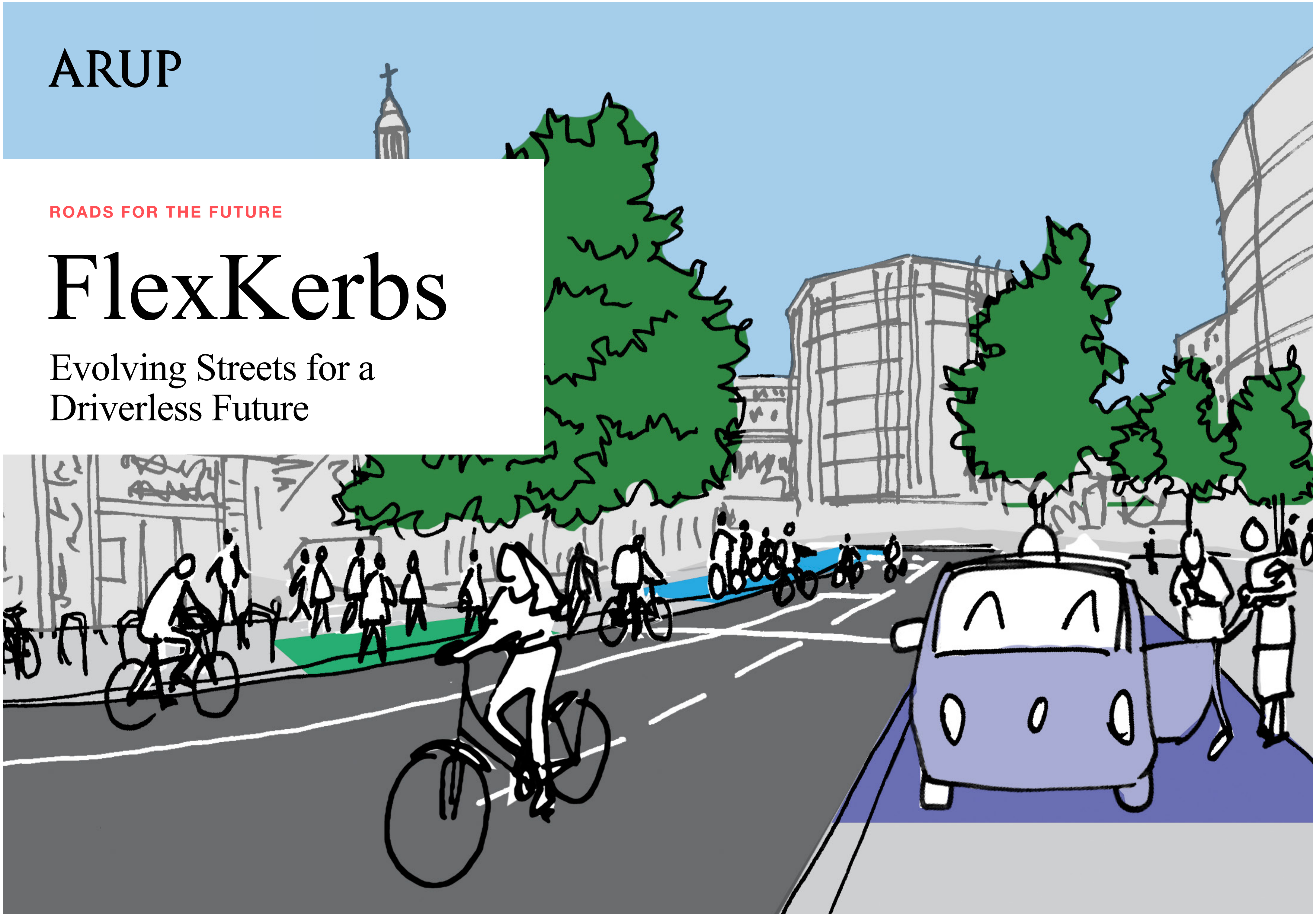
ARUP

ROADS FOR THE FUTURE

FlexKerbs

Evolving Streets for a Driverless Future



ARUP

24 August 2018

Ove Arup & Partners
13 Fitzroy Street
London
W1T 4BQ
United Kingdom

www.arup.com

We would like to thank the City of London for their time and dedication to this project.

Susan Claris
Associate Director
Transport Consulting
susan.claris@arup.com

Harrison Peck
Transport Planner
Transport Consulting
harrison.peck@arup.com

Fatema Karim Khaku
Senior Transport Planner
Transport Consulting
fatema.karim-khaku@arup.com

ABBREVIATIONS

AI Artificial Intelligence

ANPR Automatic Number Plate Recognition

CAV Connected and Autonomous Vehicles

LGV Light Goods Vehicles

MCC Manual Classified Counts

OGV Other Goods Vehicles

PHV Private Hire Vehicle

TDMC Transport Data Management Centre

TfL Transport for London

Contents

Foreword

We were thrilled to be shortlisted in the Roads for the Future competition earlier this year, and now we are delighted to submit this study for your consideration. The generosity of the National Infrastructure Commission, Highways England and Innovate UK has enabled us to explore the exciting future of connected and autonomous mobility and to devise our proposal for FlexKerbs, an ambitious yet feasible strategy for adapting road networks through dynamically adjusting kerb uses.

Arup's core mission to Shape a Better World forms the foundation of all the work we do. We believe that the Roads for the Future competition strongly supports this objective by aspiring towards a future that maximises the myriad potential benefits of connected and autonomous technologies for people across the UK.

But key to shaping a better world is a focus on people—on human interaction and experience, safe and healthy environments and thriving economies.

For this reason, we chose to take our Roads for the Future response one step beyond the competition prompt: how can the UK adapt its streets for Connected and Autonomous Vehicles… *while preserving them as places for people?* We are confident that FlexKerbs are the answer.

Isabel Dedring
Global Transport Leader
Arup

Executive summary

> …how roads are changed to accommodate connected and autonomous vehicles will reflect and impact how, where, when and why people choose to use them and other forms of transport.
>
> National Infrastructure Assessment (2018)[1]

FlexKerbs could transform fixed kerbsides into dynamic, technologically sophisticated spaces that change function throughout the day and week in response to local policy and user demand. They would directly support the introduction of Connected and Autonomous Vehicles (CAVs) onto the UK's urban road networks by maintaining an optimal supply of kerb space for the loading and unloading of people and goods, while prioritising the human scale and placemaking function of city streets.

This study demonstrates that FlexKerbs would:

- Be technologically feasible;
- Balance the needs of all road users;
- Give cities proactive agency in achieving local objectives;
- Enable efficient use of street space; and
- Effectively allocate kerb space to enhance public realm while maintaining traffic flow.

CAVs and city streets

CAVs may be the most highly anticipated transport development since the advent of the car. Experts predict that the widespread adoption of CAV technology will lead to cleaner air, safer streets, regenerated neighbourhoods; and a multitude of other benefits for cities and their inhabitants.

However, others highlight the risk that, without proper planning and infrastructure investment, CAVs can potentially exacerbate existing road network issues such as congestion, vehicle-pedestrian conflicts and challenging walking and cycling environments.

With driverless technology approaching reality, now is the time for local authorities to devise strategies for maximising the benefits of CAVs while mitigating their risks.

As the building blocks of cities, streets must be the focus for infrastructure adaptation. To adapt UK roads for CAVs, cities need to fundamentally reconceptualise what streets are and how they can operate. Today's streets, which function as static entities with fairly fixed uses, are woefully unprepared for accommodating evolving autonomous technologies without sacrificing space for walking, cycling and public transport.

To prepare streets for CAV operations while maintaining their movement and placemaking functions for people, as well as their essential freight and servicing needs, Arup proposes the conversion of static kerbs into technologically sophisticated flexible kerb spaces, or "FlexKerbs".

This study describes Arup's proposed FlexKerb concept, highlighting their technological feasibility and the benefits they could deliver. It then proves that, if implemented, FlexKerbs could vastly improve the functionality of CAV-enabled city streets by preserving a culture of walking and cycling while successfully enhancing road network performance.

What are FlexKerbs?

Underpinned by the concept of flexibility and adaptability, FlexKerbs could allow the kerbside to dynamically, safely and intelligently change use at different times of the day and on different days of the week. Led by local policy and informed by demand data, FlexKerbs would optimise kerb usage and access throughout the day to achieve a local authority's desired mix of street users while either accommodating or managing existing and new vehicle demand.

For instance, in a central business district in which local policy dictates a shift toward active mobility, and existing demand for walking space is high, a FlexKerb could offer an extra-wide footway during peak commuting hours. Late at night or after the morning rush, FlexKerbs could open up extra space for freight activity to meet policy objectives around off-peak deliveries. On weekends, local businesses could reserve pedestrianised stretches of kerb for street festivals or outdoor vending, supporting objectives around the activation of public space. Meanwhile, throughout the day and week, the FlexKerb could maintain a variable length of kerb for the exclusive use of CAVs to ensure they have safe and non-obstructive places for passengers to board and alight.

The concept of operations for FlexKerbs is complex and innovative. However, developed with digital, smart mobility and street design experts both internal and external to Arup, we are confident it is technologically feasible. Essentially, FlexKerbs would collect and process user data, then, dictated by local policy, decide whether to accommodate demand, by allocating kerb space to a particular mode, or manage demand, by limiting kerb space to that mode and allocating it to other users.

