sensors and video cameras to collect information about the traffic situation and variable-message signs to broadcast the travel conditions to drivers like current speeds and delay information [16]. The exact operational methods to mitigate traffic congestion are explained in the following subchapters.

3.2.1 Incident, Work Zone and Road Weather Management

Although accidents cannot be forecasted and are almost inevitable, incident scenes can indeed be addressed more efficiently if they are detected and addressed in less time and in a more effective manner with the right equipment [4].

For instance, the Maryland's Coordinated Highways Action Response Team (CHART). Is a program that compiles data with the aid of sensors and closed-circuit television (CCTV) [4], which is then sent to and processed by the so-called Statewide Operations Center [17]. The collected information is then used to execute real-time traffic management operations and broadcast changes and traffic conditions to drivers through telephone advisory systems, radio announcements, changeable-message signs and an

interactive mapping online service [4], [18]. In this way, drivers can view data like current speeds, lane closures, live video and the locations where an accident has been reported [19].

Incidents on highways are handled by the CHART Patrol Division, which according to the Maryland Department of Transportation website, operates over 50 emergency patrol vehicles. The division responds to over 35,000 stranded drivers and more than 30,000 incidents per year. The technicians are in charge of managing traffic control temporarily at incident scenes, relocating disabled vehicles from travel lanes and even performing minor repairs to stranded motorists [20].

A study conducted from 1999 and 2002 by Dr. Chang et al. (2003) shows that CHART has managed to reduce the average incident duration by almost 45% in 1999, from 65 to 33 minutes or in 2002 from 39 to 28 minutes. In addition, the program also saved users around 30 million vehicle-hours and over 19 million liters of gas only in the last year of the study [17].

Management of construction zones and roads under adverse weather conditions work in a similar way. For example, in Washington, D.C., the District of Columbia Department of Transportation implemented an ITS system on an 11-kilometer section of the State Highway 295 (DC-295), a six-lane freeway that carries over 100,000 vehicles per day to properly manage traffic flow near work zones. The system uses traffic sensors, variable-message signs and video cameras to provide motorists information about current delays, speed and alternate routes if certain congestion thresholds are reached. This strategy reported an average reduction of 52% in traffic volume. The same approach was used by the Texas Department of Transportation on the Interstate 35 for a work zone in Hillsboro. A study revealed an average reduction of 10% in traffic volume on the freeway during congested periods [16].

In the case of road weather management, it basically consists in the prediction of climatic conditions such as snow, ice, rain or fog on highways, which makes it possible to prepare or treat the roadway surface beforehand [4]. An example of this congestion mitigation method is the Weather-Responsive Management Strategies (WRMS), an initiative of the Federal Highway Administration (FHWA) in the U.S. It encourages the collection of road weather data from mobile and connected vehicle technologies to efficiently handle traffic flow during adverse weather [21]. Moreover, lane or road closures, the implementation of variable speed limits and dynamic-message signs to keep drivers updated with information about the situation are part of this group of methods [22].

For instance, the fact sheet on a WRMS program indicates that it employs different practices for flood event preparation, response and recovery. As a means to predict and address such natural disasters, transportation agencies utilize a light detection and ranging (LiDAR) map that shows relief features of the land to simulate where water would possibly get dammed on the road and result in an inundation. In that way, the agencies can evaluate where sandbags or water-filled barriers should be deployed to allow the free flow of vehicles [21], [23].

Thanks to this strategy, no maintenance staff is required on the spot to report on the current situation and travel times can be reduced drastically. For example, trip times flood events between the cities of Baton Rouge and New Orleans in the United States during decreased from an average of seven hours to just one hour [21], [23].

3.2.2 Events Traffic Management

As claimed in [24], one reason highway networks get highly congested during special events like concerts or sporting events are that there is a large number of attendees who "consider those [highways] to be the fastest and easiest way to reach their destination" [24, p. 1]. The other explanation is that stadiums and convention centers are often located near freeways and other high-speed routes.

Thus, the events traffic management strategy covers the planning and coordination of traffic control before and during a special event [4], [24]. The best way to mitigate congestion is by redirecting drivers onto alternate underutilized routes and so spreading traffic evenly over the entire network. This can be achieved by closing certain roads and by informing attendees as detailed as possible about these traffic diversions through variable-message signs and pre-event publicity [24].

The Texas A&M Transportation Institute and Mobility Investment Priorities (2014) suggested that transportation agencies should use CCTV to monitor roads and that parking should be managed by local officials. Other common practices involve manual traffic controls to adapt plans in real-time to current traffic conditions and the retiming of traffic signals, the prohibition of left turns and the implementation of reversible lanes, all to increase overall capacity [24].

Sometimes, transportation agencies do not even have to possess full control of traffic in these situations. Instead, there are companies specialized to do this kind of work. For example, Chevron Traffic Management Limited is a company in charge of managing traffic flow for cricket or rugby matches in the Emerald Headingley stadium in England [25], which has a capacity for nearly 20,500 spectators [26].

Before matches, Chevron begins by placing traffic cones in particular locations to avoid vehicles from parking on unauthorized zones and from interrupting the traffic flow for through traffic or for other attendees. Furthermore, two teams of operators control standby points by setting up one-way systems or even closing the road if necessary. They are also in charge of directing traffic around the stadium to secure areas [25].

3.2.3 Reversible Lanes and Left Turn Restriction

In accordance with the academic book written by the National Academies of Sciences, Engineering, and Medicine (2004), the main purpose of lane reversal is to counteract heterogeneous traffic flow. To accomplish this, it is required to reverse the direction of a single or multiple lanes of a highway, so that there are more lanes and a higher transit capacity in the saturated direction [27].

One famous example of this practice is the moveable median barrier installed on the Golden Gate Bridge in San Francisco, which during peak hours is shifted from a 3/3-lane configuration to four lanes southbound and two lanes northbound in the morning and the exact opposite in the evening commute [28]. All this is achieved by a so-called zipper truck which picks up the barriers made of reinforced concrete and moves them laterally by one lane as it travels along the bridge [29] as shown in the fig. 3.



