The Practitioners’ Guide to Safe Smart Highways

May 2023

Foreword

The Practitioners' Guide to Safe Smart Highways has been produced to fulfil the common interests of the National Road Administration (NRA) members of CEDR. It is the outcome of a collaborative research programme led by a Programme Executive Board made up of members from NRAs in Austria, Belgium (Wallonia), Finland, Germany, Hungary, Ireland, Netherlands, Sweden, and the United Kingdom.

The aim of the programme was to identify, consider, and gain an overview and greater understanding of existing measures to increase the capacity of highways within NRAs, without widening the road or compromising road safety. In this way, NRAs can learn from other NRAs and all NRAs can profit from new insights into the safety effects of these capacity increasing measures. The aim was achieved through the collaborate research project called SAFEPATH, led by AECOM and partnered with Royal HaskoningDHV, Eindhoven University of Technology, and White Willow Consulting.

The Practitioners' Guide is aimed at anyone involved in the planning, designing, or implementation of measures to increase capacity on highways. It should be used as a high-level guide to understand what measures are available and to identify which could be applicable to local circumstances. To reflect the desire of most NRAs, the Practitioners' Guide focuses primarily on helping make the most of the physical infrastructure that is already in place.

If a measure is identified, the practitioner should delve deeper into the literature, which has been carefully curated and stored in the online SAFEPATH database. It should be noted that the Practitioners' Guide is based on available evidence, and there remains a professional obligation for the practitioner to ensure the application of the measure will have the desired impact and that local frameworks are followed.

SAFEPATH used a robust research approach, involving systems analysis and systems engineering to understand the wide range and complexity of factors that influence highway capacity and safety. SAFEPATH also engaged widely with stakeholders and subject matter experts to gather appropriate literature and reports, which can be used to support practitioners in their decision making processes.

The Programme Executive Board hopes you find this Practitioners' Guide useful.

Suzanne Meade
Programme Executive Board Chair

Introduction

Highway capacity is the maximum traffic flow that can be sustained under real-world conditions. This guide considers measures that either increase that maximum traffic flow or achieve those ideal conditions for a greater fraction of the time, without worsening road safety or widening the highway.

Who is the guide for?
This guide can be used by those in the following roles:

- **Strategists and planners**. Creating long term or master plans, identifying needs, defining the infrastructure project pipeline and future investment programmes.
- **Scheme developers**. Completing feasibility studies, supporting procurement decisions, traffic modelling, and business case development.
- **Designers and operators**. Designing schemes or capacity measures.

When should the guide be used?
The guide can be consulted at any stage of the infrastructure life cycle, but is designed for use in decision making, policy development, and during the selection of appropriate measures to increase highway capacity. This guide also aims to highlight the future operational impact of new technologies such as automated and connected vehicles on capacity measures.

Where is the guide applicable?
The guide is aimed at national roads authorities managing highways in Europe (strategic or major roads). However, it includes evidence from highways outside of Europe where comparison is appropriate.

What information is included in the guide?
The guide presents measures to increase highway capacity that are well established or have a good evidence base – that is, have been assessed pre- and post-implementation, and data published.

How was the guide produced?
The research for the guide was collected as part of CEDR project called SAFEPATH. It used a systems engineering approach to define the *what* and *why* of the highway capacity issue and a systems design approach to define the *how*. This was supplemented by sustained engagement with industry, academia, and end-users.

How to use the Practitioners' Guide

The icons in the navigation bar at the top of the page can be used to jump to the desired section. A description of the sections is provided below.

Introduction
This section describes who the guide is for, when it should be used, where it is applicable, what information it contains, and how it was produced.

Options
This section lists evidence-based measures to safely increase highway capacity, without widening the highways. Each measure is briefly described with real-world examples, together with a commentary on its impact on capacity and safety. The measures are grouped in three categories, as options that:

- increase basic capacity
- increase up-time
- increase compliance

Evidence and key resources
This section provides links to external resources that can be used as evidence to support decision making. This includes the SAFEPATH literature database hosted on the CEDR web domain.

Contacts
This section provides a list of contacts of those involved in the production of this guide.

This dashed ring on the navigation bar highlights the section you are currently reading

Capacity measures comparison tables

Click the signpost to see a summary of SAFEPATH capacity measures

SAFEPATH database (online)

Click the signpost to go to the SAFEPATH web database to see all the literature evidence for the capacity measure

What is your objective?

This guide supports the objective of safely increasing highway capacity. It contains measures that are known to achieve this objective.
To help to select the most appropriate measure, it is important to define the desired impact on capacity and safety:

- For capacity, this is whether the measure helps the highway to attain its basic designed capacity for a greater fraction of the time, or whether the measure increases the theoretical basic capacity for the highway.
- For safety, this is whether the measure only maintains the level of road user safety, or whether it also improves road user safety.

The combined impact on capacity and safety can be viewed as the overall measure impact (also summarised in the table below). Measures that are intended to attain the basic design capacity for more of the time with no change to road user safety have a low overall impact, whereas measures that are intended to increase the basic design capacity whilst also improving road user safety have a very high overall impact.

Considering the overall measure impact can help to define the objective: It is inherently more challenging to increase the design capacity of a highway and improve road user safety, than it is to achieve the design capacity of the highway for more of the time whilst maintaining road user safety.

Also consider that the objective to increase capacity on highways is the opposite of the objective many cities now have for urban roads, namely, to *reduce* capacity for road vehicles in favour of greater use of public transport, active travel, or more liveable spaces.

Objective	Capacity impact	Safety impact	Overall measure impact
Safely increase highway capacity	Attain design capacity	Maintain safety	Low
		Increase safety	Medium
	Increase design capacity	Maintain safety	High
		Increase safety	Very high

Calculating the impact on capacity and safety

SAFEPATH used Objective Tree Analysis to identify the criteria used to assess the impact of a measure taken to improve capacity and road user safety. These are described in the table below, and are used throughout this guide to measure the relative and absolute performance of the capacity measures.

Capacity is generally considered to be ***the maximum traffic flow before breakdown occurs***, where traffic flow is measured in passenger car units. However, there are also instances where capacity is temporarily restricted, such as during incidents or road closures. In these cases, highway capacity is often determined by its most constrained point or time.

Objective	Criteria	Units	Definition
Capacity	Congestion severity	Kilometre-hours	The weight of traffic congestion. Congestion severity is calculated by multiplying the length of congestion (in kilometres) with the duration of congestion (in hours). A decrease in congestion severity over time indicates increased or better utilisation of highway capacity.
	Traffic flow	PCUs/hour	The total number of vehicles (or passenger car units, PCUs) that cross a given point or section of a lane or roadway during a given time interval. Highway capacity can be expressed as the maximum possible traffic flow before the point at which smooth flow breaks down.
	Delays	Minutes	Delays are calculated as the time difference between actual travel time and free-flow travel time. The total delay – measured as the cumulative delays over a fixed duration experienced by all the traffic on a road segment and expressed in vehicle-hours – is also an indicator of highway capacity.
	Journey time reliability	Planning Time Index	This is an indicator of quality of service, and is a measure of how travel time varies over time (e.g., hour-to-hour, day-to-day). The Planning Time Index is a standard measure of journey time reliability – it is an indicator of how much total time a road user should take to ensure arrival on time, and is the ratio of the 95th percentile journey time over the free flow travel time. A value of 1.5 means 50% more travel time should be planned.
Safety	Collision likelihood	Collisions / bvkm	This is the probability of being involved in a collision or incident while driving. Collision risk can be influenced by the number of lane changes and speed differences. It is measured by the number of collisions per billion vehicle kilometres travelled.
	Collision severity	EPDO / mvkm	The quantification of health and material damage once a collision has taken place. Collisions can be categorised into multiple levels of seriousness: Fatalities, severe injuries, minor injuries, and material damage. Collision severity is measured using a severity index. It is calculated by multiplying each collision type by a factor representing equivalent property damage, and dividing the total by the vehicle kilometres travelled.