This dynamic approach to kerb space assignment can enable a more seamless coexistence of presently conflicting kerbside users.

FlexKerbs proof of concept

To understand if, and to what extent, FlexKerbs could support CAV deployment while maintaining streets' active and placemaking functions, we simulated FlexKerb functionality on Cheapside—the historic high street in the City of London. To do so, we devised an illustrative 24-hour schedule of FlexKerb space allocation, informed by demand data but driven by local policy, and tested it using microsimulation modelling.

To inform the policy inputs, we carried out a detailed review of key local planning and policy documents to establish a modal hierarchy and the governing principles of FlexKerbs' 'decision-making' process. We derived data inputs from an extensive demand dataset received from the City of London, which segments user volumes by mode and time of day for one full weekday. Then, through an iterative process of comparing demand data with local policy, we determined the optimal uses for each segment of kerbside space across the day and translated this into a 24-hour FlexKerb schedule for Cheapside.

Next, using VISSIM, the industry-standard software for measuring an intervention's impact on road network performance, we tested our proposed schedule and assessed the impact of FlexKerbs on Cheapside. Through a series of microsimulation models of the study area, we developed three distinct scenarios—Existing Conditions, CAV Future No FlexKerbs and CAV Future With FlexKerbs—and modelled our proposed FlexKerb schedule for four distinct time periods.

Findings

This assessment demonstrated that FlexKerbs would serve as a highly effective tool for improving both the operational efficiency and the public realm of a CAV-enabled street. Specifically, comparing the CAV Future No FlexKerbs and CAV Future With FlexKerbs model results, we learned that FlexKerbs could offer the following benefits:

1. Extensive **reductions in motorist delay**, particularly during the busy Morning Peak period;
2. A **safer and more comfortable cycling environment**, with an extra-wide cycle lead-in lane providing safe and comfortable waiting space for the high volume of peak-hour cyclists;
3. An **abundant supply of kerb space for pedestrians**, vastly improving the walking environment over the currently congested footways; and
4. A **sufficient reserve of kerb space for CAV passenger pickup and drop-off**, nearly eliminating traffic flow impacts and minimising CAV competition for kerb space.

Lessons learned

This study demonstrates the value of building flexibility into kerb usage by applying the FlexKerbs concept. It shows that allocating kerb space according to objectives and demand can effectively support the coexistence of the various essential functions and conflicting demands of a street. Through a focus on high streets, typically a city's busiest and most complicated roadway environment, this study proves that dynamic kerbside management can maintain a street's essential movement and place functions while paving the way for an autonomous vehicle fleet.

If CAVs are indeed nearing widespread deployment, FlexKerbs will herald their arrival, while preserving streets as nuclei of civic life and human interaction.

Source: UK AutoDrive

Introduction

Visions of an autonomous future portend a dazzling transportation utopia. Sleek driverless cars glide seamlessly across pristine city streets, intelligently communicating with connected trucks, buses and other members of the autonomous family. Upon reaching the eager passengers who summoned them, they graciously cast open their doors, welcoming multiple riders to share a carefree journey to proximate destinations. Once mere strangers, but now congenial travel companions, none of these commuters own a car, as sharing is convenient, affordable and fun, and travel is, quite literally, as easy as tapping a handheld screen. What a rush it all is.

Though ambitious, this aspirational version of a future city—or at least something like it—may be largely attainable. But to successfully usher the world's next major transportation revolution, cities must take a proactive approach, not a responsive one, to both infrastructure and policy development. In the 20th century, cities were designed and built around cars, which has given rise to heavily polluted air, intensely congested roads, unsafe roadway conditions and a public realm better equipped to move cars than to nurture place and human interaction. As Connected and Autonomous Vehicle (CAV) technology matures and gains more widespread acceptance and adoption, cities must learn from the past and carefully plan for a driverless future.

> How kerb space is used by shared vehicles will be an important issue to consider if they become more widespread.
>
> Mayor's Transport Strategy (2018)[2]

Particularly in the UK's dense and historic city centres, innovation and implementation must begin on city streets. The most fundamental building blocks of urban movement and place, city streets today contend with stiff competition amongst often conflicting users for limited space.

And within the complex anatomy of an urban high street, perhaps no space faces more competition than the kerb. Occupying the area between the outermost moving lane and the footway, the kerb must accommodate a range of uses, from bus lanes, cycle paths and taxi ranks to on-street parking and freight loading zones. In a driverless future, CAVs will add yet another layer of kerbside pressure.

Arup believes that the introduction of smart, connected and autonomous vehicles can unlock the opportunity for comparably smart streets that are predictive of and responsive to real-world conditions. In response to the Roads for the Future competition, we propose reconceptualising the kerb as dynamic infrastructure that, using a suite of advanced technologies, can change function throughout the day by intelligently adjusting permitted uses of kerb space in a context-specific and user-driven manner. These flexible kerbs, or "FlexKerbs", could enable even the most space-constrained streets to accommodate a diversity of kerbside users while efficiently optimising space.

FlexKerbs will help prepare UK city streets to accommodate CAVs by reserving segments of kerbside space for CAV passenger pickup and drop-off, sized to either meet or manage vehicle demand, while ensuring that CAV technology does not advance at the expense of other street users.

Even as the vehicle fleet evolves to a higher share of connectivity and autonomy, FlexKerbs could ensure that CAVs do not dominate the public realm by preserving and, in many instances, adding kerb space for walking, cycling and public transport. Policy-led and data-informed, FlexKerbs will foster a public realm that nurtures active mobility and healthy street life while enabling safe coexistence with CAVs.

The primary objective of this study is to demonstrate the feasibility and benefit of FlexKerbs on UK high streets. It is divided into two primary sections.

The first section unpacks Arup's FlexKerb proposal in depth. It describes their general function and concept of operations, demonstrates the unique role FlexKerbs could play in nurturing a culture of walking and cycling, emphasises their ability to unlock some of the myriad benefits that CAVs could deliver to society and highlights their technological and economic feasibility.

The second section describes the proof-of-concept analysis that Arup undertook to understand the impact FlexKerbs could have on both cities and CAVs. In this stage of the study, Arup simulated the FlexKerb concept on Cheapside—one of the primary high streets in the City of London—by applying a modal hierarchy to produce an illustrative FlexKerb schedule for a typical weekday. It describes how, through VISSIM microsimulation modelling, we tested the proposed schedule and found that FlexKerbs would successfully enable Cheapside to meet CAV demand while maintaining active mobility and achieving other multi-modal transport goals.

To conclude, the study draws upon the global conversation around the need to optimise kerbside space with a discussion of next steps toward making flexible kerb space a reality.

The FlexKerbs future

> If autonomous vehicles make car use more appealing and easier to do, people may walk around their neighbourhoods less.
>
> Mayor's Transport Strategy (2018)

By actively managing access to kerb space, FlexKerbs could help cities to achieve their desired mix of street users. This section describes Arup's FlexKerbs proposal, explaining their essential functions, highlighting their benefits for all users of a street and detailing their concept of operations.

What are FlexKerbs?

SPOTLIGHT ON THE KERB

This study focuses on the allocation and optimisation of kerb space. Defined as the area between the outermost moving lane and the footway, kerbs serve three essential functions:

Movement
Kerbs can support the street's movement function by providing additional throughput for cyclists, buses and those on foot.

Place
Kerbs can also promote a street's placemaking functions by providing parklets, sites for street vending, seating, art or other public activities and amenities.

Interface
In addition to movement and place functions, which they share with the rest of the carriageway, kerbs also serve as the point of interface between streets and adjacent land uses. They provide space for parking, passenger pickup and drop-off, freight servicing, bus stops and other activities that involve vehicles stopping for the loading and unloading of people and goods.

FlexKerbs could enhance all three of these functions by allocating this finite strip of coveted roadway real estate in the most space-efficient, user-driven manner possible.

Streets today function as relatively static entities. While signage and road markings can indicate variations in usage regulations, the configuration of streets themselves, and their capacity for throughput and modal split, remain essentially constant. Particularly in older UK cities, where historic building lines have defined and fixed street widths for centuries, rigid street functions could hinder innovation and slow the adaptation to new travel behaviours and technologies.

FlexKerbs could entirely change this paradigm. Transforming fixed kerbs into dynamic, intelligent infrastructure, FlexKerbs could adjust permitted kerbside uses throughout the day, week and year, conveying information to the public through dynamic visual representations, audible signals and mobile applications.

For instance, in a town or city prioritising an increase in cycle commuting, the kerb could create additional space for cyclists during peak commuting hours. A nightlife destination district could expand the stretch of kerb available to CAVs during late-night hours when public transport operates limited services, while the same space could create extra pedestrian capacity on weekend afternoons to accommodate street vendors, shoppers, and other daytime activities.