Fig. 3 Zipper Truck Moving the Barrier [30]

The advantages of this specific system is that the 5 km of barriers [29] can be shifted in only about 30 minutes while still preventing head-on collisions of vehicles coming from opposite directions unlike other reversible systems where opposing flows are only separated by traffic cones [28].

This reversal of lanes may sound complicated to assimilate. However, Wolshon and Lambert (2006) claimed in their report that evidence collected over the years demonstrated that users have become familiar to this practice with ease. The paper also alleges that there is proof indicating reversible operations are safe and efficient even on roads where this treatment was not common nor signaled appropriately. This is achieved without further complication under the principle of following the car in front, which contributes to the reduction of collisions with oncoming vehicles [31].

The report mentions that reversible lanes have been showing positive results for the Interstate 95 in Virginia as they perform better on roads with restricted access and higher pass-through traffic volumes. For this same reason, the implementation of reversible lanes is more common on arterials and freeways [31].

DeRose (1966) explains in his study the advantages of reversing lanes and restricting turns on the U.S. Highway 12 (US 12) in Michigan. This 1.9-km stretch of the arterial was first configured as a six 3.05-meter-lane road and was later modified to only have five lanes with a width of 3.66 meters each. The center lane was designated to carry the traffic of the direction with the heaviest traffic flow, i.e., eastbound at rush hours in the morning and westbound at peak hours in the afternoon as well as during the whole night. At these same peak hours, all left turns were prohibited whereas the center lane was only reserved to perform left turns during off-peak hours [32].



Fig. 4 Reversible center-lane signal; green arrow for center-lane usage [32]

As a result of the reversible operation, the lanes heading west could carry 2818 vehicles per hour, which is a growth of ca. 12% over the 2514 vehicles that they could previously carry at the most critical hour. Users could then drive on the highway at an average speed of 36 km/h at peak hours, 7 km/h faster than before. In this way, average travel time was reduced by a maximum of 20% at rush hours [32]. A more detailed overview of the benefits are shown in tab. 2 and tab. 3.

Station	1			3			5		
	Before	After	After 2	Before	After 1	After 2	Before	After 1	After 2
Date	Aug. '63	Oct. '63	Jan. '65	Aug. '63	Oct. '63	Jan. '65	Aug. '63	Oct. '63	Jan. '65
Peak Period Totals	6338	6641	6321	5500	5739	5879	4406	4567	4463
% Increase		4.8	-0.3		4.3	7.2		3.7	1.3
High 2 hr.	4619	4908	4754	4278	4218	4453	3189	3361	3339
% Increase		6.2	2.9		-2.2	3.3		5.4	4.7
High hour	2514	2818	2705	2351	2467	2500	1772	1867	1879
% Increase		12.1	7.6		5.0	6.3		5.4	6.0
High 15 minute	697	764	719	678	692	737	505	509	564
% Increase		9.6	3.2		2.1	8.0		0.8	11.7

Tab. 2 Traffic Volume Comparisons (Peak-Period – Peak Direction, Westbound, 3-6 p.m.) (adapted from [32])

	7 – 9 a.m.				4 – 6 p.m.			
	Eastbound				Westbound			
	Before	No.	After*	Increase or Decrease	Before	No.	After*	Increase or Decrease
Average Travel Time	3'28"	1	2'54"	-16.0%	4'39"	1	4'09"	-11.0 %
		2	2'49"	-18.8%		2	3'45"	-20.0%
Average Speeds	39 km/h	1	47 km/h	+20.0%	29 km/h	1	33 km/h	+12.0%
		2	48 km/h	+23.2%		2	36 km/h	+23.8%

* After study No. 1 ~ Dec. 1963, after study No. 2 ~ Mar. 1964

Tab. 3 Travel Time and Speed Comparisons (adapted from [32])

Although employing reversible lanes has shown to be effective for alleviating traffic congestion, they must be controlled cautiously. It is fundamental to make use of the appropriate traffic control techniques with the purpose of orientating drivers correctly into the entries and exits of these lanes and avoiding confusions in that way. For lanes that do not get reversed regularly, the traffic control systems are generally cheaper, portable and can be reprogrammed with ease [31].

For instance, these systems are more complex for lanes that get reversed in a more frequent basis. They incorporate barriers, entry and exit gates, and changeable-message signs. Traffic control systems also demand to be automated in order to reduce manual labor at all times [31].

As specified by the National Academy of Sciences, Engineering and Medicine (2004), management costs of reversible lanes may include police surveillance to make sure that they are used under the allocated current restrictions, personnel to operate the reversible system and staff to install, maintain or remove traffic control devices like the aforementioned examples [27].

3.2.4 Coordinated Timing of Traffic Signals

This other employed mechanism has a significant impact by avoiding the formation of traffic waves. The competent local authorities handle the operation of their traffic signals. Nevertheless, as the report by Urbanik et al. (2006) [33] explains, transportation agencies put into practice a congestion mitigation method on their jurisdiction without taking into consideration the other one, which can lead to a reverse effect.

Precisely for this reason, the aforementioned report [33] suggests that the solution to this coordination problem is to extend traffic signal administration beyond jurisdiction boundaries. For example, if only transportation agency 1 is in charge of operating the traffic signals on an interchange but the signals approaching this same interchange are controlled by agency 2, a possible solution is that the traffic signals operated by agency 1 are also added into the system of the other transportation agency to create an interconnection between both entities. It is claimed in [33] that this does not necessarily mean that an agency hands over its control. As a matter of fact, this strategy only requires that the other jurisdiction supports the coordination functionality needed instead.

As stated in [33], this cooperation can be achieved by agreeing on the timing parameters of the traffic lights in question such as cycle length, time reference and offset. Setting a formal agreement on the demands of the procedures to deal with the corresponding operation and maintenance of the traffic signals also contribute to the development of cross-jurisdictional traffic control. Finally, both parties would have to make use of the required communications infrastructure to coordinate the operation of traffic signals efficiently.