Implementation checklist

Things to consider during the implementation of a measure to increase capacity on highways

Identify

Understand your problem

- ☐ The current level of capacity is known
- ☐ The desired capacity level is known
- ☐ The current level of safety is known

Plan

Chose the most appropriate measure and consult

- ☐ The chosen measure will not reduce road user safety
- ☐ If the measure has not been used in the country before, it has been assessed as feasible
- ☐ If the measure has not been used in the country before, it has been trialled
- ☐ All stakeholders have been identified and engaged
- ☐ The technology readiness level of the measure is high (7 to 9)
- ☐ The risk profile of the road users has not changed significantly
- ☐ Road user acceptability of the measure is known to be good
- ☐ Road user confidence will improve with the measure

Design

Customise the measure

- ☐ The impact of local driving styles has been considered
- ☐ Local driving regulations match those where the measure is known to work
- ☐ The measure has been assessed for changes to road user behaviour
- ☐ The measure will deliver sustainable improvements
- ☐ The impact of the measure on vehicle emissions is understood
- ☐ The impact of the measure on noise pollution is understood
- ☐ The impact of future changes (e.g. automated vehicles) has been considered
- ☐ Other measures to mitigate any negative impacts (e.g. on safety or society) have been identified

Implement

Learn lessons from previous implementations

- ☐ The road authority has relevant technical expertise (or can procure this)
- ☐ The back-office systems of the NRA can integrate the measure
- ☐ The performance of the technology is understood (accuracy, precision, downtime)
- ☐ There is a competitive market for the technology
- ☐ Literature about the measure has been examined for lessons learned

Evaluate

Monitor and evaluate impact and share results

- ☐ Feedback from the implementation of the measure has been shared
- ☐ The authors of this guide have been informed for inclusion in the database

Summary of the options to increase highway capacity

Summary of measures that increase basic capacity

Objectives:

⇧⇧ Effective
⇧ Probably effective
— Minor change
⇩ Probably ineffective
⇩⇩ Ineffective

Future safety:

⇧ **Gain**
⇩ **Loss**
– **No change**

	Objectives		Cost	Future safety		Existing highway characteristics								
Measures with strong evidence:	**Capacity**	**Safety**		**Impact of CAV**	**Impact of C-ITS**	Rural locations	Urban locations	3+ lane carriageways	High traffic volume	Dense interchanges	Additional TMC role	Roadside sensors	Applicable to roadworks	High % of HGVs & buses
Hard shoulder running (ALR)	⇧⇧	⇧	€€€	⇧	⇧	✓		✓	✓		✓	✓		
Hard shoulder running (Dynamic)	⇧⇧	⇧	€€€	⇧	⇧	✓		✓	✓		✓	✓		
Moving road barriers	⇧⇧	⇧	€€	⇧	⇧		✓	✓	✓		✓		✓	✓
Measures with some evidence:														
Tidal flow operation	⇧⇧	**–**	€€	⇧	⇧	✓	✓	✓	✓		✓	✓	✓	
Express lanes	⇧	⇧	€€	—	—		✓	✓	✓	✓				✓
Measures with limited evidence:														
Plustrook (Plus Lane)	⇧	⇧	€€€	—	—		✓	✓	✓	✓				✓
Optimising lane widths	⇧	—	€€	⇧	⇧	✓	✓	✓	✓				✓	✓

Summary of measures that increase up-time

Objectives

- ⇧⇧ Effective
- ⇧ Probably effective
- — Minor change
- ⇩ Probably ineffective
- ⇩⇩ Ineffective

Future safety

- ⇧ **Gain**
- ⇩ **Loss**
- — **No change**

	Objectives		Cost	Future safety		Existing highway characteristics								
Measures with strong evidence:	**Capacity**	**Safety**		**Impact of CAV**	**Impact of C-ITS**	Rural locations	Urban locations	3+ lane carriageways	High traffic volume	Dense interchanges	Additional TMC role	Roadside sensors	Applicable to roadworks	High % of HGVs & buses
Stopped vehicle detection	⇧	⇧⇧	€€€	⇧	⇧	✓	✓	✓	✓	✓	✓	✓	✓	✓
New safety barriers	⇧	⇧⇧	€	⇧	⇧		✓	✓	✓	✓	✓		✓	✓
Recovery vehicles near hotspots	⇧	⇧⇧	€€	⇧	⇧	✓	✓	✓	✓		✓		✓	✓
Queue protection	⇧	⇧	€€	⇧	⇧	✓	✓	✓	✓	✓	✓	✓	✓	✓
Measures with some evidence:														
Incident screens	⇧	⇧	€	—	—		✓	✓	✓	✓			✓	✓
CCTV (continuously monitored)	⇧	⇧	€€	—	⇧		✓		✓		✓	✓	✓	✓
Emergency verge gates	—	⇧⇧	€	—	—		✓		✓			✓	✓	✓
Automatic emergency braking	—	⇧⇧	n/a	—	—	✓	✓	✓	✓	✓				
Vehicle roadworthiness	—	⇧	n/a	—	—	✓	✓	✓	✓	✓				✓
Stricter driver licensing regulations	—	⇧	n/a	—	—	✓	✓	✓	✓	✓			✓	✓

Summary of measures that increase compliance (1 of 2)

Objectives:
⇧⇧ Effective
⇧ Probably effective
– Minor change
⇩ Probably ineffective
⇩⇩ Ineffective

Future safety:
⇧ **Gain**
⇩ **Loss**
– **No change**

	Objectives		Cost	Future safety		Existing highway characteristics								
Measures with strong evidence:	**Capacity**	**Safety**		**Impact of CAV**	**Impact of C-ITS**	Rural locations	Urban locations	3+ lane carriageways	High traffic volume	Dense interchanges	Additional TMC role	Roadside sensors	Applicable to roadworks	High % of HGVs & buses
Mandatory variable speed limits	⇧⇧	⇧	€€€	⇧	⇧	✓	✓	✓	✓		✓	✓	✓	✓
Ramp metering	⇧	⇧	€€	⇧	⇧	✓	✓	✓	✓	✓		✓		✓
Intelligent traffic control system	⇧⇧	⇧	€€	⇧	⇧	✓	✓	✓	✓	✓	✓	✓	✓	✓
No HGV overtaking	⇧⇧	⇧⇧	€€	⇧	⇧	✓	✓	✓	✓	✓	✓	✓	✓	
Tolling and congestion pricing	⇧	⇧⇧	€€	⇧	⇧	✓	✓	✓	✓	✓		✓		✓
Speed enforcement using cameras	⇧	⇧⇧	€	⇧	⇧	✓	✓	✓	✓	✓	✓	✓	✓	✓
Measures with some evidence:														
Lane change restrictions	⇧	⇧	€	⇧	⇧	✓	✓	✓	✓		✓	✓		✓
High occupancy vehicle lanes	–	–	€€	⇧	⇧	✓	✓	✓	✓			✓		✓
High-occupancy toll lane	⇧	–	€€	⇧	⇧		✓	✓	✓			✓		✓
Smart road studs	⇧	–	€€	–	–	✓	✓	✓	✓	✓	✓		✓	✓
Intelligent speed assistance	–	–	n/a	–	–	✓	✓	✓	✓	✓	✓	✓	✓	✓

Summary of measures that increase compliance (2 of 2)

⇧⇧ Effective
⇧ Probably effective
– Minor change
⇩ Probably ineffective
⇩⇩ Ineffective

⇧ **Gain**
⇩ **Loss**
– **No change**

	Objectives		Cost	Future safety		Existing highway characteristics								
Measures with limited evidence:	**Capacity**	**Safety**		**Impact of CAV**	**Impact of C-ITS**	Rural locations	Urban locations	3+ lane carriageways	High traffic volume	Dense interchanges	Additional TMC role	Roadside sensors	Applicable to roadworks	High % of HGVs & buses
Dynamic re-routing	⇧	⇧	€	⇧	⇧	✓	✓	✓	✓	✓	✓	✓	✓	✓
Shockwave suppression	⇧	⇧	€ €	⇧	⇧	✓		✓	✓		✓	✓	✓	✓
Reducing sign clutter	–	⇧	€	–	–	✓	✓	✓	✓	✓			✓	✓
Lane keeping assist	⇧	⇧	n/a	–	⇧		✓		✓		✓	✓	✓	✓
Distracted driving intervention	–	⇧	€	⇧	⇧	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tailgating intervention	–	⇧	€	⇧	⇧			✓	✓		✓	✓	✓	✓
Highways in learner driver training	–	⇧	€ €	⇧	⇧			✓	✓	✓				✓
Public transport lanes	More research required													
Vehicle-sharing applications														
Journey planning														
Lane-hogging intervention														
Allow undertaking														
Automatic vehicle platooning														

How the research is summarised

SAFEPATH has identified many measures to increase highway capacity. Those with strong evidence are presented over the following pages. Each page provides a summary of the measure, examples of its implementation, the main challenges, and the impact it has on highway capacity and safety. If further information is required, the complete literature can be found in the online SAFEPATH database.

To help compare the various measures they have been divided into three categories

Increase basic capacity

Measures that increase the theoretical maximum capacity of a highway. For example, utilising the hard shoulder to create more lane running area.

Increase up-time

Measures that increase the time during which the highway's basic capacity is available. For example, resolving incidents faster to recover capacity.

Increase compliance

Measures to improve road user compliance to achieve the basic capacity. For example, using speed enforcement to reduce flow breakdowns.

There are five types of measure based on the primary focus of any change

Capacity measure type	✓	Infrastructure
	✓	Regulations
	✓	User behaviour
	✓	Incident management
	✓	Vehicle

And the way the measure improves safety is referenced to the safe system

Safe system	✓	Roads
	✓	Speeds
	✓	Vehicles
	✓	People
	✓	Post-incident

The impact the measure has on highway capacity and safety is summarised on a scale from ineffective to effective

➡	🟩 Effective
	🟩 Probably effective
	🟨 Uncertain or ineffective

If you wish to learn more about a measure, the underlying evidence can be found by following the SAFEPATH database signpost

SAFEPATH database (online)

Options to increase highway capacity by increasing basic capacity

Increase basic capacity

Hard shoulder running (all lane running)

About the measure

Hard shoulder running (all lane running, ALR) converts the hard shoulder to a permanent running lane. Hard shoulders are a longstanding safety feature of highways with which the public are familiar.