FlexKerbs could efficiently manage temporary access to kerb space through a dynamic reservation system. For instance, similar to ride-hailing platforms today, a user could request a CAV pickup using a smartphone application. A nearby CAV would accept the journey and scan the area proximate to the rider's origin for an appropriately sized kerbside segment currently accepting CAV pickups. It would then "reserve" the right amount of kerbside space for enough time to complete its pickup and drop-off, notifying the rider of exactly where the trip will start and finish. Similarly, this FlexKerb reservation system could facilitate kerb access for freight loading and unloading, allowing lorries to reserve kerb space adjacent to the destination of their deliveries during times when freight servicing is allowed.

FlexKerbs can impart an array of benefits to improve mobility and urban realm. FlexKerbs can be:

1 Adaptable
The future of transport systems is inherently uncertain. But FlexKerbs build adaptability into the road network so streets are prepared to accommodate new technologies and behaviours as they arise. This feature will prove particularly valuable during the period of fleet transition, when the vehicle fleet consists of a fairly balanced mix of autonomous and human-driven vehicles. As a larger share of the fleet shifts toward autonomy, FlexKerbs can adapt by continually allocating a proportionate share of kerb space to CAV pickup and drop-off.

2 Responsive
Streets are slow to catch up with changes in their use. For instance, if a street experiences an increase in taxi volumes, allocating additional taxi bays to absorb new demand may be an arduous and contentious process with clear winners and losers. As smart, data-informed infrastructure, FlexKerbs would be able to respond to increases in demand by allocating additional kerb space for taxis only when they need it most, obviating the need for expensive and time-consuming road works.

3 Predictive
Not only would FlexKerbs be able to respond to changing usage patterns, but their predictive capabilities will allow them to adjust in advance of demand fluctuations. For instance, if historical data indicates a surge in cyclist volumes on a particular street between 8:00 and 9:00am, the FlexKerb can begin to expand its cycling facilities—such as cycle lane, advanced stop line, etc.—in the moments leading up to the anticipated spike to give cyclists sufficient space to ride.

4 Space-efficient
Communicating with all CAVs, FlexKerbs will be able to position vehicles in the most space-efficient arrangement possible to optimise kerbside space. In other words, whether a CAV is privately owned, shared, freight, or public transport, FlexKerbs would know exactly how much space it requires to park and perform its loading and unloading functions. When a vehicle reserves a spot on the kerb, the FlexKerb would assign it the right amount of space in a position that maximises the number of vehicles capable of accessing the kerb at once. This benefit would become particularly evident when CAVs comprise a majority of the vehicle fleet, as they will automatically comply with FlexKerb allocations.

5 Future-proof

FlexKerbs can prepare growing cities to accommodate future transport demand. For example, the Greater London Authority expects to see nearly 1.3 million additional Londoners, an increase of 15%, in the next two decades,[3] while the city's historic street network will remain largely the same size. The Mayor of London aims to achieve an 80% sustainable mode share in London, while encouraging at least 20 minutes of active travel per day.[4] Building flexibility into London's existing street network will enable the seamless absorption of these volumes of pedestrians, cyclists and buses at the times these capacity increases are needed most, while allowing for technological adaptation in an uncertain future.

6 Revenue-generating

FlexKerbs create new opportunities for monetising the kerb, generating revenue to help offset their own capital and maintenance costs. At present, towns and cities generate kerbside revenue through parking fees and penalty charges. However, through their dynamic reservation system, FlexKerbs could charge users for the amount of kerb time and space they use. For CAV pickup and drop-off, this fee could be bundled into passengers' total fare, while freight companies could choose to absorb it into the cost of a delivery. Meanwhile, cities could also assess penalty charges through the reservation system, as the FlexKerbs network will be able to identify which vehicles have exceeded their time and space allotments and by how long.

7 Versatile

While this study focuses on the benefits of FlexKerbs to high streets, the technology could easily be applied to a diversity of contexts where increased flexibility can improve a street's operational efficiency. Some examples include the following:

Airports: With wide but somewhat predictable fluctuations in demand profiles across a day, week and year, airports could transform their kerbside arrival zones into dynamic spaces that accommodate passenger drop-off, pedestrian activity, public transport services, and freight movements.

School zones: When the school day begins and ends, adjacent streets quickly fill with additional pedestrians, buses and vehicular traffic. FlexKerbs could help regulate and separate these travellers to create an orderly and safe environment for children.

Motorways: Akin to the technology deployed on smart motorways, FlexKerbs could adjust motorway capacity to accommodate additional lanes for cars, CAVs, buses, high-occupancy vehicles, or other motorway user types that could benefit from dedicated space at certain times of day.

Low-emission zones: FlexKerbs can facilitate the operation of low-emission zones by reallocating kerb space from vehicles to pedestrians and cyclists during periods of poor air quality.

Special events: Councils, businesses or local organisations could reserve FlexKerb space for special events such as street fairs, food festivals, or other public uses that could benefit from extra street space to accommodate crowds and vendors.

Towns and cities across the UK could implement FlexKerbs wherever they are needed. A key benefit underpinning this idea is FlexKerbs' adaptability and flexibility in application, location and implementation.

How will FlexKerbs work?

> Government and cities need to act now to ensure that space in cities is used effectively.
>
> National Infrastructure Assessment (2018)

To optimise kerb usage throughout the day, FlexKerb space allocation decisions must be led by local policy and informed by demand data. This means that usage data will inform the demand for kerb space from different users, while policy will dictate whether demand should be accommodated or managed.

This section describes the proposed concept of operations for FlexKerbs, highlighting existing technologies that may be incorporated into real-world implementation.

We have developed this section in collaboration with digital, smart mobility and street design experts and are confident that it is technologically feasible. Specifically, FlexKerbs would function through a three-stage process, illustrated in Figure 1.

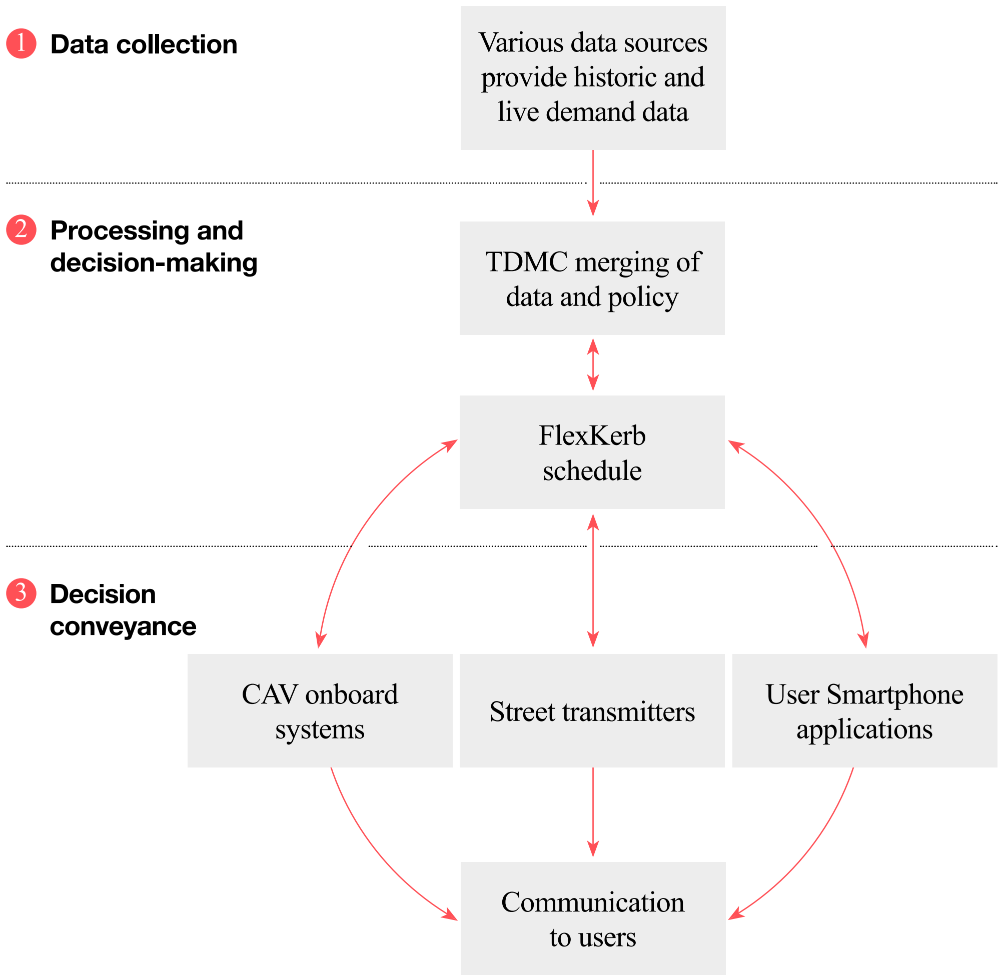


Figure 1: Concept of operations for FlexKerbs data collection, data processing, and decision conveyance

1 Data collection

Accurate and contextual data will be critical to informing the most appropriate function for kerbside space at different times of day and on different days of the week.