However, boundaries are not only geo-political divisions; they also exist between arterial and freeway traffic signal controls within the same jurisdiction. In this case, there are some strategies that can be used to coordinate traffic signals in an effective way [33].

The local coordinated strategy consists in programming a close and responsive interaction between a traffic signal controller and a ramp meter controller. The timing of traffic signals should be calibrated based on current rates of the ramp meter controller,

or ramp-metering rates should be calibrated according to current timing of the traffic signal controller, depending on which one is more critical at the moment [33].

Second, the report [33] also describes the areawide integrated strategy, which frequently modifies the metering rates based on short-term changes in traffic condition of the roadway and not just the local traffic flow at the interchange.

Finally, the congestion strategy comes into force when traffic demand is higher than the actual capacity in a section of the highway. This strategy focuses specifically on mitigating the spread of traffic waves rather the demand itself. The aim is to reduce the negative impact that traffic jam causes on the overall system performance by having control on the position of vehicles queues.

The report by Hatcher et al. (2014) presents the benefits of coordinated signal operations across neighboring transportation agencies in the U.S. It is shown in [34, Fig. 2-3] a travel time reduction of up to 35%, an increase in average speed between 8% and 18%, a decrease in the number of vehicle stops of up to 75% and a delay reduction of a maximum of 93%.

3.2.5 Traffic Signal Timing Optimization

In compliance with Koonce (2008), traffic signals may also come in the form of pre-timed or actuated signals. The latter are a system in which timing intervals are adjusted in response to current vehicle detections. Tab. 4 describes these different classes of traffic signals and their benefits in the alleviation of traffic congestion.

	Pre-timed		Actuated		
	Isolated	Coordinated	Semi-Actuated	Fully Actuated	Coordinated
Type of Operation	Isolated	Coordinated	Semi-Actuated	Fully Actuated	Coordinated
Fixed Cycle Length	Yes	Yes	No	No	No
Conditions Where Applicable	Where detection is not available	Where traffic is consistent, closely spaced intersections, and where cross street is consistent	Where defaulting to one movement is desirable, major road is posted <40 mph and crossroad carries light traffic demand	Where detection is provided on all approaches, isolated locations where posted speed is >40 mph	Arterial where traffic is heavy and adjacent intersections are nearby
Example Application	Work zones	Central business districts, interchanges	Highway operations	Locations without nearby signals; rural, high speed locations; intersection of two arterials	Suburban arterial
Key Benefit	Temporary application keeps signals operational	Predictable operations, lowest cost of equipment and maintenance	Lower cost for highway maintenance	Responsive to changing traffic patterns, efficient allocation of green time, reduced delay and improved safety	Lower arterial delay, potential reduction in delay for the system, depending on the settings

Tab. 4 Relationship between intersection operation and control type (adapted from [35])

It is worth mentioning that in relation to the fully actuated traffic signals, Day et al. (2008) explained in their study that although the green time that was reduced from the undersaturated phases had a minor impact on the traffic flow quality of an intersection, the green time added to other phases brought in fact more significant advantages [36].

As specified by Gordon (2003) in his synthesis, traffic control systems can be classified in 4 levels [37]:

Level 1 – Time Base Coordination

Intersection controllers implement coordinated signal timing plans in spite of not being linked to the traffic management center. The advantages of this approach are the entailment of a relatively low capital cost and the use as a backup plan in the event that the central computer fails. Nonetheless, by selecting this technique for traffic control, the equipment failure cannot be identified automatically by the traffic management center and timing plans not previously stored in the system require to be manually programmed in situ. Normally this system operates only with up to three weekday timing plans [37].

Level 2 – Interconnected Control

Level 2 resolves the deficiencies of time base coordination by having wired or wireless communication to the network of the corresponding traffic management center. Hence, timing plans can either be selected by an operator or by means of time-of-day selection. Other important features that level 2 systems utilize are, first, the fact that they allow timing plans to be downloaded and stored in the intersection controller, and second, that they do provide intersection and equipment status to the traffic management center in case the central computer fails [37]. Conforming to Gordon (2010), most of these systems use three to five weekday timing plans plus an extra plan for other purposes that could be for holidays, weekends, heavy weather, special events and incident responses [38].

Level 3 – Conventional Traffic-Responsive Control

Apart from the characteristics of interconnected control, this practice can also display and record traffic conditions, which can later be provided for an analysis to implement timing plans fitted for recurrent traffic variations thanks to the higher number of detectors that are installed on the road. Hence, level 3 systems allow traffic operators to supervise traffic conditions and select an adequate timing plan, change the timing of an intersection controller or execute the plan that is best suited for the ongoing situation [37].

Level 4 – Adaptive Control

In compliance with the manual published by Koonce et al. (2008) and the synthesis written by Gordon (2003), adaptive traffic signal control is a method to identify road traffic in a network, and to predict the time and location when and where a portion of the traffic will be by the means of an algorithm. Given these predictions, signal timing parameters can be adjusted simultaneously and autonomously in real-time within the traffic cycle or during each signal phase [35][37].

Gordon (2010) claimed on his report [38] that according to many studies, signal timing is in fact a very effective way to manage traffic for the amount of monetary resources that it requires. The paper also explains that “traffic signals should be reviewed and retimed at intervals of 30 months to 3 years” [38, p. 2] according to current guidance. Additionally, it is also alleged that further research should be made to work design requirements in detail for signal timing management systems because it would bring down the cost for examining current timing plans and it would increase their capacity to determine when timing needs to be reprogrammed.

Koonce et al. (2008) stated that in contrast to other advancements in transportation, it is common that enhanced signal timing requires little or no infrastructure costs at all and provides a very high benefit-to-cost ratio by managing the already existing traffic control system more efficiently and helping with congestion [35].

Furthermore, these authors also mentioned that in accordance with many studies, adaptive signal control increases average performance metrics up to 50% or more in the case of poorly performing systems.