This measure requires additional roadside infrastructure to monitor traffic (such as radar or CCTV systems) and to close lanes as necessary (for instance, if there is an incident). This additional infrastructure typically provides other information (such as warnings), as well as variable mandatory speeds limits (with enforcement). A major requirement for this measure is the existence of a hard shoulder with sufficient width and construction to use as a permanent running lane. There is good willingness to use amongst truck drivers, but this is low amongst passenger cars.

Countries with evidence of use

Capacity measure type		
	✓	Infrastructure
		Regulations
	✓	User behaviour
		Incident management
		Vehicle

Safe system		
	✓	Roads
	✓	Speeds
		Vehicles
	✓	People
	✓	Post-incident

Key challenges and considerations

- Closing the lane in case of an emergency using variable message signs is challenging as road user compliance can be low.
- Unavailability of the hard shoulder makes emergency rescue operations difficult.
- Legislation or approvals can be time-consuming.
- In case of vehicle breakdown, there are fewer safe spaces to park the vehicle. This, and other factors, may reduce road user perception of safety. This needs to be mitigated, such as by including more emergency refuge areas.
- Driver training and education are required to teach what should be done in case of an incident.
- As demonstrated in the UK, there may be significant public dissatisfaction.

Impact on capacity

Hard shoulder running is one of the most effective measures of increasing road capacity. Capacity rises by an average of 20 to 25% on a 3-lane highway.

It has also been shown to be effective in easing congestion. Morning rush hour congestion has been found to decrease by up to 79% and lost vehicle hours to decrease by up to 73%.

➡ Effective
Probably effective
Uncertain or ineffective

Impact on safety

Hard shoulder running is, with proper design and deployment, probably effective at improving road user safety, due to the resulting reduction in congestion. In the UK slight and serious casualty rates have been found to be slightly higher than highways with hard shoulders, but fatal casualty rates are lower. Hard shoulder running combined with Stopped Vehicle Detection and dynamic message signs improve safety compared to hard shoulder running only.

Effective
➡ Probably effective
Uncertain or ineffective

Increase basic capacity measures comparison table

SAFEPATH database (online)

Increase basic capacity

Hard shoulder running (dynamic)

About the measure

This is a measure similar to ALR, but instead of making the hard shoulder a permanent running lane, it is instead only used as a running lane when required (for instance, to provide temporary additional capacity when the traffic flow is high). The measure requires comprehensive roadside or overhead infrastructure and signage, for example on gantries, to monitor traffic (for instance, such radar or CCTV systems) and inform road users (for instance, using digital matrix signs) of which lanes are available.
As with All Lane Running, there is good willingness to use from truck drivers. However, there is a tendency for all road users not to use the lane when it is open as it is still visibly marked as a hard shoulder.

Countries with evidence of use

Capacity measure type	✓	Infrastructure	Safe system	✓	Roads
		Regulations		✓	Speeds
	✓	User behaviour			Vehicles
		Incident management		✓	People
		Vehicle		✓	Post-incident

Key challenges and considerations

- Closing the lane in case of an emergency using variable message signs is challenging, as road users' compliance can be low.
- Unavailability of the hard shoulder makes emergency rescue operations difficult.
- Emergency areas are still needed.
- Changing legislation and securing approvals can be time-consuming.
- Driver training and education are required to teach what should be done in case of an incident.
- Local standards need to be maintained regarding the characteristics of the hard shoulder to ensure it can be used as desired (for example, lane width minimums), which may require significant construction expenditure.

Impact on capacity

Dynamic hard shoulder running is one of the most effective measures of increasing road capacity when it is needed, i.e. during peak hours. Capacity can rise by an average of 20-25% on a 3-lane highway.
It can also reduce congestion.

➔	Effective
	Probably effective
	Uncertain or ineffective

Impact on safety

Dynamic Hard Shoulder Running is probably effective at improving road user safety. Slight and serious casualty rates are slightly higher than conventional highways with hard shoulders, but fatal casualty rates are lower.
Hard shoulder running combined with Stopped Vehicle Detection and dynamic message signs improve safety compared to hard shoulder running only.

	Effective
➔	Probably effective
	Uncertain or ineffective

Increase basic capacity measures comparison table

SAFEPATH database (online)

Increase basic capacity

Tidal flow operation

About the measure

This measure – also known as a *reversable lane system* – is suitable for roads on which the flow of traffic has a predictable daily rhythm, for example in to a city centre in the morning and away in the afternoon.

The central lane(s) of a highway are configured to operate in different directions depending upon the time of day, affording more lanes for the direction with the greater flow.

Countries with evidence of use

Capacity measure type	✓	Infrastructure
		Regulations
		User behaviour
		Incident management
		Vehicle

Safe system	✓	Roads
		Speeds
		Vehicles
		People
		Post-incident

Key challenges and considerations

- A scheme in Portugal has been implemented – but not yet evaluated in real life.
- Care must be taken in the design of the lead-up to the tidal flow section, with enough lanes to offer access in case of emergency.
- It must be controlled by traffic lights at either end to stop all vehicles to clear flow while the section's direction of flow is being reversed.
- Markings on the reversable section must be distinctive, to alert road users and pedestrians.
- All pedestrian crossings need to be signalised.

Impact on capacity

The system has been simulated using PTV Vissim. The results showed that operation of the reversible lane was, in general, always more favourable for capacity than a central lane of fixed direction, although for some variables the differences were not significant.

➡	Effective
	Probably effective
	Uncertain or ineffective

Impact on safety

In many cases there is no central barrier which is moved across to offer physical separation between contraflowing vehicles.

There are also places where pedestrians cross the road: although this is very rare on major highways, consideration may be required to ensure they know which way to look as they cross the central lane.

As far as is known, no incident figures are available for comparing before and after implementation.

	Effective
	Probably effective
➡	Uncertain or ineffective

Increase basic capacity measures comparison table

SAFEPATH database (online)

Increase basic capacity

Moving road barriers

About the measure

Also known as the *road zipper* or *barrier transfer*, this is a central barrier which can be moved from side to side (thus enabling a tidal flow set-up) by driving a special vehicle along its length, moving a section at a time without the need for any staff to be out of the vehicle. The road can remain open during this process. The road zipper adjusts the moveable barrier to keep at least two lanes of traffic moving in each direction at all times. The zipper vehicle travels following the direction of the carriageway being narrowed.

Countries with evidence of use

Capacity measure type	✓	Infrastructure
		Regulations
		User behaviour
		Incident management
		Vehicle

Safe system	✓	Roads
		Speeds
		Vehicles
		People
		Post-incident

Key challenges and considerations

- Poses potential problems if there are ever difficulties with the equipment.
- Cannot be used in road sections where there is already a physical separation between lanes, for example a central reservation or an island.
- May cause confusion among road users, who will keep having to adjust to different layouts on what, they might feel, should be a familiar route.

Impact on capacity

If ideally timed, the zipper should afford almost the same capacity as an entire extra lane.

- ➡ Effective
- Probably effective
- Uncertain or ineffective

Impact on safety

Moving road barriers are probably effective. The heavy barrier deployed by this system offers greater protection against oncoming traffic than a conventional contraflow system with portable barriers. Incidents, which previously happened on average twice a year, have been reduced to zero on the Golden Gate bridge.

- Effective
- ➡ Probably effective
- Uncertain or ineffective

Increase basic capacity measures comparison table

SAFEPATH database (online)

Increase basic capacity

Express lanes

About the measure

These are lanes that bypass junctions.

Junctions will slow traffic, even if unintentionally, because road users slow down to leave the highway or change lanes to accommodate vehicles coming on.

The goal of an express lane is to ease congestion, improve the flow of traffic, and give road users more travel options.

Countries with evidence of use

🟦 USA

Capacity measure type		
	✓	Infrastructure
		Regulations
		User behaviour
		Incident management
		Vehicle

Safe system		
	✓	Roads
		Speeds
		Vehicles
		People
		Post-incident

Key challenges and considerations

- Many roads in Europe lack long enough stretches between junctions to make this worthwhile.
- The Basket Weave junction (in the Netherlands – the most densely populated country in Europe – has an extensive land-take.

Impact on capacity

Express lanes may improve capacity if implemented at unpopular junctions.

Extended length junctions increase capacity, and lower and regulate speed, resulting in fewer abrupt speed changes.

However, few locations in Europe allow for the long separation between junctions that would give express lanes any significant advantage.

Effective
➡ Probably effective
Uncertain or ineffective

Impact on safety

Express lanes are probably effective at improving safety.

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Effective
➡ Probably effective
Uncertain or ineffective

Increase basic capacity measures comparison table
SAFEPATH database (online)

Options to increase highway capacity by increasing up-time

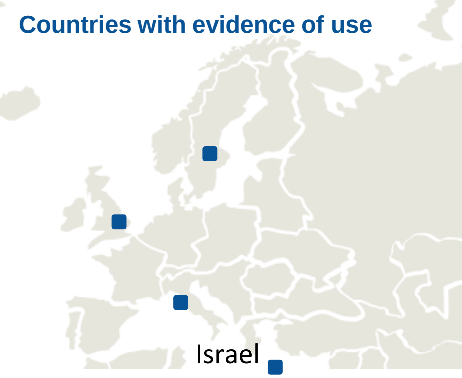
Increase up-time

Stopped vehicle detection

About the measure

Particularly vital in an All Lanes Running (ALR) and Dynamic Hard Shoulder highways where a vehicle may fail to reach the nearest refuge in the event of a breakdown, this measure detects stopped vehicles in the carriageway so that lanes can be closed and warning messages can be displayed upstream for safety. It also enables faster incident response.