Integrating live information with historical data will paint a precise and nuanced portrait of kerbside behaviours, and a variety of data collection methodologies may be used to achieve this balance. For instance, several technology companies are currently experimenting with surface panels and paving materials that can collect information about travel volumes and user types. Pavegen, a UK-based start-up, has developed flooring tiles that generate traffic and movement analytics (Figure 2).[6] Umbrellium, also based in the UK, has piloted the Starling Crossing, which responds to walking activity in real time by illuminating crossings along desire lines (Figure 3).[7]

Additionally, mobile sensing technologies—including GPS, Wi-Fi and cellular data sources—could inform the intelligence gathering and decision-making on kerb usage and provide the location data (and other derivatives such as speed, acceleration and transport mode) of different road users. Additionally, fixed, infrastructure-based sensing technology—road sensors such as loop detectors and mounted infrastructure like radar detection, as well as Automatic Number Plate Recognition (ANPR), Closed-Circuit Television (CCTV) cameras and advanced computer vision technology—could provide precise and real-time information about street usage that can augment and/or validate mobile sensing technologies.

Figure 2: Pavegen "smart flooring" captures and wirelessly communicates pedestrian data in real time[5]

Figure 3: Starling Crossing

2 Processing and decision-making

Data processing would take place through a centralised Transport Data Management Centre (TDMC), which would produce a responsive and predictive programme of kerb regulations. This cycle would be generated by a sophisticated, Artificial Intelligence (AI)-driven decision-support system that, by algorithmically synthesising historical, real-time, and predicted future data with pre-determined local policy requirements, decides the optimal kerb usage over time to meet or manage user demand and facilitate efficient kerbside operations in a manner that is consistent with local objectives.

This information would be conveyed via two-way communication between the TDMC and all CAVs, including shared and private passenger cars, buses and delivery vehicles. As a result, CAVs would know which segments of kerb are available for the loading and unloading of passengers or goods so they may plan their routes accordingly.

CAV users, whether passengers or freight recipients, could reserve kerb space through a mobile application. The TDMC could be responsible for processing these reservations, calculating kerb booking fees, collecting payments and issuing fines to users.

While technologies will continue to evolve, several existing systems demonstrate the potential for advanced TDMC functionality. For example, UK-based technology start-up Grid Smarter Cities has developed Kerb, a kerbside reservation and space management software that allows commercial vehicles to book “virtual loading bays” in advance, with the goal of reducing circling and promoting an integrated approach to kerbside space management (see Figure 4). Users can both pay for their timeslot and top up as needed remotely. Kerb determines booking fees based on the bay’s location and the Euro Rating of the vehicle.[9] Moreover, New York City-based start-up Coord has developed a digital inventory of kerbside regulations in four major American cities, demonstrating the existing capacity for and interest in data-driven kerbside management tools.[10]

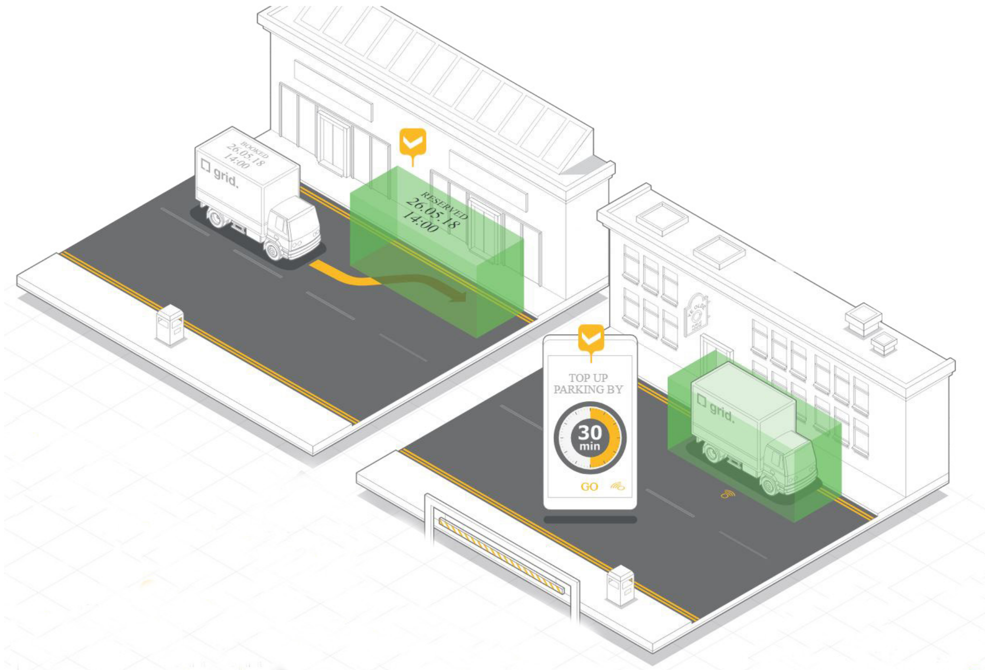


Figure 4: Example reservation system by Grid Smarter Cities[8]

3 Decision conveyance

The final step of FlexKerb functionality is the dissemination of data from the TDMC to people so they may plan their travel accordingly. This conveyance would take three forms. First, FlexKerbs must indicate to passers-by the usage regulations that are currently in effect. This indication may be achieved through dynamic signage, lighting embedded in "smart flooring" panels, or other technological interventions such as mobile phone applications and audio signals. Second, CAV passengers could receive information directly from the vehicles in which they are travelling. Similar to the manner in which Google Maps, Waze, and other navigation applications function today, the CAVs would inform passengers of their intended route and drop-off location. If conditions change while the vehicle is in transit, the CAV can alert the passenger, who can then choose whether to accept or decline the new route. Third, non-CAV travellers will also need access to up-to-date information on kerbside uses so they may choose their modes and plan their routes accordingly. This data would be available via Smartphone applications so users can always check the latest information whilst on-the-go.

Several emerging technologies may achieve FlexKerb visual indication. For instance, in Toronto, Sidewalk Labs is developing a "Dynamic Street", comprised of modular, hexagonal pavers with integrated lighting to communicate changing street uses throughout the day (Figure 5).[12] Alternatively, digital totems, installed adjacent to the kerb, can display a range of information including current and future kerbside usage, CAV arrival time and route information, real-time statuses of nearby public transport systems, weather forecasts and more. Figure 6 shows a prototype digital totem. Furthermore, technologies such as Microsoft's Soundscape could integrate audible information about users' surroundings with cues about kerb usage.[13]

An overarching challenge with FlexKerbs is this communication stage for those who are walking and cycling and people who may not be 'connected' all the time. Visual indicators are necessary and should be clear and allow safe transition between uses. Signal crossings and pelican crossings have a similar role in communicating to pedestrians when it is safe to cross and when it is not, and following public acceptance of FlexKerbs, a similar approach could be employed.

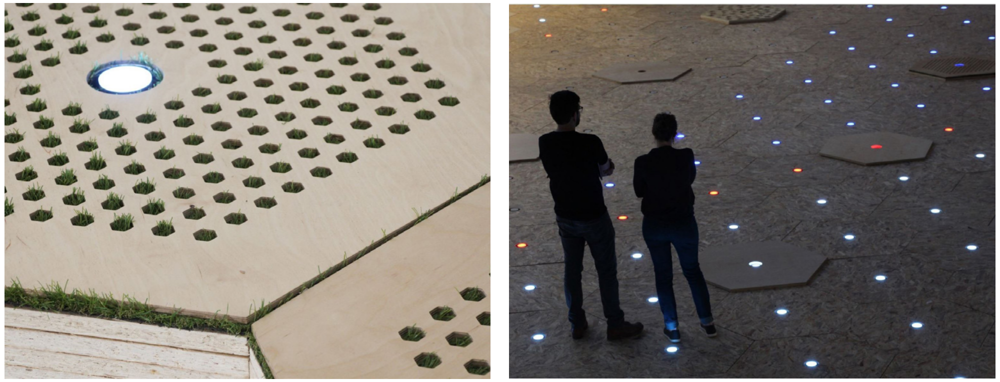


Figure 5: Modular street prototype[11]

Figure 6: Digital totems can display information about CAV arrivals, as well as kerbside function

Delivery of CAV benefits

A fleet consisting primarily of autonomous vehicles can offer significant advantages to society vis-à-vis today's conventional cars. However, a lack of strategic infrastructure investments and demand management mean these benefits may be lost amongst traffic-clogged streets and inefficient kerb usage.

Not only will FlexKerbs enable a smoother rollout of CAV technology, but they can also help to maximise many of the societal benefits CAVs can deliver, particularly within the challenging, complex high street environment. In particular, we anticipate that FlexKerbs will help to unlock the following benefits:

1 Reduction in car ownership

As demonstrated by existing transport services such as UberPOOL and Chariot, travellers are willing to share rides with others in exchange for a cheaper fare than a private taxi. Mobility experts predict that, in a future scenario in which autonomous ridesharing becomes conventional, only a small fraction of urban residents will own a car. In fact, researchers in Toronto found that the number of private cars in the city would decline by 80% by the mid-2030s if Torontonians widely adopt autonomous ridesharing.[14] The growth in hail services such as Uber also affects the attractiveness of owning a car. Even if journeys are not always shared, they provide access to convenient car trips, which could impact the demand for private car ownership.

Such reductions in vehicle fleet size could reshape cities in dramatic ways, most notably through narrower carriageways, additional public spaces and conversion of parking structures into different land uses. However, the success and desirability of shared CAVs is contingent upon their ability to provide convenient journeys to passengers; people are unlikely to relinquish their cars if CAVs are unable to access kerb space relatively close to their origins and destinations.