One example of a measure of effectiveness is presented in [39, Tab. 3]. The table shows the results of the implementation of an adaptive signal timing system at 11 intersections of a six-kilometer-long portion of the 10th Street corridor in the American city of Greeley, Colorado. A decrease of 9% on weekdays and 11% on weekends in journey times, 13% on weekdays and 37% on weekends in delays and an 11% increase in the average speed on weekdays and 13% on weekends are reported. Additionally, another important improvement is the reduction in the number of stops along the study area: a change of 37% on weekdays and 52% on weekends.

Other benefits are found in the report [40] written by Greenough and Les Kelman (1998). A bar chart [40, Fig. 3] shows a decrease in travel time between 6% and 11%, a reduction from 10% up to 31% in vehicle stops and between 6% and 27% less in vehicle delay in Metropolitan Toronto, Canada.

3.2.6 Ramp Metering

Conforming to Mizuta et al. (2004), ramp meters are “traffic signals installed on freeway on-ramps to control the frequency at which vehicles enter the flow of traffic on the freeway” [41, p. 2]. The main job of this ramp control system is to disband platoons coming into the mainline. Thus, vehicles form a queue behind the stop bar and are then released onto the mainline at a rate adapted to the current mainline traffic volume and speed [41].

An end-of-queue sensor, or an advanced queue loop like the one shown in fig. 5, detects when the queue of vehicles exceeds the ramp limits and invades part of the adjacent road. If this is the case, the sensor triggers a signal to speed up the metering rate [42]. Otherwise, the ramp meter would create a traffic jam on the adjacent highway instead of reducing traffic congestion on the mainline.

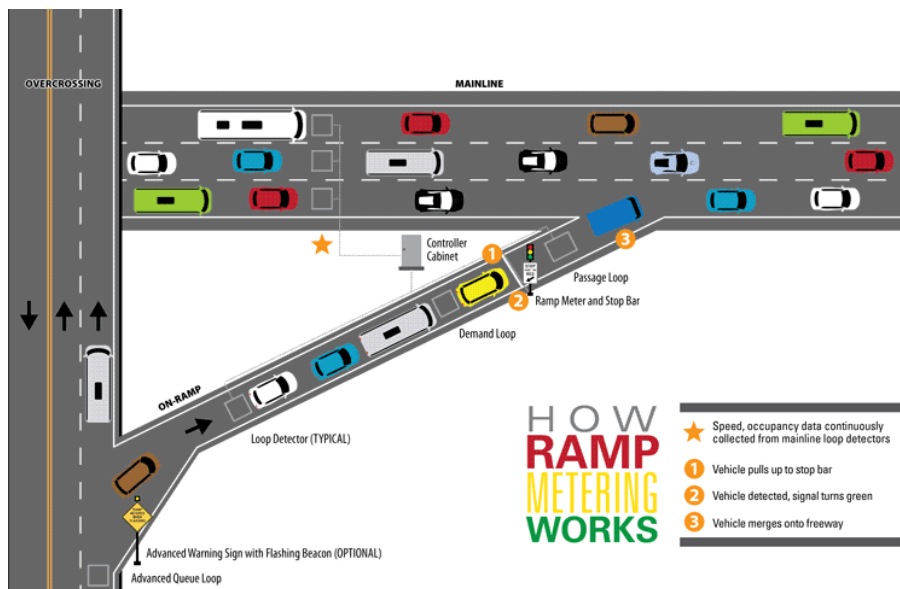


Fig. 5 Ramp metering configuration [41]

The report by Hatcher et al. (2014) explained that metering rates can be adjusted according to the ramp or local arterial traffic, or depending on current traffic conditions on the freeway [34]. By 2008, ramp meters controlled access to ca. 13% of freeway miles in the 78 largest metropolitan areas of the United States [43].

The conference paper written by Diakaki, Papageorgiou and McLean (1999) presents the advantages that the utilization of ramp meters has on motorways, which is the Scottish equivalent for freeways, and urban diversion routes. As seen in [44, Tab. 1], the amount of vehicles per hour that drive across freeways increased by 5% and across urban roads by 13%.

Another example of the benefits of this access control strategy is demonstrated in the study by Hourdakis and Michalopoulos (2000). They conducted a simulation of a 20-km-long section of the Trunk Highway 169 in the U.S. The results presented in [45, Tab. 2] show an increment of 18% in the average speed. The total delay reduced from 1099 to 303 vehicle-hours, which is an improvement of 263%. Moreover, the total number of stops on the mainline decreased from 153,177 to 7,256, which is crucial for the avoidance of stop-and-go traffic. All this translates to an improvement of 21% for the total travel time on the mainline.

3.2.7 Variable Speed Limits

As Mobility Investment Priorities (2014) stated on its report [46], variable speed limits, which are also called dynamic speed limits, are displayed by variable-message signs when critical traffic conditions are present. In this way, the normal speed limit is reduced automatically in increments of 5 mph (8 km/h) or 10 mph (16 km/h) to slow down traffic flow uniformly when sensors installed along the highway detect that congestion levels have reached a determined value. The aim of this technique is to prevent stop-and-go traffic oscillations from forming and thus, maintain a smooth and uninterrupted traffic flow. New speed limits are either mandatory or advisory, depending on the intentions of the transportation agency.

The same paper [46] presents some points that should be taken into account to achieve a successful implementation of this strategy. It is essential that transportation agencies notify highway users about the new speed regulations when they come into force. These type of variations should be justified by communicating the current traffic conditions, otherwise, motorists would not believe in the legitimacy of the changes made to speed limits. Finally, signs showing the new speed limit must be installed on highway gantries over every lane so they can be clearly visible.

The implementation of this system has brought several benefits in different countries around the world. The FHWA International Technology Program (1995) claimed on its report [47], empirical evidence showed improvements in traffic flow on highways in the Netherlands and on German autobahns. These studies showed a reduction from 5% to 15% in total journey time.

3.3 Promoting Less-Congesting Travel Practices

Cambridge Systematics, Inc. and the Texas Transportation Institute (2005) describe this last group of congestion mitigation methods as an approach to put “more people into fewer vehicles” [4, 4-5].