A CEDR project – SHADAR – investigated ways of bringing together the various means by which stopped vehicles are presently detected (for example, eCall, social media, drone videos, roadside detection) so as to form an effective, integrated system. Such means may be integrated to check or validate the presence of a stopped vehicle.



Countries with evidence of use

Capacity measure type	✓	Infrastructure
		Regulations
		User behaviour
	✓	Incident management
		Vehicle

Safe system	✓	Roads
	✓	Speeds
		Vehicles
		People
	✓	Post-incident

Key challenges and considerations

- Sensors need to distinguish a single stopped vehicle (as a result of breakdown) from a queue of stationary vehicles (a result of congestion).
- There is no point in having incident detection unless it goes hand-in-hand with the resources to respond (including prompt signage).
- When RADAR is used for detection, more failure rates were predicted. Thus ensure equipment is fit for purpose. Radar-based stopped-vehicle detection equipment appears to come from a very small supply base, this has cost and pace of deployment issues.
- Could encourage road users to use the e-call system to call in alerts if they spot stopped vehicles, but that would constitute road user distraction.

Impact on capacity

This measure improves capacity both by shortening the duration of incidents (by alerting services more promptly), and by avoiding further incident as a stopped vehicle's are at risk of being collided with by oncoming vehicles.

Effective
➡ Probably effective
Uncertain or ineffective

Impact on safety

SVD is vital in the absence of a hard shoulder, both for incident reduction and for pubic confidence.

Drivers stopped in the designated emergency areas are safer than if they were stopped on a conventional hard shoulder – the difficulty lies in getting the vehicle to the next space when already broken down.

➡ Effective
Probably effective
Uncertain or ineffective

Up-time measures comparison table

SAFEPATH database (online)

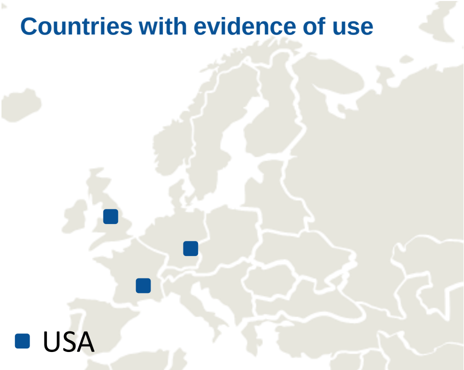
Increase up-time

New safety barriers

About the measure

Specialist safety barriers have been designed for a variety of purposes: to prevent vehicles proceeding when unauthorised (e.g. into pedestrian precincts), enable vehicles to pass only at designated times, or prevent vehicles in a workplace environment getting involved in serious incidents.

This measure involves the installation or upgrade of barriers to prevent vehicles crossing the centre of the highway into oncoming traffic, or leaving the carriageway, and can improve up-time by reducing the probability and severity of incidents.



Countries with evidence of use

Capacity measure type		
	✓	Infrastructure
		Regulations
		User behaviour
	✓	Incident management
		Vehicle

Safe system		
	✓	Roads
		Speeds
		Vehicles
		People
		Post-incident

Key challenges and considerations

- Costs can be quite high.
- Although unlikely for major highways, safety barriers (guard rails) between urban (30 kph speed limit) roads and footpaths are discouraged now on the grounds that they do not appear to improve safety, while also constraining pedestrian movements, thus discouraging footfall.
- Replacing central reserve barriers is very disruptive to both carriageways. Thus it may be prudent to carry out such works in parallel to other initiatives.

Impact on capacity

Well-designed safety barriers can increase the availability of full highway capacity by reducing both probability and severity of incidents.

Effective
► Probably effective
Uncertain or ineffective

Impact on safety

This measure is effective. Safety barriers improve safety by preventing vehicles from being where they ought not to be.

► Effective
Probably effective
Uncertain or ineffective

Up-time measures comparison table
SAFEPATH database (online)

Increase up-time

Recovery vehicles near hotspots

About the measure

Recovery vehicles can be stationed close to known incident hotspots. This reduces the response time as the vehicles do not need to travel as far.

In a similar way, some road authorities will also deploy patrol vehicles to provide a rapid response to incidents. For instance, in Austria these are called Traffic Managers and in England these are called Traffic Officers. They are given powers to manage the traffic and help coordinate the response from other emergency services.

Countries with evidence of use

Capacity measure type		
		Infrastructure
		Regulations
		User behaviour
	✓	Incident management
		Vehicle

Safe system		
	✓	Roads
		Speeds
		Vehicles
		People
	✓	Post-incident

Key challenges and considerations

- This requires good knowledge of incidents across the whole network.
- Can be viewed as a temporary solution, as the underlying problem (the creation of incidents) is not being addressed.
- It's relatively labour-intensive, as vehicles have to be staffed at all times.

Impact on capacity

The effect of a faster response is to reduce the duration of the congestion caused by the incident. So it increases the capacity as blocked lanes can be opened faster due to the faster arrival of recovery and emergency services.

Effective
➡ Probably effective
Uncertain or ineffective

Impact on safety

Faster response to incidents is effective at improving road user safety. For example, many places lack direct automatic matrix boards to close a lane, which leaves vehicles and their occupants exposed in traffic. In addition, road users make unpredictable manoeuvres around incidents (either due to stress or curiosity), which negatively affects road safety. Finally, response time may be critical to injury outcomes, for example in the event of fire.

➡ Effective
Probably effective
Uncertain or ineffective

Up-time measures comparison table
SAFEPATH database (online)

Increase up-time

Queue protection

About the measure

A detection system is used to protect the rear of queues of stationary or slow-moving traffic from secondary collisions. Traditionally, this system has been based on in-road detection induction loops, but it now increasingly uses roadside or gantry-mounted radar-based vehicle detection systems.
Warning messages are displayed to vehicles upstream. Implementing speed limit restrictions is also possible if the accompanying infrastructure is in place.

Key challenges and considerations

- Induction loops or radar sensors need maintenance.
- Loops can be inadvertently damaged by other roadworks**.**
- Radar is not always reliable, for example in wet weather.
- Additional infrastructure is required to relay messages to road users (such as message signs).

Countries with evidence of use

Impact on capacity

Queue protection may improve capacity by evening out variations in speed.

Effective
➡ Probably effective
Uncertain or ineffective

Impact on safety

The impact on safety is positive – it reduces rear-end collisions in vehicle queues.

➡ Effective
Probably effective
Uncertain or ineffective

Capacity measure type		
	✓	Infrastructure
		Regulations
		User behaviour
	✓	Incident management
		Vehicle

Safe system		
	✓	Roads
	✓	Speeds
		Vehicles
	✓	People
	✓	Post-incident

Up-time measures comparison table

SAFEPATH database (online)

Increase up-time

Incident screens

About the measure

Incidents are screened from the view of other road users, to reduce distraction. They are deployed by incident response teams.
The basis for their introduction is the reduction in ‘rubbernecking’ – the phenomenon of other road users being distracted by incidents, which can lead to secondary collisions in the nearby traffic, or simply increases the chance of traffic flow breakdown.

Key challenges and considerations

- Screens need to be robust against wind.
- In implementing this measure, it must also be borne in mind that screens are not barriers and will provide no physical protection from fast-moving vehicles.
- Screens must be rapidly available (i.e. stored in the local vicinity), which might explain why in the UK they had so few outings in their first several years.

Countries with evidence of use

Impact on capacity

The effect may be positive, through preventing the slowdown of vehicles which results from road users being tempted – sometimes without themselves realising it – to look at incidents.
This measure will also avoid the danger of road users filming incidents.

	Effective
	Probably effective
➡	Uncertain or ineffective

Impact on safety

The effect is probably positive, through reducing road user distraction. However little definite information is yet available.

	Effective
➡	Probably effective
	Uncertain or ineffective

Capacity measure type		
		Infrastructure
		Regulations
	✓	User behaviour
	✓	Incident management
		Vehicle

Safe system		
		Roads
		Speeds
		Vehicles
	✓	People
	✓	Post-incident

Up-time measures comparison table

SAFEPATH database (online)

Increase up-time

Closed-circuit television (CCTV)

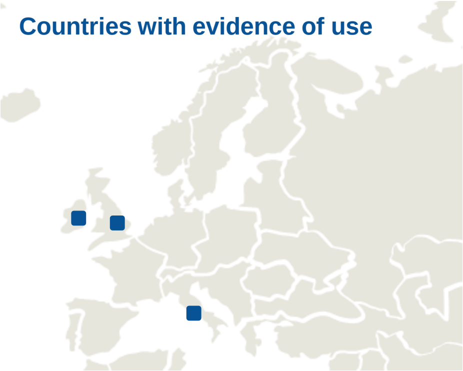
About the measure

This is used for incident detection. CCTV systems are deployed across the network and systematically monitored by control centre operatives.
It is considered an important component of Intelligent Transportation Systems (ITS).