By maintaining available kerb space for CAV pickup and drop-off, and adding extra kerbside capacity to accommodate demand during busy times, FlexKerbs could help CAVs to provide more direct journeys. Without dedicated kerb space, CAVs would either conduct pickups and drop-offs at inconvenient locations, or they would be forced to stop in moving lanes, obstructing through traffic, causing delays and presenting safety hazards for passengers and other road users.

> The interactions of connected and autonomous vehicles with people walking, people cycling and conventional vehicles will also need to be made in a safe, predictable and manageable way.
>
> Mayor's Transport Strategy (2018)

2 Better road network performance

With the ability to safely platoon on streets and park themselves with precision, CAVs require less road space than non-autonomous vehicles, effectively increasing the capacity and efficiency of existing street networks. FlexKerbs capitalise on these efficiencies by maximising kerbside capacity for all users. Intelligent, data-driven streets will communicate with CAVs to ensure they position themselves as compactly as possible, increasing the volume of potential kerbside activity.

This functionality extends to autonomous lorries and buses as well, as FlexKerbs would know how much space each vehicle requires and would assign them positions that optimise kerb space. High streets in particular, with their dense concentration of businesses dependent on reliable and frequent deliveries, will benefit from the extra capacity afforded to freight CAVs.

3 Improved air quality

The proliferation of CAVs is widely anticipated to improve air quality. Mass vehicle electrification combined with lighter vehicles and higher vehicle occupancy rates can produce significant reductions in fossil fuel consumption and carbon emissions. However, demand management interventions will be necessary to usher sustainable behaviours and vehicle technologies.[15]

FlexKerbs could support CAVs' clean-air benefits in a number of ways. First, by preserving kerb space for passenger pickup and drop-off and allowing advanced kerb reservations, FlexKerbs would eliminate the need for circling, reducing vehicle miles travelled and petrol or electricity usage. Second, FlexKerbs would also regulate the amount of kerb space allocated to CAVs in an effort to mitigate demand and help to prevent surges in vehicle travel. Third, as mentioned in Section 2.1, FlexKerbs could be used to support the operation of low-emission zones by restricting kerb access to high-polluting vehicles—and reallocating kerb space to electric cars or active travellers—especially during periods of poor air quality.

4 Land use enhancement

Owing to a more efficient use of road space and a reduced need for parking, CAVs could be expected to generally enhance the public realm. In addition to improving mobility, FlexKerbs would create new public spaces during the times when they will be utilised most heavily by pedestrians. For instance, on a Sunday afternoon, a food market operator could request to pedestrianise the kerb to add extra space for vendors and shoppers. Similarly, along a high street with heavy tourist foot traffic, the pedestrianisation of the kerb during holidays, special events, and other busy periods could make popular destinations safer and more pleasant to explore on foot.

Moreover, in addition to supporting CAVs, FlexKerbs would promote a multi-modal transport environment, safely and seamlessly converting the kerb from bus lane to cycle path to footway as conditions warrant. This dynamic, responsive approach to mobility would help to maintain the vibrant, active nature of high streets even as CAVs provide an attractive alternative to active travel.

5 Better travel opportunities and accessibility

CAVs could open new travel opportunities for people who cannot readily drive, including elderly and disabled people, who need a safe, convenient space on the kerb to be picked up and dropped off. By offering priority kerb access to vulnerable travellers, FlexKerbs can amplify this benefit by ensuring that those with reduced mobility can access their destinations safely and conveniently.

We believe that CAVs have the potential to deliver all these benefits, and more. But simply introducing CAVs into the road network will not inherently result in such dramatic improvements to quality of life. FlexKerbs could help unlock and maximise these benefits by improving CAV operation and efficiency while supporting public realm objectives.

SECTION 2.4

FlexKerbs business case

While the construction, installation and maintenance of FlexKerbs would constitute a large public expense, the financial benefits they could be capable of delivering could outweigh these costs. FlexKerbs could generate economic value in several ways.

First, to understand the economic value of FlexKerbs, one need only visualise a driverless future in which flexibility is not built into streets. For instance, as described in Section 2.1, London's population is forecast to swell by nearly 15% over the next two decades. During that same period, the city expects to see the gradual addition of CAVs into its transport network. Both of these trends will mandate some degree of modification to the size, configuration and operation of London's road network to accommodate the anticipated levels of growth and change. Repeated and widespread road works are expensive and inconvenient, not to mention detrimental to public realm and quality of life. However, FlexKerbs can help to deliver capacity increases and right-size roads as needed over time, saving future expenditure on costly construction projects.

Second, FlexKerbs should be good for business. Research indicates that businesses benefit from pedestrian-friendly streets, as human-scale streets with heavy foot traffic drive customers into shops and restaurants. Car-oriented streets that prioritise movement over place form more challenging environments for businesses to prosper. Not only will FlexKerbs be designed to create more attractive environments for pedestrians, increasing walking space whenever practicable, but, particularly during weekend and night-time hours when vehicle volumes may be lower, FlexKerbs could transform kerb space into public space, creating mutual economic opportunity for street vendors and adjacent businesses who will benefit from additional footfall.

Finally, as described in Section 2.1, FlexKerbs could commodify kerb space in innovative ways and create new revenue sources for towns and cities. Local authorities could charge higher rates for kerb reservations in high-demand locations during peak hours to both increase revenue and control demand for kerb space.

> Maximise opportunities to use infrastructure assets for more than one purpose, to make the best use of land and support efficient maintenance.
>
> Draft New London Plan (2017)[16]

Implementation challenges

> The Mayor will... develop more creative solutions to managing freight and deliveries. This will include considering different uses of London's streets across the day so that more street space is available for walking, cycling and leisure purposes, while ensuring shops and services continue to thrive.
>
> Draft New London Plan (2017)

While the purpose of this study is to test and validate the feasibility of the FlexKerbs concept, there are a number of challenges that, though outside the scope of this study, must be the critical focus of future research prior to implementing any degree of flexible street technology. Through many conversations with transport and technology industry professionals from the public, private, and academic sectors, the following issues consistently emerged:

Physical infrastructure: What will FlexKerbs look like? How will they indicate to street users their current permissions? And how will they signal a change in regulation? FlexKerbs could consist of modular panels overlaid atop a street indicating kerb regulations through coloured lighting, which flashes in advance of changing regulations to give users warning (akin to a flashing pedestrian crossing signal today). However, conversations with numerous technology providers have revealed a range of existing infrastructure options that require further exploration.

Disabled people: FlexKerbs would dedicate more street space to pedestrians and discourage excessive vehicle traffic. Creating a low-speed, pedestrian-oriented public realm will inherently produce safety benefits for all users, particularly disabled people. However, in designing FlexKerb infrastructure, understanding how disabled people, particularly the visually impaired or those with mental health challenges, would interact with a dynamic street environment must be a key consideration. For instance, aural cues or personalised smartphone alerts could help the visually impaired navigate changing streets uses.

Enforcement: In a fully autonomous world, enforcement will become a marginal concern, as autonomous vehicles would be programmed to know that they cannot use kerb space that is not presently allocated to them. But in a mixed-fleet world, adaptive kerb regulations are only effective if people adhere to them, and proper enforcement and penalties will increase the likelihood of adherence. Future research will need to explore strategies for enforcing regulations that are not always as predictable to users as they are today.

Charging regime for kerb space: As previously mentioned, FlexKerbs could create new revenue streams for cities by charging users for kerbside access. Fee structures, reservation and payment functionality, risks and opportunities, and equity concerns must all form part of future FlexKerb research.

Cybersecurity: Machine-driven cars communicating directly with intelligent roads are likely to be high-risk for cybercrime. To guarantee safety for CAV passengers and all other street users, sophisticated cybersecurity is essential.

Government regulations: At present, stringent regulations governing roadway materials and functions, traffic management, signalisation and a host of other infrastructural parameters may complicate FlexKerb implementation. A fully flexible kerb would require a suite of policy changes at multiple levels of government, which agencies must start considering as a future world with CAVs comes into clearer focus.

Funding sources: Local authority and national government budgets are often constrained, and it is important to look at the business case for FlexKerbs to identify suitable sources of funding for their design and implementation. However, the cost to local authorities of 'doing nothing' for the future of CAVs and future of transport is also very high, and adapting the kerbside should form an integral part of the transport budget as CAV technology matures.

FlexKerbs proof of concept

> City leaders need to consider how to manage the impacts of changing travel patterns in their transport planning. But the basic challenge of urban transport is still the same: there is simply not enough space in cities for everyone to travel by car.
>
> National Infrastructure Assessment (2018)

This proof-of-concept study (referred to henceforth as "The Study") tests and validates the FlexKerb concept. Using policy and data from a real London high street, through The Study we have simulated the algorithmic functionality of the TDMC described in Section 2.2, manually creating a 24-hour FlexKerb schedule that optimises kerb space, advances local policy objectives, accommodates or manages demand and enhances the street environment for active mobility, all the while supporting and enabling CAV operations.