3.3.1 High-Occupancy Vehicle Lanes

There is no doubt that people have developed a strong dependency on the automobile. In compliance with the American Community Survey (2019), over 76% of American workers commute by driving alone in their vehicles, and only about 9% commute by carpooling [48]. That means, there is a large number of automobiles on the roads carrying only one single person, the driver, which occupies the same physical space as a five-person carpool.

Hence, the concept of high-occupancy vehicle (HOV) lanes was created. An HOV lane is a preferential lane on one side of the road that is only restricted to vehicles carrying one or more passengers. Depending on the current traffic circumstances and transportation agencies decisions, other vehicle categories may be allowed to drive in the HOV lanes like motorcycles, buses, emergency vehicles, patrol cars, hybrid and electrical automobiles. This strategy for solving congestion problems on the freeway was first implemented in the early 70s and gained so much popularity, that by 2008, there were already almost 350 HOV lanes in over 30 metropolitan areas in the United States. This trend to address traffic congestion has the purpose of encouraging carpooling and thus, incrementing person throughput on highways. As a result, this system provides reliable travel times for motorists as well as a growth in highway capacity and a reduction of air pollution levels [49].

In conformity with the Urban Transportation Showcase Program (2007), in order to prevent unauthorized vehicles from using HOV facilities, traffic authorities are in charge of supervising them constantly [50]. Currently, HOV lane violations, e.g., in California, are punishable with a 490 USD fine [51], and they may even cost points on the driving record in other states [52].

Nonetheless, HOV lanes do not always perform the way they are expected to. In some cases, these lanes can become oversaturated or underutilized. Operators of these HOV facilities are in charge of implementing the most adequate strategy to properly balance the traffic volumes in these lanes [49].

Some potential policy adjustments to balance traffic flow in a highway with an underutilized HOV lane are suggested in [49, Tab. 4-3]. Possible solutions include allowing

automobiles that did not match previously the criteria for eligibility like motorcycles or low emission vehicles. Another solution is achieved by giving drivers, regardless of how many passengers they may be driving with, the opportunity to acquire the legal right to travel in the HOV lane in change of a monetary charge. In this case, the HOV facility is denominated as a high-occupancy toll (HOT) lane, which is actually a congestion pricing strategy that is explained in the next chapter of this paper.

To solve congestion problems in HOV lanes, plans include the reversion of the aforementioned adjustments in regard to vehicle eligibility requirements as seen in [49, Tab. 4-4] and increasing vehicle occupancy restrictions, i.e., allowing only vehicles with three or more people instead of only one passenger.

Another challenge that HOV facilities face is the fact that they appear to be underperforming. This illusion is something that HOV lanes critics point, although the Urban Transportation Program (2007) claimed that they could be carrying an equal or higher amount than the general-purpose lanes next to them [50].



Fig. 6 An HOV lane in Toronto (on the right): even a successful HOV lane can look underutilized compared to a regular traffic lane [50]

In the U.S., it has been reported that the implementation of HOV lanes achieved a trip time saving of 37 minutes on the State Route 85 (SR 85) in the San Francisco Bay Area, 35 minutes on the Interstate 95 (I-95) in the District of Columbia and 28 minutes on the Interstate 10 (I-10) in Los Angeles among many other examples [49].

A study conducted by Nee, Ishimaru and Hallenbeck (2002) presents several general-purpose and HOV lanes throughput comparison. The most significant takeaways from this report are shown in [53, Fig. 2-39]. The table indicates that the HOV lane in the State Route 520 (SR 520) in Washington moved around 28% of the people in only about 4% of the moving vehicles in the morning peak period and 30% of the people in 13% of the vehicles at the afternoon peak hours.

3.3.2 Congestion Pricing

In conformity with the Federal Highway Administration (2014), this concept takes into account that “trips have different values at different times and places and for different individuals” [54]. The aim of this measure is to manage highway capacity and travel demand [4] by encouraging drivers to take alternative, non-congested roads, to use alternate transportation means or to travel at different hours by charging them a suitable fee during the hours with the highest congestion levels [54], [55]. There are different congestion pricing strategies like collecting tolls for driving in certain highway lanes, on the whole highway or in an entire area, also called zone-based pricing [56].

Thanks to the sponsoring programs of the Federal Highway Administration, congestion pricing projects are getting more attention by transportation agencies in the United States [57]. One key aspect to understand how beneficial this practice is, is that by diverting vehicles away from a congested highway, it ensures a higher vehicle throughput in the same facility without any physical changes. Economists agree that this method is the most feasible and convenient to alleviate traffic congestion. Furthermore, collected revenues could be used to reduce fuel taxes and vehicle registration fees [56].

In compliance with surveys, the congestion pricing strategy has already acquired public acceptance thanks to the reliable trip times it achieves. Charging tolls for the use of roads avoids a collapse of the traffic flow and keeps in that way a high number of vehicles that can travel during rush hours, even at a speed three to four times faster compared to the speed on lanes with no tolls [56].

For example, on the State Route 91 (SR 91) in California, vehicle throughput is twice as much on priced lanes than on free lanes during rush hours [56]. Some months after the opening of the express toll lanes on the SR 91, evidence showed an increase of 40% in the number of vehicles with three or more occupants [58]. As specified by Cambridge Systematics, Inc. and the Texas Transportation Institute (2005), analysis show that toll lanes on the SR 91 carry about 40% of the total traffic volume during rush hours despite only composing one-third of the physical capacity of the six-lane highway [4].

Research data also indicates that while the toll facility is operating on State Route 520 (SR 520) in Seattle, Washington, adjacent highways with lanes free from charge like the Interstate 90 (I-90) and State Route 522 (SR 522) increase in volume according to the FHWA. This suggests that motorists really take the decision to drive on alternate routes to avoid paying tolls. Furthermore, these adjacent roads also increase in volume

when toll rates become higher at peak hours and then decrease in volume when the price goes down [59].