Key challenges and considerations

- CCTV for incident detection presently requires human supervision at all times, which can be costly and resource-intensive. However, AI alternatives are being developed.
- Handling of data such as vehicle registration marks and in-vehicle photographs may have privacy or confidentiality issues, or be unpopular as a result.
- Photographs of car occupants sent with enforcement letters can result in privacy violations as the road user and owner may not be the same individual.

Countries with evidence of use



Impact on capacity

CCTV is probably effective, if used to back up other measures by helping with enforcement.

Effective
➡ Probably effective
Uncertain or ineffective

Impact on safety

CCTV is probably effective at increasing safety, if used to back up other measures by helping with enforcement.
The impact may be negative, if traffic is redirected onto rat-runs where there are more likely to be pedestrians and cycles.

Effective
➡ Probably effective
Uncertain or ineffective

Capacity measure type	✓	Infrastructure
		Regulations
		User behaviour
	✓	Incident management
		Vehicle

Safe system	✓	Roads
		Speeds
		Vehicles
	✓	People
	✓	Post-incident

Up-time measures comparison table
SAFEPATH database (online)

Increase up-time

Emergency verge gates

About the measure

An emergency cut-through barrier or CADO is a removable section of guide rail (or vehicle restraint system) that allows quick access – for example from a parallel road or the opposite carriageway – for emergency services in the event of an incident.

They were developed in the 1970s as the *Calamity Crossing* (CADO) by Jansen Venneboer with RWS Construction Service. They can be controlled both locally and remotely. They typically create a gap between 6 and 9 metres wide.

Key challenges and considerations

- There may still be delays to emergency services, resulting in failure to reach the incident location in time within the set standards.
- The safety of emergency service employees and other road users needs to be assured.
- If the gates are replacing a gap, they may make it harder to transport victims away, or to be able to do so in time.

Countries with evidence of use

Impact on capacity

No study has yet evaluated the impact on capacity. The main benefit is expected to come from an improved response time to incidents, which would restore the full capacity of the highway faster.

	Effective
	Probably effective
➡	Uncertain or ineffective

Impact on safety

By expediting access to emergency incidents, this measure should reduce the possible harm done by a given incident, for example by reaching fires, or critically injured people, in good time.

➡	Effective
	Probably effective
	Uncertain or ineffective

Capacity measure type		
	✓	Infrastructure
		Regulations
		User behaviour
	✓	Incident management
		Vehicle

Safe system		
	✓	Roads
		Speeds
		Vehicles
		People
	✓	Post-incident

Up-time measures comparison table

SAFEPATH database (online)

Increase up-time

Automatic emergency braking (AEB)

About the measure

This measure relates primarily to vehicle technology, but national road authorities are able to influence the uptake through government lobbying.

The system uses sensors to detect obstacles ahead and assess whether a collision is likely. It will usually start by warning the road user, using a dashboard message or an audible alarm, that a collision is likely. If the road user fails to brake, the automated part of the system will enable and apply the brakes automatically.

This system is particularly useful in avoiding rear-end collisions. The on-board system in the following vehicle detects the braking of the leading vehicle and triggers braking in the following vehicle.

Countries with evidence of use

EU regulations now require all new cars to be fitted with AEB.

Capacity measure type		Infrastructure
		Regulations
		User behaviour
		Incident management
	✓	Vehicle

Safe system		Roads
	✓	Speeds
	✓	Vehicles
	✓	People
		Post-incident

Key challenges and considerations

- It may result in road user complacency.
- The system does not always detect bicycles or pedestrians.

Impact on capacity

There is no definitive study on the impact on capacity. However, as with other measures that reduce the number or severity of incidents, this measure is theoretically expected to increase the up-time of highways.

	Effective
	Probably effective
➡	Uncertain or ineffective

Impact on safety

This measure is effective. A 2015 study by The European New Car Assessment Programme (Euro NCAP) and Australasian NCAP found that fitting vehicles with AEB led to a 38% reduction in real-world rear-end crashes.

➡	Effective
	Probably effective
	Uncertain or ineffective

Up-time measures comparison table

SAFEPATH database (online)

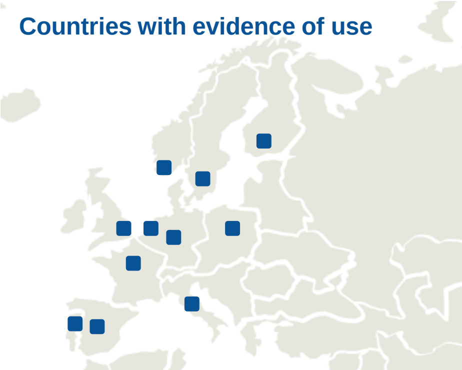
Increase up-time

Vehicle roadworthiness

About the measure

This measure relates primarily to vehicle legislation, but national road authorities are able to influence the uptake through government lobbying.
Manufacturing standards and testing are laid down by law, including crash testing. Tests are mandated for vehicles' basic safety functions.
Media can be employed to encourage prospective vehicle buyers to take safer design into account, and owners to pay attention to vehicle condition.

Countries with evidence of use



Capacity measure type		Infrastructure	Safe system	✓	Roads
	✓	Regulations			Speeds
		User behaviour		✓	Vehicles
		Incident management			People
	✓	Vehicle			Post-incident

Key challenges and considerations

- This is relatively straightforward to implement as tests are discrete events and records can easily be accessed. However, compliance is not 100%.
- As part of its efforts to cushion the cost of living crisis the UK government considered reducing the frequency of MOT testing, to once every two years. The idea did not prove popular with the vehicle industry, motoring organisations, or anyone concerned with road safety.

Impact on capacity

There is no direct impact, but it may increase capacity by reducing the probability and severity of collisions and other incidents.

Effective
Probably effective
▶ Uncertain or ineffective

Impact on safety

The effect will be profound, but possibly unquantifiable as no control case is available.
The expected result is that nearly all collisions involve human error rather than vehicle defects.

Effective
▶ Probably effective
Uncertain or ineffective

Up-time measures comparison table

SAFEPATH database (online)

Increase up-time

Stricter driver licensing regulations

About the measure

This measure relates primarily to driving legislation, but national road authorities are able to influence the uptake through government lobbying.

At present drivers, having passed their test, are not re-tested until they are much older (for example, 70 years old in the UK) or they have been involved in an incident for which a re-test is ordered.

Tests of vision are not compulsory, and many vision defects have gradual onset and can remain un-noticed for long periods.

Countries with evidence of use

Capacity measure type		
		Infrastructure
	✓	Regulations
		User behaviour
		Incident management
		Vehicle

Safe system		
		Roads
		Speeds
		Vehicles
	✓	People
		Post-incident

Key challenges and considerations

- A compulsory scheme would be costly to implement.
- There may be a public backlash: rural dwellers may panic at the possibility of sudden loss of their driving licence.
- The UK government are presently considering the reverse of this proposal, for example, relaxing the conditions for obtaining a goods vehicle licence on the grounds that there is at present a shortage of drivers.
- In the UK the idea of a *graduated driving licence* with restrictions for those under 24 or with under a year of driving experience was abandoned, as many young people needed to be able to drive for employment.

Impact on capacity

There is no direct impact, but it may increase capacity by reducing the probability and severity of collisions and other incidents.

- Effective
- Probably effective
- ▶ Uncertain or ineffective

Impact on safety

Its opposite case (relaxation of regulations) is probably not optimal, although data are not yet available for the effects of the temporary relaxation of conditions introduced as a result of Covid-19 and other circumstances giving rise to a shortage of HGV drivers in the UK.

- Effective
- ▶ Probably effective
- Uncertain or ineffective

Up-time measures comparison table

SAFEPATH database (online)

Options to increase highway capacity by increasing compliance

Increase compliance

Mandatory variable speed limits

About the measure

Variable Speed Limit (VSL) systems are an important highway control strategy. They are used to legally demand road users adjust their speeds to better respond to changing traffic conditions downstream. This is typically in response to lane closures, reduced visibility, slippery road surfaces, and developing queues. Variable speed limits are achieved by using variable message signs (VMS) on roadside or overhead electronic signage to provide the information to road users. Speed limits can be adapted remotely, either automatically by an algorithm or manually by an operator. This makes it possible to show different speed limits at different times.

In the Netherlands, a version of this measure is known as *speed section control*.

Countries with evidence of use

Capacity measure type		
	✓	Infrastructure
		Regulations
	✓	User behaviour
	✓	Incident management
		Vehicle

Safe system		
	✓	Roads
	✓	Speeds
		Vehicles
	✓	People
		Post-incident

Key challenges and considerations

- In Belgium it has been found that the cost of installing the equipment is highly location-specific. This is likely to be the case elsewhere.
- Additional operational costs need to be considered to maintain and supervise the systems.
- Speed enforcement is necessary for the system to be effective.