We tested the schedules by running them through a microsimulation model to prove that FlexKerbs can effectively manage kerb space to maximise benefits for all street users. Figure 7 illustrates the methodology we developed to undertake The Study.

This section describes the assumptions, methodology, and results of the three-month FlexKerbs proof-of-concept analysis, conducted between June and August 2018.

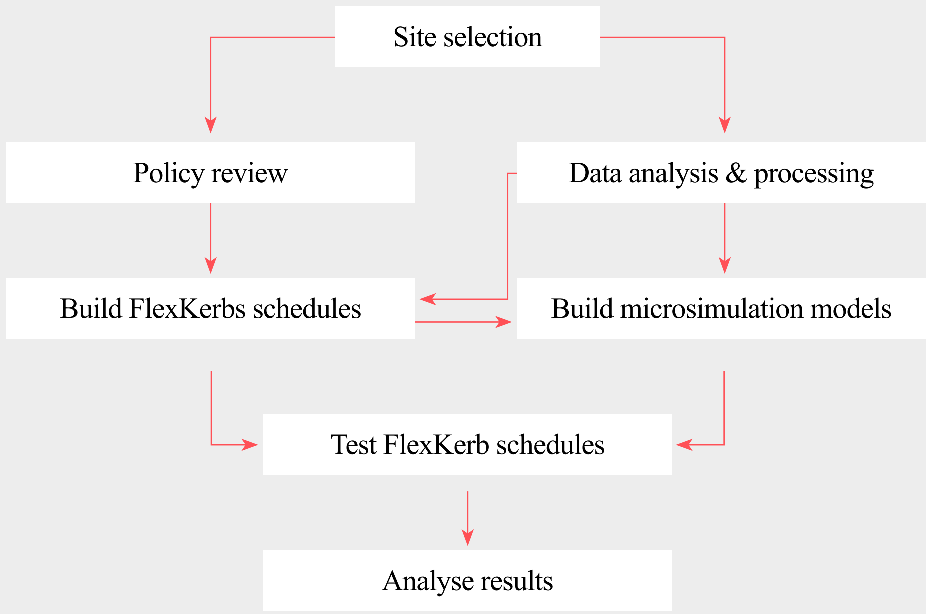
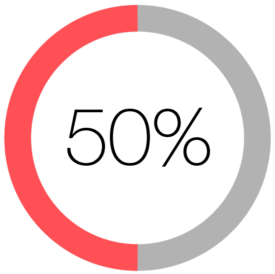
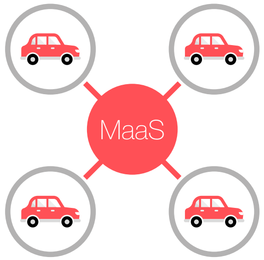


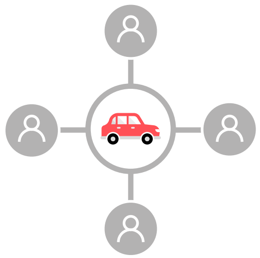
Figure 7: Proof-of-concept study methodology

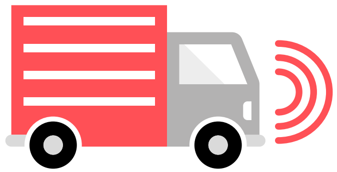
Study assumptions

Forecasts of a driverless future are murky at best. Leading experts in the financial, transport and automobile industries vary widely in their predictions for technological adoption, market penetration, vehicle ownership rates and impacts on travel behaviours. Given the difficulties of planning for an uncertain future, The Study makes the following assumptions about autonomous mobility in 2050, the focus year for the Roads for the Future competition:









1. Roughly half of the passenger vehicle fleet (both private cars and private hire vehicles) will consist of Level 5 CAVs (fully autonomous vehicles).[17]

2. CAVs will function under a “Mobility as a Service” (MaaS) model, meaning that a centralised software platform will monitor and manage CAV operations.[18]

3. Individuals will be unlikely to own CAVs and highly likely to share rides with other passengers.[19]

4. The freight and logistics industry will be among the first to widely adopt autonomous technologies, and most deliveries will be completed by autonomous vans and lorries,[20] with the potential for innovative last-mile delivery solutions like “portering.”

Site selection

To ensure The Study would yield useful and widely applicable results, we sought to select a site that would epitomise the anticipated challenges of integrating CAVs into an existing urban high street. To find the right street, we first developed a set of selection criteria that defined an optimal high street for The Study. Next, through conversations with London transport experts, we compiled a list of potential high street segments that would likely satisfy our desired characteristics. We then assessed these streets from different central London boroughs against the criteria and selected the highest scorer.

After running through this process, we selected Cheapside, which connects St. Paul's and Bank Junction in the City of London ("the City", the financial and historic centre of London, located north of the River Thames), as the street segment for our study. More specifically, we chose to focus on the western half of Cheapside, the roughly 300-metre segment between New Change and Queen Street.

In addition to Cheapside's satisfaction of our site selection criteria (see Appendix A), the appeal of this street as a study site was reinforced by the collaborative partnership we forged with the City of London's transport team, who provided us with rich datasets, valuable location-specific insights and active consultation with us throughout the study.

About Cheapside

Dating back to the 12th century, Cheapside has traditionally served as the City of London's central shopping street, its name derived from the Old English word for "market".

An ancient street like Cheapside epitomises the advantages of in-built flexibility. Though occupying roughly the same space for centuries, Cheapside's character and usage profile has changed over time. Even recently, in the early 2000s, the City and Transport for London (TfL) narrowed Cheapside's carriageway, allocating extra space to pedestrians to absorb the additional footfall new shopping destinations like One New Change have generated. The installation of FlexKerb technology could prepare Cheapside for its future so its physical space can evolve in line with its changing uses and users more rapidly in future.

Figure 8: Cheapside in 1909[21]

Figure 9: Footway at rush hour on Cheapside

Anatomy of Cheapside
Cheapside supports a diversity of uses and users at different sections of the street. While small segments approaching the junctions with Queen Street and New Change feature narrow (1.6-metre) cycle lead-in lanes (Figure 10), Cheapside's typical cross section, shown in Figure 11, comprises a carriageway of two moving lanes, one eastbound and one westbound, each of which doubles as a bus stop west of Bread Street; two footways adjacent to the northside and southside building lines; and, sandwiched between the carriageway and the footways on either side of the street, two multifunctional "flex spaces" whose use varies along the length of the corridor. For example, while some stretches of flex space act as extensions of the footway by providing additional walking space, others provide loading and unloading zones, a taxi rank, bus stops, trees, or cycle parking.

These variable flex spaces acted as the sites for simulated FlexKerbs. Not quite footways, yet distinctively separated from the carriageway, they offered numerous advantages for FlexKerb modelling.

For instance, as opposed to a typical carriageway, their uses vary along different segments of kerb in a fashion that, though relatively static throughout the day and week, may be considered a rather primitive form of FlexKerb. Moreover, situated between the carriageway and the footway, they constitute ideal settings for the fulfilment of the kerb's interface function, creating new opportunities to allocate space to CAVs.

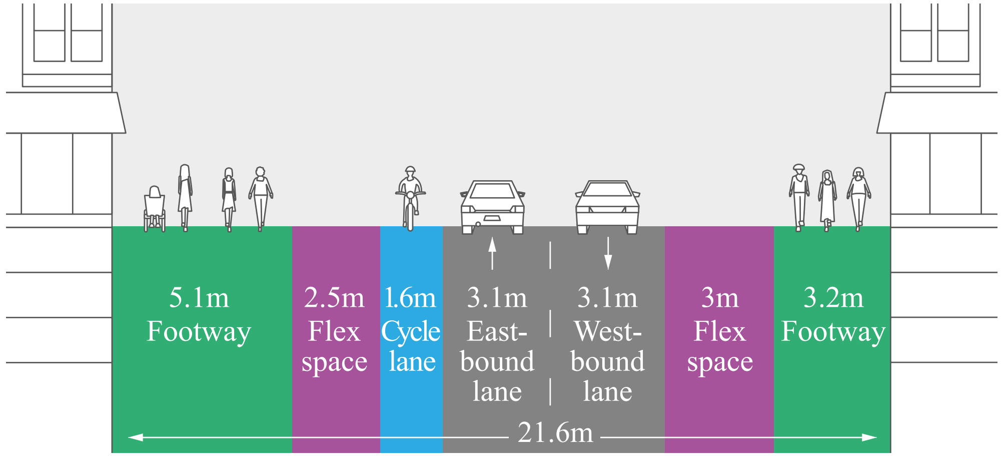


Figure 10: Cheapside cross section near New Change, with cycle lane

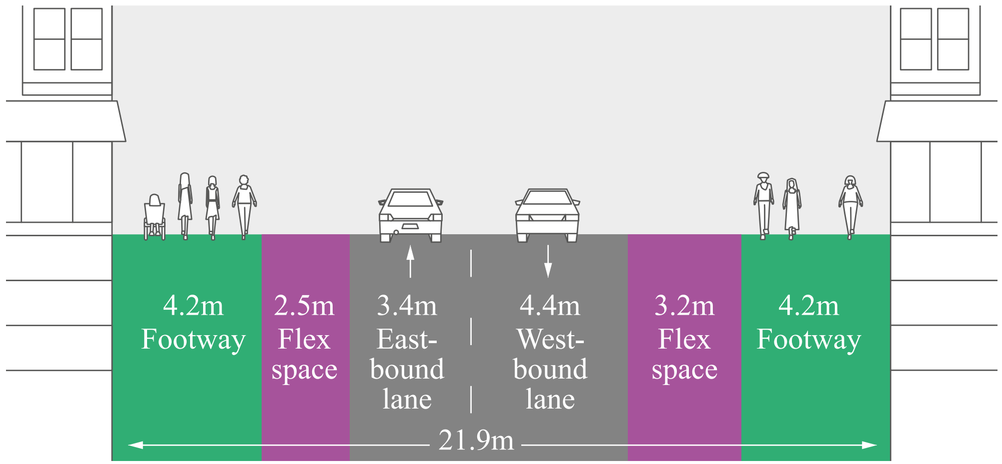


Figure 11: Typical Cheapside cross section

Policy-led and demand-informed: FlexKerb inputs

> Street space will be used more flexibly, recognising that priorities can vary by time of day and seasonally.
>
> City of London: Transport Strategy, Vision, Aims and Outcomes (2018)[22]