Tolls are collected by an electronic toll collection system. Drivers do not need to slow down and stop by a toll booth. Instead, antennas installed on highway gantries detect “tags”, an electronic device in the form of a thin and small plastic stuck on the inside of the windshield of a vehicle [56], [60]. This tag works exactly as a prepaid card which balance can be topped up by using a debit or credit card or even a bank account [60].

Tag users also have the possibility to link these options to their accounts, so that when their balance reaches a preset low amount, the balance will be topped up automatically [60]. How much do drivers have to pay to use these toll facilities is defined by the current toll rates regulation system, which can be either static or dynamic. This means, toll rates can either vary only by preestablished times of the day or they can change every few minutes to guarantee the full utilization of lanes while avoiding a collapse of the traffic flow [56].

Tags can be purchased for less than 10 dollars in the U.S. and even comes with pre-paid tolls. In case that a motorist does not have enough money on his or her account or does not have a TxTag installed, the toll bill will be sent by mail. However, the price is higher and even includes a \$1.15 fee [60], [61]. For example, rates for highways in the area of Austin, Texas, vary between \$0.67 and \$2.00 if the tag is used, otherwise, tolls go from \$1.01 up to \$4.00 [62]. Some transportation agencies like the Texas Department of Transportation do allow the transit of vehicles that do not have an electronic device installed. Instead of overhead antennas, cameras are used to charge motorists using toll lanes [56].

Zone-based pricing is another congestion pricing strategy. One example of this variation is found in the City of London, which implemented this system in 2003 to solve the traffic congestion problem in the area and to simultaneously enhance transportation with the collected profits. This project has been accepted by the public and is willing to be implemented in other areas of the English capital and in other cities of the U.K. [4]

Congestion Charge, which is the official name for this system in London, entails a charge of £15 each day a motorist drives in the Congestion Charge area. This policy is applied between 7 a.m. and 10 p.m. every day except from Christmas until New Year’s Day [63]. There are some discounts and exemptions to the Congestion Charge. For example, taxis, buses and motorbikes are excluded from paying this fee and residents of the Congestion Charge zone pay only £1.50 instead of the full price of £15 [64]. There is a £160 fine for drivers who do not pay this fee. However, if this penalty

is paid within the first 14 days, this will have a discount of 50% [65]. Fig. 7 shows a map of London where Congestion Charge applies.

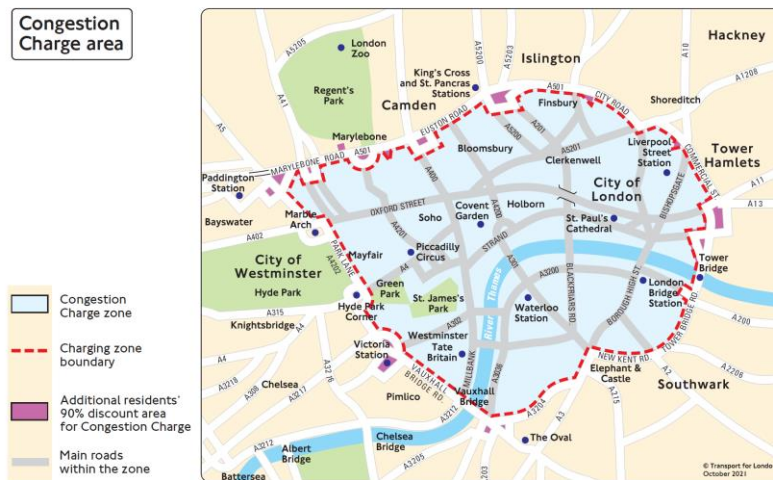


Fig. 7 Congestion Charge area [66]

3.3.3 Pico y Placa

This is a Spanish expression used by some Latin American countries which means peak hour and license plate. “Pico y placa” is a strong traffic restraint policy which consists in restricting the use of a several number of private vehicles by their license plate number on certain freeways or long avenues during a specific time schedule [67].

This practice is especially common and relatively new in major cities of South America like Bogota or São Paulo, where traffic conditions are really heavy due to their large population, their deficient public transportation system and their poor transportation infrastructure [1], [68].

This regulation varies depending on the city in which it is applied. For example, in Lima, a city with a population of almost 11 million, only automobiles with license plate numbers ending in an even number have permission to drive on four important freeways and avenues on Tuesdays and Thursdays, whereas vehicles with license plate numbers ending in an odd number are only allowed to travel on Mondays and Wednesdays. Unlike congestion pricing, motorists affected by the driving restriction do not have the opportunity to pay any transit permission fees to travel on the restricted roads. This four roadways comprehend over 64 km of road. The restriction schedule is split up into two shifts: one in the morning from 6:30 a.m. to 10:00 a.m. and the other one in the afternoon from 5:00 p.m. to 9:00 p.m. [67], which is generally when people commute or go to their educational institution and then return home.

This traffic law encourages drivers to use alternative routes, share a car with neighbors or work colleagues or use public transportation. Surveillance cameras and transit police are in charge of controlling the obedience of this traffic code. In case of failure to comply with this law, the driver is fined the equivalent of 87 U.S. dollars, which is about 37% of the minimum wage in the country. A study was conducted right after the implementation of these penalties, which showed that the average speed of private vehicles increased in about 19% in two of the four affected freeways and avenues [67].

4. Conclusion and Final Thoughts

Drivers have been experiencing traffic jams for more than a century [69] although numerous efforts have been made to improve traffic flow on highways. The well-known phenomenon of traffic congestion is not going to disappear so quickly, at least not in the next decades. Nevertheless, the various methods compiled in this research paper help indeed with mitigating and even temporarily solving this problem. It is also important to identify the direct causes of traffic congestion to ensure that it can be addressed correctly and, in that way, avoid misusing federal fundings.