Impact on capacity

Implementation of VSL in Belgium and the UK has resulted in an increase in highway capacity. Journey time reliability has improved in all time periods since the implementation of the schemes. Average journey times had improved in some time periods. When traffic volumes are high, the impact is reduced.

[✓ Effective]
Probably effective
Uncertain or ineffective

Impact on safety

Mandatory VSL systems are effective at improving road user safety. Collisions resulting in injury have been shown to decrease significantly (-18%), and serious and fatal injuries have decreased by 6%.

[✓ Effective]
Probably effective
Uncertain or ineffective

Compliance measures comparison table

SAFEPATH database (online)

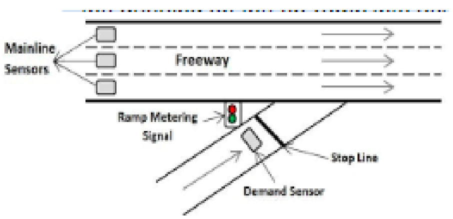
Increase compliance

Ramp Metering

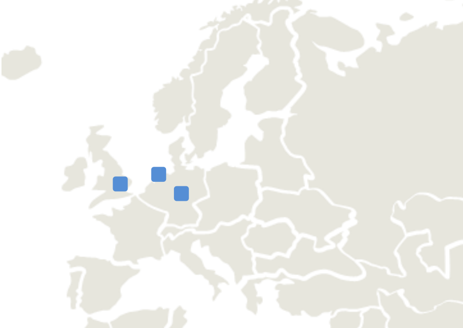
About the measure

Ramp metering is the control of traffic from an on-ramp (or slip road) on to the highway. This is done using traffic signals that allow vehicles to enter the highway one by one or in small platoons. The objective is to improve traffic conditions on the highway, but conditions on the on-ramp and connecting roads in urban areas also need to be considered.

Traffic flow is measured upstream and downstream of the on-ramp, compared to threshold values, and the system is activated or deactivated as necessary. During the green-light phase, only a few vehicles per lane are allowed to enter the highway. The length of the red-light phase varies, dependent on the situation on the highway and the queue on the on-ramp.



Countries with evidence of use



Capacity measure type		
	✓	Infrastructure
		Regulations
		User behaviour
		Incident management
		Vehicle

Safe system		
	✓	Roads
		Speeds
		Vehicles
		People
		Post-incident

Key challenges and considerations

- Ramp metering concentrates pollution at the entrance to the highways so can raise emissions by between 1% and 4% there.
- Issues can arise if the ramp metering traffic signals cause traffic queues on roads managed by different road authorities.
- Road users in the ramp queue become stressed and frustrated if held too long.
- Capacity improvements may be small, which may not be visible to politicians.
- Costs vary significantly depending on context, and from country to country.
- Even though it may delay rather than prevent the onset of congestion by only a few minutes, this can have a notable effect in reducing overall congestion.

Impact on capacity

All reports indicated ramp metering offered an increase in highway capacity, although it is important to note it is not applicable at all junctions.

A large-scale study in the Netherlands indicated a maximum 5% gain in highway capacity (average 2%), fewer (50%) and less severe shockwaves, and 10% fewer vehicle lost hours. A UK study found a 26% reduction in delay through congested junctions.

⇨	Effective
	Probably effective
	Uncertain or ineffective

Impact on safety

Ramp metering is probably effective at improving road user safety. Safety analysis by National Highways in England estimated a 37% reduction in the collision rate.

	Effective
⇨	Probably effective
	Uncertain or ineffective

Compliance measures comparison table

SAFEPATH database (online)

Increase compliance

Intelligent traffic control system

About the measure

An intelligent traffic control system (ITCS) connects traffic light systems directly with vehicles through apps and is able to adjust the green phases to give as little stop time as possible. This allows traffic to flow smoothly at busy times and road users spend less time waiting at red phases watching empty green phases.

Specific traffic flows can be given priority at the request of the road authority, including, for example, to police and emergency services, heavy freight traffic, cyclists, or public transport.

Note that traffic lights are not typically used on major highways, but those used to control traffic at on- and off-ramps can be used to manage capacity.

Countries with evidence of use

Capacity measure type			Safe system		
	✓	Infrastructure		✓	Roads
		Regulations			Speeds
		User behaviour			Vehicles
		Incident management			People
		Vehicle			Post-incident

Key challenges and considerations

- The main effect of ITCS on an NRA network is to lower spill-over on the main highways by improving traffic flow on connecting roads, leading to lower congestion overall.
- The proportion of vehicles that can communicate with the controllers is still low. This is anticipated to improve in the coming years as the technology catches on.

Impact on capacity

In locations where this has been installed, traffic flow improved by an average of 5%, and there was an average capacity improvement of 2%.

➡ Effective
Probably effective
Uncertain or ineffective

Impact on safety

ITCSs are probably effective at improving road user safety. On average there have been 19% fewer collisions, ranging from 15% to 45%, where the systems have been implemented. There are also approximately 35% fewer secondary collisions.

Effective
➡ Probably effective
Uncertain or ineffective

Compliance measures comparison table

SAFEPATH database (online)

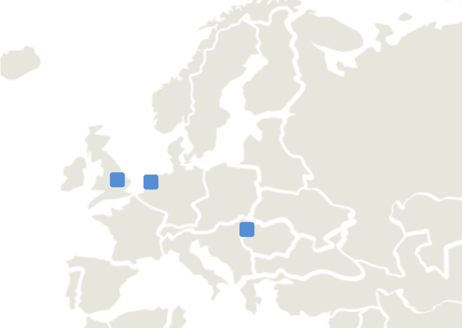
Increase compliance

No HGV overtaking

About the measure

Heavy goods vehicles are forbidden to overtake on highways, sometimes within specified time limits (for example, during peak hours).
The time taken for heavy goods vehicles to overtake other slower vehicles is often quite long and can hold up other vehicles that are able to travel faster. This is because heavy vehicles have lower maximum speeds (either due to mandatory speed limits or vehicle speed limiters). This causes congestion during periods of higher traffic flow.
Restrictions are put in place during peak periods to prohibit HGV overtaking (such as between 7am and 7pm), enforceable by traffic police with on the spot fines.

Countries with evidence of use



Capacity measure type	✓	Infrastructure
	✓	Regulations
	✓	User behaviour
		Incident management
		Vehicle

Safe system	✓	Roads
		Speeds
		Vehicles
		People
		Post-incident

Key challenges and considerations

- Cameras or traffic police patrols are required for enforcement.
- Platoons of HGVs may form in nearside lanes, obscuring signs and junctions for motorists travelling in offside lanes. One scheme in the UK, at a location where junctions were only 1 km apart, has had to be abandoned on these grounds.
- Freight groups typically object on the grounds of the negative impact on their users from increased journey times.
- The measure is most effective on highways with uphill gradients.

Impact on capacity

The capacity effect, measured by a large-scale evaluation in the Netherlands, is location-specific, ranging between -4% to +4%, with an average of +1%.
In Hungary the permanent ban on the nation’s highways has been shown effective in increasing both safety and capacity.
A simulation study showed the most benefit (up to 11% additional traffic flow) on uphill gradients (the simulation used a 2% gradient).

➡ Effective
Probably effective
Uncertain or ineffective

Impact on safety

In addition to the findings in Hungary, large-scale evaluation (in simulation and real-world studies) has detected an increase in safety, which is attributed to a reduction in non-HGV road user frustration

➡ Effective
Probably effective
Uncertain or ineffective

Compliance measures comparison table

SAFEPATH database (online)

Increase compliance

Tolling and congestion pricing

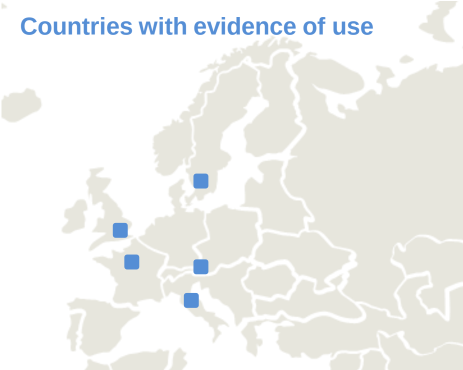
About the measure

This measure involves requiring road users to pay for using particular sections of road (e.g. bridges or highways) or entire areas (e.g. urban areas). Toll routes accessible by paying a fee at a toll booth are very common, such as the Autoroutes in France, and Autostrada in Italy.

Driving on Austria's Autobahn requires purchasing a Vignette, which is displayed in the windscreen.

Many cities are now implementing CAZ (Clean Air Zones) involving tolls commensurate with vehicle pollution, although this does not typically include major highways.

Countries with evidence of use



Capacity measure type		
	✓	Infrastructure
	✓	Regulations
		User behaviour
		Incident management
		Vehicle

Safe system		
	✓	Roads
		Speeds
	✓	Vehicles
	✓	People
		Post-incident

Key challenges and considerations

- Local opposition can be vociferous, in particular as the tolls generally use a flat rate, meaning that they are more burdensome for poorer road users.
- Poorer road users are also least able to avoid the tolls by changing their transport mode (such as purchasing an electric vehicle).
- Small businesses can also object.
- Absolute transparency is needed – in London this led to successful measures to support low-income and disabled Londoners, and small businesses.