As described in Section 1, a fusion of local policy and real-time demand data would shape FlexKerb regulations throughout the day and week. Though the TDMC will automate this process in 2050, The Study replicates TDMC functionality through a manual process of policy and data aggregation. This section describes the inputs we used to inform our FlexKerb schedules, while the next section explains the process of translating these into an illustrative 24-hour FlexKerb programme for Cheapside.

Policy

Local policy must serve as the driving force behind FlexKerb functionality. As different local authorities adopt different priorities and objectives for their streets, FlexKerb policy inputs will vary based on an array of factors including the authority in which they are located, street typology, area demographics and adjacent land uses.

In general, Central London street policy frameworks tend to promote active mobility over driving, a vibrant and attractive public realm, space-efficient mobility, and a shift in vehicular travel demand, particularly for freight, outside of peak hours. This section describes the local policy inputs that inform Cheapside's FlexKerb schedule.

Policy review

As shown in Figure 12, four primary policy documents govern street and transport policy for Cheapside, ranging from broad ("Draft New London Plan") to specific ("City of London Draft Transport Strategy, Vision, Aims and Outcomes"). A comprehensive policy review can be found in Appendix B.

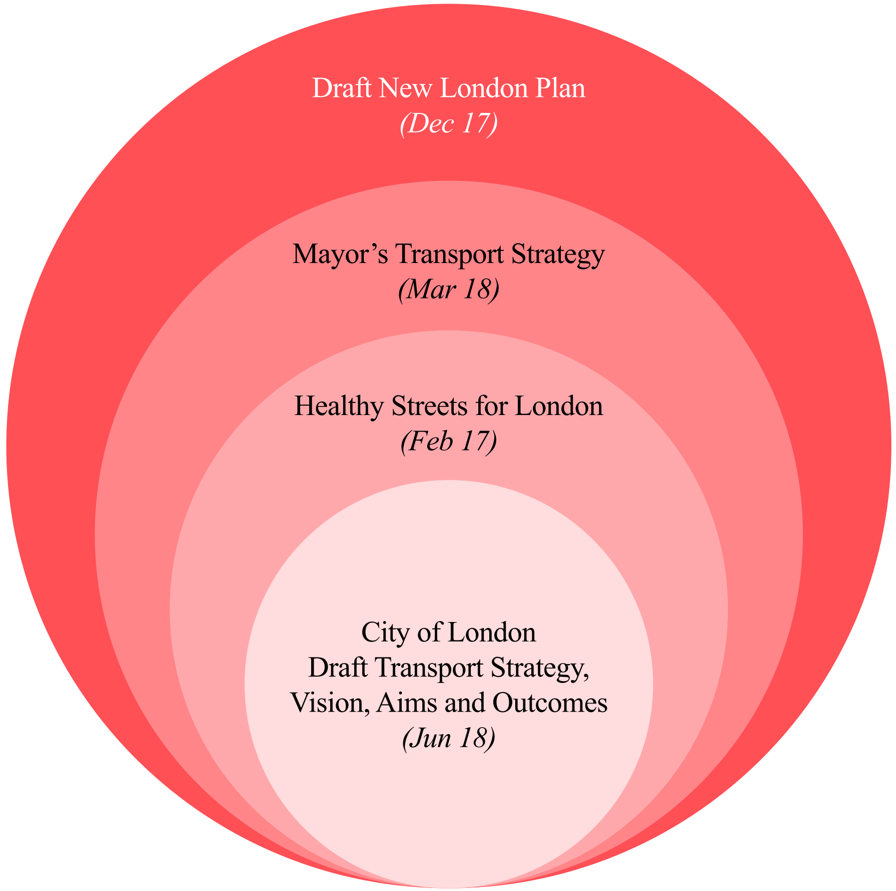


Figure 12: Policy review for Cheapside

1 **Draft New London Plan (Dec 17)** This citywide document guides Greater London's spatial development over the next 25 years through holistic strategies in transport, the environment, economic development, housing, culture and public health. It calls for prioritising active mobility, allocating additional street space to pedestrians and cyclists, making more efficient use of road space, versatile uses of infrastructure throughout the day, and encouraging off-peak deliveries.[23]

2 **Mayor's Transport Strategy (Mar 18)** Focussing on transport, this plan provides detailed metrics and strategies for achieving mode shift targets toward active mobility and public transport. It also introduces a policy of "Good Growth", guiding future population increases in a healthy and sustainable way. Particularly germane to FlexKerbs, it proposes varying street space allocation by time of day and day of week, while thoughtfully designing and managing the kerb, particularly for shared vehicles.[24]

3 **Healthy Streets for London (Feb 17)** Providing a framework for the "Mayor's Transport Strategy", TfL's "Healthy Streets for London" advances a laser focus on street design as a means of delivering an array of public health benefits for London residents. Through 10 "Healthy Streets Indicators" (shown in Figure 13), this manual lays out TfL's landmark policies and strategies for achieving the Mayor's goal of Londoners completing 20 minutes of active travel each day.[25]

4 **City of London: Transport Strategy, Vision, Aims and Outcomes: Draft for Consultation (Jun 18)** In June 2018, the City of London released its first long-term transport strategy, which will guide transport investments across the Square Mile over the next 25 years. Within this plan, the City calls for flexibly varying street usage throughout the day and year to improve space efficiency, leveraging autonomous vehicles as a traffic reduction and inclusive transport tool, prioritising the needs of pedestrians and cyclists, changing the requirements for goods movement, and readying streets for unplanned disruption.[26]

These four documents constitute the core influences in our FlexKerb schedule development for Cheapside. Together, they informed our Cheapside modal hierarchy, which is defined in the next section.

Figure 13: Healthy Streets Indicators, Source: Lucy Saunders

Modal hierarchy

Clear patterns of modal priorities for street space allocation emerge across these four policy documents. In order to drive FlexKerb uses in a consistent and practical fashion, we established a clearly defined hierarchy of modal priority that will dictate how Cheapside's FlexKerbs could allocate kerb space throughout the course of the day (see Figure 14a).[27]

In its most simplistic form, transport modes are arranged, from top to bottom, by active mobility, mass transport, delivery and servicing, shared services, and privately-owned vehicles. It is important to note, though, that this pyramid is unique to Central London and, specifically, to Cheapside.

A FlexKerb in a different section of London or in a different town or city with lower rates of public transport usage would look different from the one shown in Figure 14a. And it is important to note that, while this pyramid dictates kerbside prioritisation, exceptions must exist for certain users, such as disabled travellers and emergency services, which are discussed in Section 3.4.

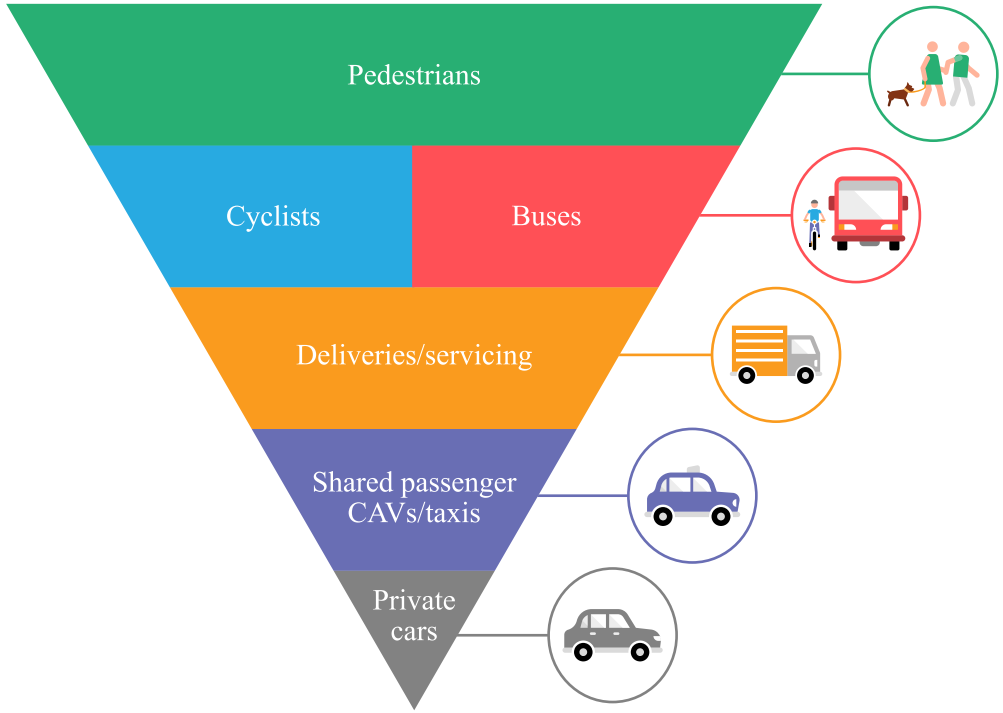


Figure 14a: Cheapside FlexKerb hierarchy of transport modes

[27] While the contents of this hierarchy were gleaned from the four policy documents, it is not officially endorsed by the City of London or any other public entity. It is meant to serve as a conceptual input into illustrative FlexKerb functionality.