Improving freeway efficiency and reliability has proved to be a way of addressing traffic congestion at a significantly lower cost, with more public acceptance and can be implemented in less time than building new transportation infrastructures. Strategies like opening part-time shoulders, reversible lanes, ramp meters and HOV lanes have not only helped in reducing congestion levels, but also in reducing fuel consumption, money waste and toxic greenhouse gases bad for humans and the environment. Moreover, these operational improvements can be considered as a strategy to enhance the revenues on the investment made for the construction of a new highway or lane and also as an option to fund other infrastructure projects [4] or improve the quality of public transportation without the need to increase taxes [70].

It is not enough to just implement the aforementioned methods individually to successfully combat congestion. In fact, they perform better if combined [4]. For example, in chapter 3.2.1, various combined strategies are implemented to address this single problem. Installing traffic cameras, providing travelers with enough information about current traffic conditions and temporarily taking manual control of traffic at an accident scene are part of the congestion relief package explained in the chapter.

All in all, if transportation agencies of adjacent jurisdictions coordinated with each other and implemented the measures compiled in this thesis, several and significant improvements in travel time reliability, avoidance of car accidents and overall road users satisfaction can be achieved; and the best way to implement these strategies is on highways, their entries and their exits, where traffic jams harm the highest number of people. Governments need to rethink their plans to mitigate traffic congestion and evaluate if managing road capacity and traffic demand more effectively would solve this problem rather than spending a huge amount of money on expanding highways, which could not even solve the congestion problem as expected [11].

In the big picture, it would be also reasonable to make a precise cost-benefit comparison of each of the aforementioned congestion relief strategies, and thus, evaluate

where they would be more suitable to implement, taking into account different factors such as congestion levels on a specific highway, traffic conditions on the adjacent entries and exits of the highway, wages and technologies available in the country, fuel tax and the willingness of a country or state to invest federal fundings.

For example, installation of a moveable median barrier system in developing countries does not cost the same as in a well industrialized country. The construction of the jersey barriers and operation of the system in a first world country may be much more expensive because of the higher wages. However, a developing country is more likely to not have the necessary industrial capabilities to develop a zipper truck that can shift the barriers. This machine would have to be bought to another country, like the United States, where this technology already exists. This means, there are already extra costs at stake like the import, the taxes paid to the manufacturer country and the payment for the net sale profits to the company that builds such special vehicles.

Furthermore, not every country or state imposes the same tax percentage to fuel, which is normally used to finance every investment made in transportation. The higher the tax fuel is, then the bigger is the amount of money collected that can be invested to implement and operate the many different strategies to address traffic congestion. Moreover, traffic congestion is not the only problem that a country has. It has to deal with several many other issues such as social problems, poverty, health and safety of citizens, etc. That is why not every country is willing to invest in transportation the same way as other countries do. They manage their budgets in different ways and according to their necessities. To summarize, the cost is perceived differently by each country. An investment made to improve the efficiency and reliability of private transport on the freeway may mean for countries with not enough budget to put other important interests aside.

Talking about the benefits, a recurrent high-congested highway does not necessarily mean to be more important than a less congested road. A proper evaluation must be conducted in order to identify which highway is more significant to the economy of the country and to the quality of life of the population. For example, a congested arterial road that guides to an industrial or urban area should be addressed first than a more congested freeway carrying only through traffic or people going to a vacation spot on holidays or weekends. Of course, highways leading to an industrial park plays a more important role in the economy as it carries freight transport with merchandise and cargo that is going to be sold and shipped afterwards. And highways in direction to urban centers are used by commuters and students, which are essential activities for the society.

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List of Figures

Fig. 1	[Traffic Congestion in Work Zone] [6]	3
Fig. 2	Interstate 405 northbound shoulder bypass near Bothell, WA [13]	7
Fig. 3	Zipper Truck Moving the Barrier [30]	12
Fig. 4	Reversible center-lane signal; green arrow for center-lane usage [32]	13
Fig. 5	Ramp metering configuration [41]	19
Fig. 6	An HOV lane in Toronto (on the right): even a successful HOV lane can look underutilized compared to a regular traffic lane [50]	22
Fig. 7	Congestion Charge area [66]	25
Fig. 8	I-610 in Houston, TX, accessible through frontage roads [81]	40
Fig. 9	Washington State Route 9 [84]	41
Fig. 10	Highway Functional Classification System Hierarchy (adapted from [85, Exhibit 2-9])	42

List of Tables

Tab. 1	Advantages and disadvantages of left and right part-time shoulder use (adapted from [12])	7
Tab. 2	Traffic Volume Comparisons (Peak-Period – Peak Direction, Westbound, 3-6 p.m.) (adapted from [32])	14
Tab. 3	Travel Time and Speed Comparisons (adapted from [32])	14
Tab. 4	Relationship between intersection operation and control type (adapted from [35])	16

List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
A&M	Agricultural and Mechanical
CCTV	Closed-circuit television
CHART	Coordinated Highways Action Response Team
FHWA	Federal Highway Administration
HOT	High-occupancy toll
HOV	High-occupancy vehicle
ITS	Intelligent transportation systems
LiDAR	Light detection and ranging
WRMS	Weather-Responsive Management Strategies

Glossary

Actuated signal control	A system in which timing intervals are adjusted in response to current traffic conditions [35]
Carpooling	When two or more people travel together in the same car, especially to work or to their educational institution [71]
Connected vehicle	A vehicle that connects over wireless networks to other nearby vehicles or devices [72]
Heterogeneous flow	When there are significantly more vehicles traveling in one direction than in the other direction
High-occupancy vehicle	A car, van or bus that carries one or more passengers [73]
LiDAR	A laser that measures variable distances used to generate precise, 3D information about the form of the Earth [74]
Offset	Time delay between the green period of a reference signal and the green period of a master reference signal [75]
Ramp meter	A traffic control device installed on highway interchanges which controls the flow of vehicles entering a freeway according to the current traffic conditions [41]
Turnout area	A small area of free space next to the road where a slower vehicle can stop to let others pass [76]

Appendix A: American Highway System

In accordance with the Federal Highway Administration, the word highway is just "a general term for denoting a public way for purposes of vehicular travel [...]" [77, p. 14]. Furthermore, there are four different types of highways or highway systems in the United States.