Impact on capacity

Tolling and charging effects capacity by encouraging vehicle sharing and smoothing traffic flow. As they are better funded, toll roads can also benefit from improved asset maintenance and incident response.

Effective
➡ Probably effective
Uncertain or ineffective

Impact on safety

Congestion charging has been shown to reduce the number of incidents by reducing the total number of vehicles on the road.

Air quality improvements have been noticeable, leading to fewer hospitalisations for respiratory conditions.

➡ Effective
Probably effective
Uncertain or ineffective

Compliance measures comparison table

SAFEPATH database (online)

Increase compliance

Speed enforcement using cameras

About the measure

Speed enforcement using speed cameras is an effective way of improving road user behaviour. There are two types of speed camera enforcement techniques: spot cameras and average speed cameras.

Speed enforcement improves traffic flow and improves safety through reducing both the probability and severity of collisions, and harmonising speed differences between vehicles.

Key challenges and considerations

- Police enforcement produces only temporary changes in road user behaviour in which reductions in speed are mainly limited to times of deployment, and when road users have passed the enforced area, they may speed up again.
- While road engineering and enforcement can reduce speeds, their measurable effects are limited to those locations on the road network where they operate.

Countries with evidence of use

Impact on capacity

Most evaluation studies have reported an increase in traffic flow after the implementation of this measure, but no detailed figures on highway capacity have been found. The primary cause of improvements in traffic flow is a reduction in the number of incidents which in turn leads to lower congestion.

- Effective
- ➡ Probably effective
- Uncertain or ineffective

Impact on safety

Speed cameras are effective at improving road user safety. The pre/post reduction has been found to range from 8% to 49% for all collisions and 11% to 44% for fatal and serious injury collisions.

- ➡ Effective
- Probably effective
- Uncertain or ineffective

Capacity measure type		
		Infrastructure
	✓	Regulations
	✓	User behaviour
		Incident management
		Vehicle

Safe system		
		Roads
	✓	Speeds
		Vehicles
	✓	People
		Post-incident

Compliance measures comparison table

SAFEPATH database (online)

Increase compliance

Lane change restrictions

About the measure

Frequent lane changes by road users slow overall vehicle flow, as a vehicle changing lanes effectively occupies double the space for a short while. They also result in increased chances of an incident or collision.

Different approaches may be used. Advisory signage may be used during temporary periods of congestion to advise road users to stay in their lane. A mandatory approach may use clear lane boundaries that should not be crossed (such as solid line markings or hashed areas).

Key challenges and considerations

- Road user compliance with such restrictions varies between countries.
- Enforcement of lane change restrictions is uncommon, with offences only being recorded following incidents. New technology using cameras and AI may be explored.
- There may be times when a lane change is necessary to avoid a collision or incident, hence most schemes will take an advisory approach.

Countries with evidence of use

Impact on capacity

This measure may result in a slight increase in capacity if used in congested conditions, as a vehicle while changing lanes (a process which takes several seconds) effectively occupies two spaces simultaneously.

Lane change restrictions are best used temporarily, such as at times of lane restriction due to roadworks.

Effective
➡ Probably effective
Uncertain or ineffective

Impact on safety

Lane change restrictions may result in a general improvement, but there may be individual cases where a lane change is necessary to avoid a collision.

Effective
➡ Probably effective
Uncertain or ineffective

Capacity measure type		Infrastructure
	✓	Regulations
		User behaviour
	✓	Incident management
		Vehicle

Safe system	✓	Roads
		Speeds
		Vehicles
	✓	People
		Post-incident

Compliance measures comparison table
SAFEPATH database (online)

Increase compliance

High-occupancy vehicle lanes

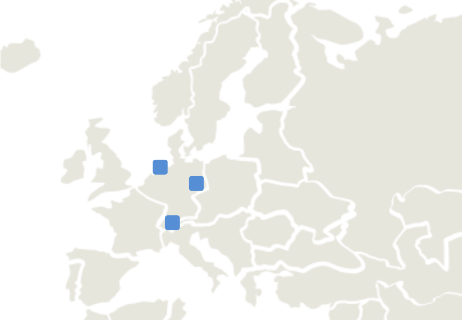
About the measure

High-occupancy vehicle (HOV) lanes are designed to discourage single or low occupancy vehicle use by prioritising vehicles with a minimum number of occupants (usually two or three) and buses.

They encourage car sharing or public transport use by allowing users to reduce their journey times relative to single-occupant vehicles, mainly when the general purpose lanes are congested. The primary objective of HOV lanes is to increase the average vehicle occupancy, and respectively to reduce the number of vehicles and thus reduce road congestion and vehicle emissions.

This measure is common in the United States, and on commuter roads approaching urban areas.

Countries with evidence of use



Capacity measure type		
	✓	Infrastructure
	✓	Regulations
	✓	User behaviour
		Incident management
		Vehicle

Safe system		
	✓	Roads
		Speeds
		Vehicles
	✓	People
		Post-incident

Key challenges and considerations

- It is difficult to monitor whether multiple occupants are in the vehicle. Cameras have been tried, but it is not easy to see in. Cameras have been known to check vehicles in the wrong lane.
- Public acceptance is low because the measure is too complicated, and the benefit is not clear to road users.
- Vehicles stopping and changing lanes can have a negative impact on capacity.
- HOV lanes often do not change traveller behaviour - many HOVs would have been high-occupancy anyway, for example families.
- Drivers in the HOV lane often slow down beside congested lanes as they find it disconcerting to experience high speed differentials.

Impact on capacity

In theory, the HOV lane offers an advantage for occupants of HOVs at no cost to passengers of buses. A study in the Netherlands found driving time for the HOV group decreased. This was sometimes at the expense of other traffic, but more commonly it benefits other traffic. However, with anything but the optimum ratio of HOVs to single-person vehicles, they reduce, rather than increase, road capacity.

	Effective
	Probably effective
➡	Uncertain or ineffective

Impact on safety

HOV lanes are probably effective at improving road user safety. Safety issues are fewer with concrete barrier separated HOV lanes with no intermediate access points, but will be more significant with road marking separation and many intermediate access points. There may be some last-second lane changes when road users find themselves in the HOV lane in error.

	Effective
➡	Probably effective
	Uncertain or ineffective

Compliance measures comparison table

SAFEPATH database (online)

Increase compliance

High-occupancy toll lane

About the measure

High-occupancy toll (HOT) lanes is a measure that creates a tolled highway, with exemptions from the toll for high-occupancy vehicles (and other vehicles with exemption). All other vehicles are required to pay a fee, which may vary in response to demand.

Countries with evidence of use

Capacity measure type		
		Infrastructure
	✓	Regulations
		User behaviour
		Incident management
		Vehicle

Safe system		
	✓	Roads
		Speeds
	✓	Vehicles
	✓	People
		Post-incident

Key challenges and considerations

- The same vehicle can be a HOV or have only the driver at different times – so implementation needs full video surveillance and not just ANPR.
- Surveillance of people inside vehicles is expensive and time-consuming (pictures can be screened by AI but need human verification).
- Not all passengers are visible (children, short people, people in rear seats).
- Inflatable passengers are now available, or people have been known to simply borrow friends.
- In the aftermath of Covid-19, people are preferring to drive alone.
- Liaison with local employers to encourage workplace car-sharing may help.

Impact on capacity

This measure is not always effective – there may simply not be enough HOV traffic to justify it.

	Effective
➡	Probably effective
	Uncertain or ineffective

Impact on safety

There may be some last-second lane changes when road users find themselves in the HOV lane in error.

	Effective
	Probably effective
➡	Uncertain or ineffective

Compliance measures comparison table

SAFEPATH database (online)

Increase compliance

Smart road studs

About the measure

Cat's eyes or road studs are a retroreflective safety device used to provide greater visibility of lane markings by reflecting vehicle headlights in dark conditions. Smart road studs include LED lights which can change colour, for example in phase with traffic lights at a junction.

The devices can be either wired or wireless, and may work in coordination with other nearby roadside infrastructure under the control of an automatic controller unit.

Smart road studs are visible up to 1,000 metres away – far further than conventional road studs. More advanced smart road studs can detect vehicles or measure and transmit road surface temperature.

Countries with evidence of use

Capacity measure type		
	✓	Infrastructure
		Regulations
		User behaviour
	✓	Incident management
		Vehicle

Safe system		
	✓	Roads
	✓	Speeds
		Vehicles
		People
		Post-incident

Key challenges and considerations

- Unlike conventional road studs, these are not a passive device that reflects, but an active light that requires power, so can break down or the cable can be severed by careless future roadworks.

Impact on capacity

Due to their novelty, there is little real-world evidence to show this has a significant impact on capacity. In modelling and theory, these devices should reducing incidents and improve traffic flow by reducing congestion.

	Effective
➡	Probably effective
	Uncertain or ineffective

Impact on safety

The safety effect has not yet been evaluated. In a trial in the UK, young road users have taken it as a challenge to see the smart road studs activate, by driving with their cars' headlights off.