Interstate Highway System

The Dwight D. Eisenhower National System of Interstate and Defense Highways, better known as Interstate System [78], is a 75,439-km-long network [79] of arterial roads, which "provide the highest level of mobility and the highest speeds over the longest uninterrupted distance" [80, p. 1]. The Interstate System is composed of divided, fully-controlled-access highways which are only accessible through ramps or frontage roads. All intersections with crossroads are grade separated. A frontage road [78] is used for accessing the Interstate from a parallel road at the same height level. Interstates can also be categorized as freeways, because according to the FHWA, a freeway is "a divided highway with full control of access" [77, p. 14]. A divided road means that both travel directions are separated by a median, which could consist of jersey barriers, a green area, or similar approaches.



Fig. 8 I-610 in Houston, TX, accessible through frontage roads [81]

The minimum design speeds for interstates are either 110 km/h for rural, non-mountainous areas or 80 km/h for urban and rural mountainous areas. Moreover, the traffic lanes have a minimum width requirement of 3.6 meters [78].

As all other highways in the U.S., interstates are numbered by the American Association of State Highway and Transportation Officials (AASHTO) [77, p. 142] with one, two or three digits. For example, the longest interstate in the United States is the I-90 [82], which is also referred to as "Interstate 90".

U.S. Highway System

This was the first numbered system of highways in the United States. This system exists since 1926, which is the year when it was first commissioned. Nevertheless, some of these also-called U.S. Routes turned later into proper interstates or got truncated and became irrelevant as interstates were built next to and parallel to them [83].

U.S. highways were also numbered by the AASHTO [77, p. 142] either with one, two or three digits. One example is the famous US 66, also referred to as “U.S. Highway 66” or “U.S. Route 66”, which is in some sections an undivided highway with several at-grade intersections and traffic lights. In other areas, the US 66 can be considered to be an expressway. The FHWA defines this term as "a divided highway with partial control of access" [77, p. 14]. That means, the high-speed road could encounter some at-grade intersections.

State Highway System

As the name suggests, these highways are maintained and numbered by a State itself [77, p. 142]. A same state route denomination can apply for different states. However, that does not mean that it is being referred to the same highway. For example, there is a State Route 9 (SR 9) in California and in Washington. To avoid confusions, these are also called by transportation agencies as CA-9 and WA-9 respectively. Just like U.S. highways, state highways can also be expressways like shown in fig. 9 or have several at-grade intersections when passing through an urban area.



Fig. 9 Washington State Route 9 [84]

County Highway

Very similar to state highways, a county highway is also maintained and numbered by its corresponding jurisdictions, its county. County highways come in multiple forms: from undivided roads with multiple lanes to dirt roads like the W66 north of Cotter, Iowa.

Appendix B: Highway Functional Classification

There is a hierarchy established within the Highway Functional Classification System, which groups arterials, collectors and local roads. There are minor and principal arterials. The latter constitutes the aforementioned interstates, other principal arterials, freeways and expressways [85]. Whereas speed limits on interstates range between 89 km/h and 121 km/h, speed limits in other arterials go normally around 80 km/h and 113 km/h [80]. Moreover, unlike interstates, other principal and minor arterials do not have any inside shoulders, may be undivided, have uncontrolled access and also have a tighter lane and outside shoulder width [86].

Collector roads are also separated in two groups: major and minor collectors. Collectors have posted speed limits commonly between 56 km/h and 86 km/h [80], they do not have inside shoulders, they are undivided, have uncontrolled access and their lane and outside shoulder width are narrower than those of a minor arterial. Finally, there are local roads, which are undivided, non-controlled roads which have a lane width even smaller than collectors, have no inside shoulders and may not have outside shoulders [86]. Speed limits of local roads vary from 32 km/h to 72 km/h.

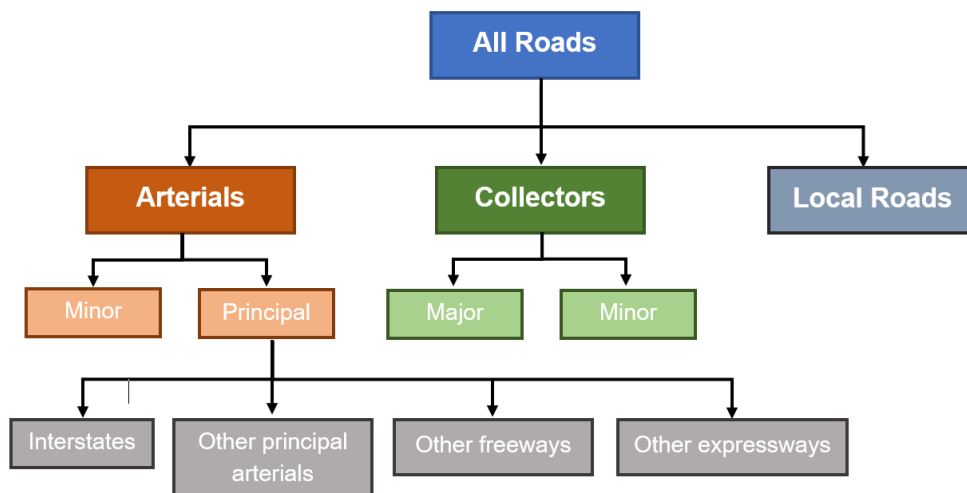


Fig. 10 Highway Functional Classification System Hierarchy (adapted from [85, Exhibit 2-9])

Thus, this hierarchy is a transition from having greatest mobility and less access possibilities in the case of arterials, to having greatest access and less mobility in the case of local roads. Collectors are used as a bridge to connect local roads to arterials.

Declaration concerning the Bachelor's Thesis

I hereby confirm that the presented thesis work has been done independently and using only the sources and resources as are listed. This thesis has not previously been submitted elsewhere for purposes of assessment.

Munich, February 25th, 2022.

Rai Edú Córdova Vidal