	Effective
	Probably effective
➡	Uncertain or ineffective

Compliance measures comparison table

SAFEPATH database (online)

Increase compliance

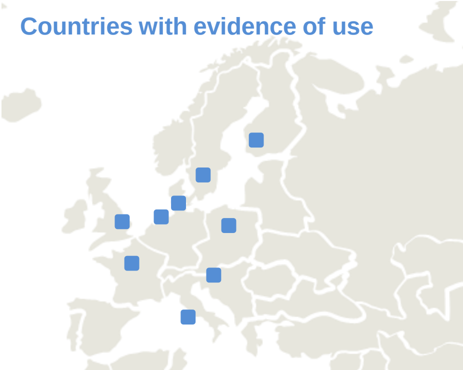
Intelligent speed assistance

About the measure

This measure relates primarily to vehicle technology, but national road authorities are able to influence the uptake through government lobbying.

EU legislation made intelligent speed assistance (ISA) mandatory for all new vehicles starting in 2022, and mandatory for all existing carlines by 2024. The legislation applies to all European cars, vans, trucks and buses.

ISA helps road users to comply with the speed limit. A variety of ISA systems have been developed that can provide information on safe speeds to the road user (advisory/informative ISA), warn the road user when they are exceeding the speed limit (supportive ISA), or control the brakes or throttle to prevent speeding (mandatory/limiting ISA).



Countries with evidence of use

Capacity measure type		
		Infrastructure
		Regulations
		User behaviour
		Incident management
	✓	Vehicle

Safe system		
		Roads
	✓	Speeds
	✓	Vehicles
	✓	People
		Post-incident

Key challenges and considerations

- It may distract the road user, or result in indirect effects such as behavioural adaptation.
- Research outcomes suggest that those who would most benefit from ISA (young, male, and/or inexperienced road users) are least willing to use it.
- However, several studies also indicated that ISA would significantly reduce fuel consumption and emissions.

Impact on capacity

One large scale UK study showed that ISA resulted in an improvement of approximately 4.4% in journey time on national, regional, and local roads but no increase on highways. However, other studies showed that ISA helped improve traffic flow – a counterintuitive result that may be explained either by shorter safe distances between vehicles or by reduction in shockwaves in flow. The impact on capacity is therefore unclear.

Effective
Probably effective
➡ Uncertain or ineffective

Impact on safety

The impact of ISA on road user safety is unknown.

None of the studies on ISA was sufficiently large to provide evidence of safety improvement. Indeed, it is likely that the true effects of ISA will only emerge once a larger percentage of vehicles equipped with ISA are being used.

Effective
Probably effective
➡ Uncertain or ineffective

Compliance measures comparison table
SAFEPATH database (online)

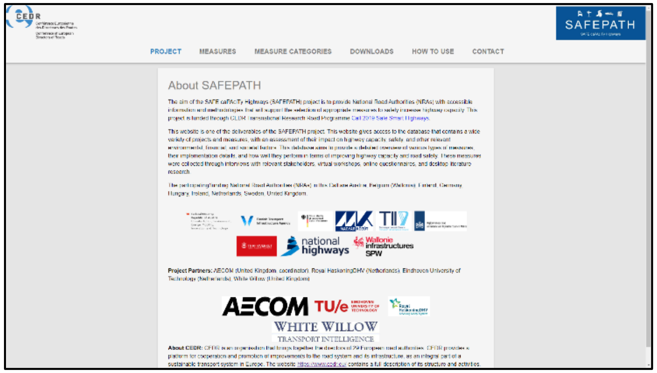
Evidence and key resources

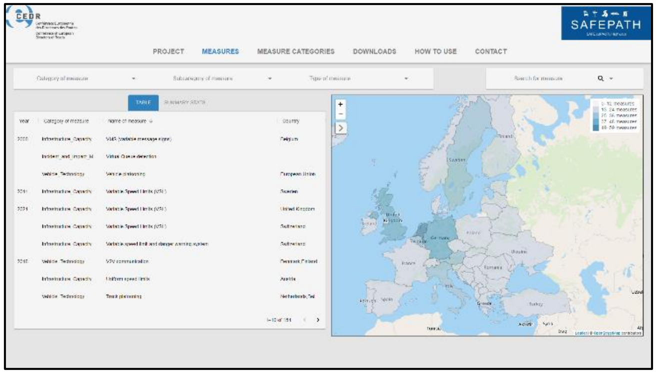
Evidence and key resources

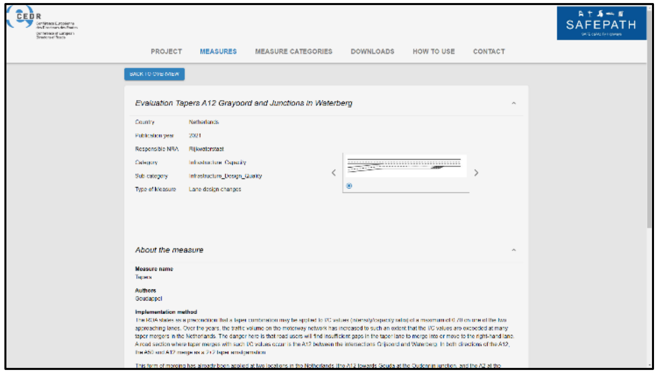
All evidence used for this Guide is stored in the SAFEPATH database and can be accessed at:

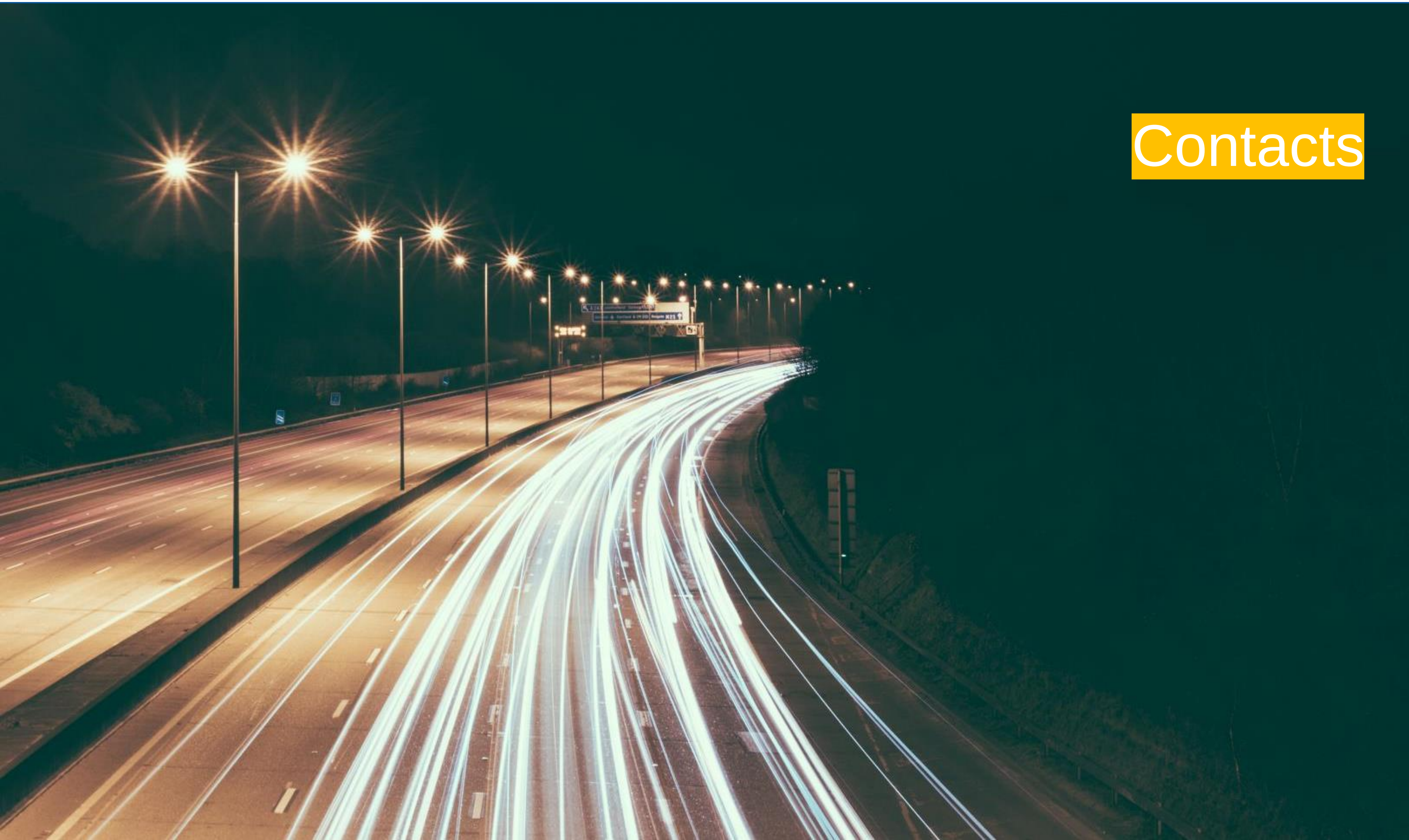
https://project-safepath.azurewebsites.net/ *or by clicking this signpost*

SAFEPATH database (online)









Contacts

Contacts

The list below shows key contacts related to the production of this Guide.

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