1 Pedestrians
All four of these policy documents agree that street space should be allocated to pedestrians whenever and wherever possible. Making walking the natural and most desirable transport choice contributes to a cross-cutting set of goals from cleaner air to healthier lifestyles and more space-efficient movement.

2 Cyclists and buses
After pedestrians, cyclists and mass transport share the second level on the pyramid. While some policy documents rank cyclists and pedestrians together, or rank cyclists above buses, the City of London's public consultation revealed that Square Mile residents, commuters and businesses tend to prioritise cyclists and buses about equally.[28] Thus, these two modes capture the second-highest priority for their ability to move passengers more efficiently than cars.

3 Deliveries/servicing
Kerbside access for delivery and servicing vehicles is critical to the economic viability of a high street. However, most policy documents also recognise the contribution delivery trips make to congestion during peak hours and propose retiming deliveries or discouraging lorry and van travel during the times when streets are busiest with other users. For this reason, delivery vehicles occupy the middle rung of the pyramid, below active and mass transport but above cars.

4 Shared passenger CAV/taxi
All of the four primary policy documents agree that street policy and design should discourage car travel. However, vehicle sharing is widely recognised as a strategy to reduce car ownership and slim down the size of the total vehicle fleet.

Moreover, providing ample kerb space for CAVs will help to unlock their benefits and reduce their potentially negative impacts on streets. For this reason, shared vehicles, such as CAVs, private hire vehicles (PHVs) and taxis, fall near, though not at, the bottom of the pyramid.

5 Private cars
By 2050, car ownership rates should be far lower than today. A key strategy to achieving this decline is to reduce the amount of road and kerb space allocated to them. In particular, a Central London high street like Cheapside should reserve little to no street space for private vehicle standing or parking. Accordingly, private vehicles receive the lowest priority.

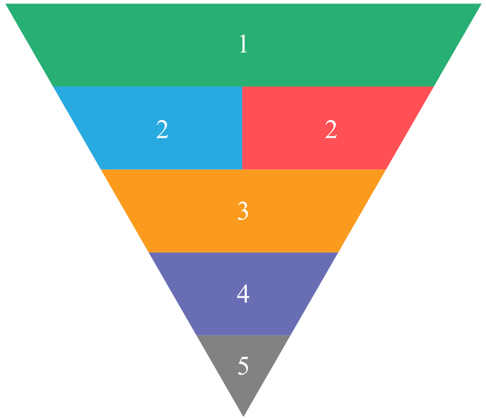


Figure 14b: Cheapside FlexKerb hierarchy of transport modes

Demand data

While local area policy drives FlexKerb space allocation, demand data informs their operation in real time, allowing them to be both responsive to and predictive of changes in usage patterns. To inform The Study's FlexKerb schedule and VISSIM model, we processed a series of datasets from the City of London that summarised multimodal travel data and detailed kerbside loading activity. The City collected demand data through manual classified counts (MCC) in October 2016 (before the experimental daytime closure of Bank Junction to all modes except buses and bicycles) for cars, taxis, goods vehicles and cyclists, while pedestrian and bus data was collected in November 2017. This section details these data inputs.

All modes

As shown in Figure 15, Cheapside experiences three notable peak periods each day: the Morning Peak (roughly 7:00–9:00), a Lunchtime Peak (roughly 12:00–14:00) and an Evening Peak (roughly 16:00–18:00). Volumes reduce overnight, particularly after 23:00, when many pubs in the City close, and between the hours of 2:00–5:00.

Pedestrians

With nearly 47,000 pedestrians passing through the study area in a day, walking comprises the vast majority (nearly 80%) of total trips on Cheapside. For this reason, the pedestrian demand profile (Figure 16) closely resembles that of all modes.

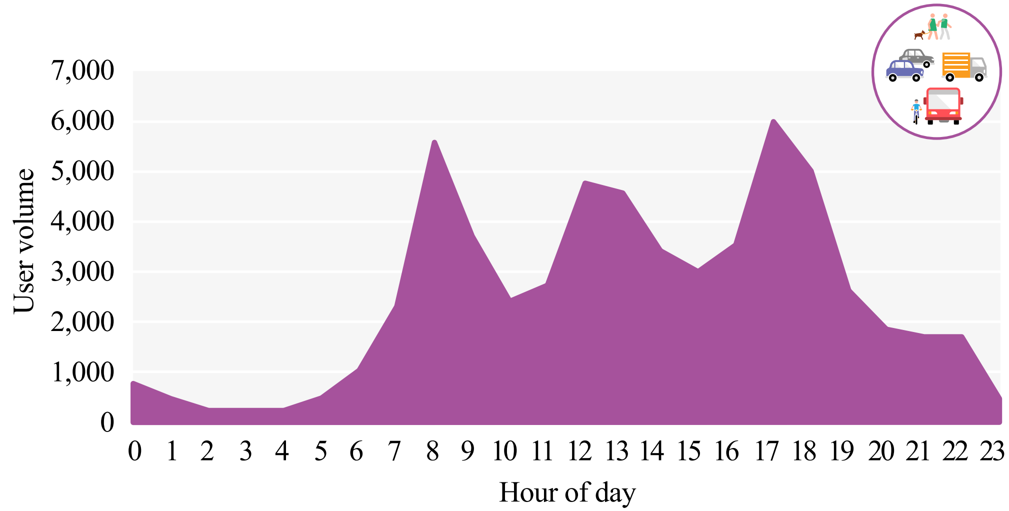


Figure 15: Cheapside demand profile - all modes

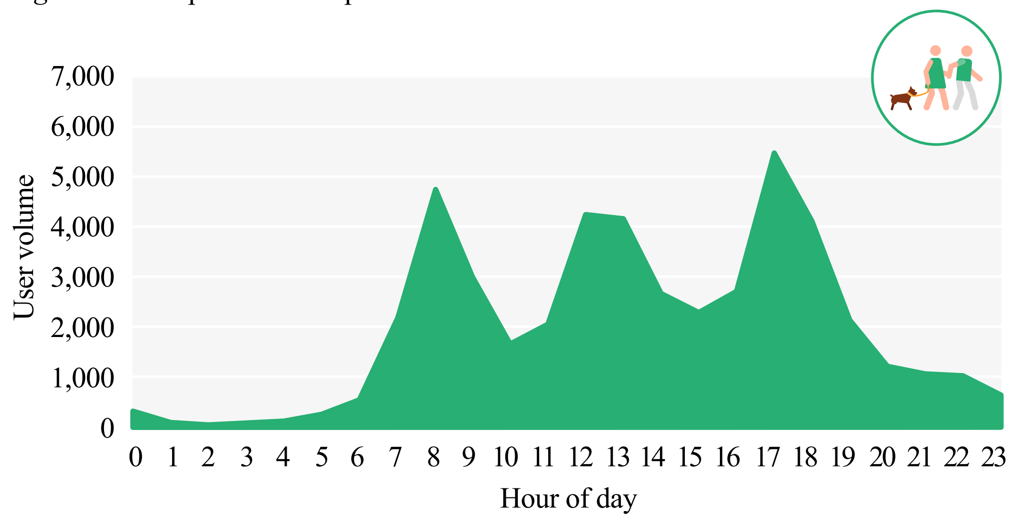


Figure 16: Cheapside demand profile - pedestrians

Cyclists

Cyclists comprise the next highest user group, with more than 3,000 cyclists passing through the study area per day. Cheapside experiences distinctive spikes in cyclist activity during the Morning and Evening Peaks, with substantially lower volumes at midday and late at night.

Cars

While Cheapside presently sees minimal car traffic due to daytime restrictions at Bank Junction, in 2016, when these counts were recorded, cars represented the study area's third-highest user group. As opposed to cyclists and pedestrians, car volumes dip slightly during peak hours and rise significantly in the evenings.

Taxis

Trailing just behind cars in volume, black taxis also experience a rise in volume later in the day, with peak taxi volumes (about 200 per hour) travelling through Cheapside around 20:00–22:00. Taxi volumes decline slightly during the Evening Peak and reduce during early-morning hours when most area businesses are shut.

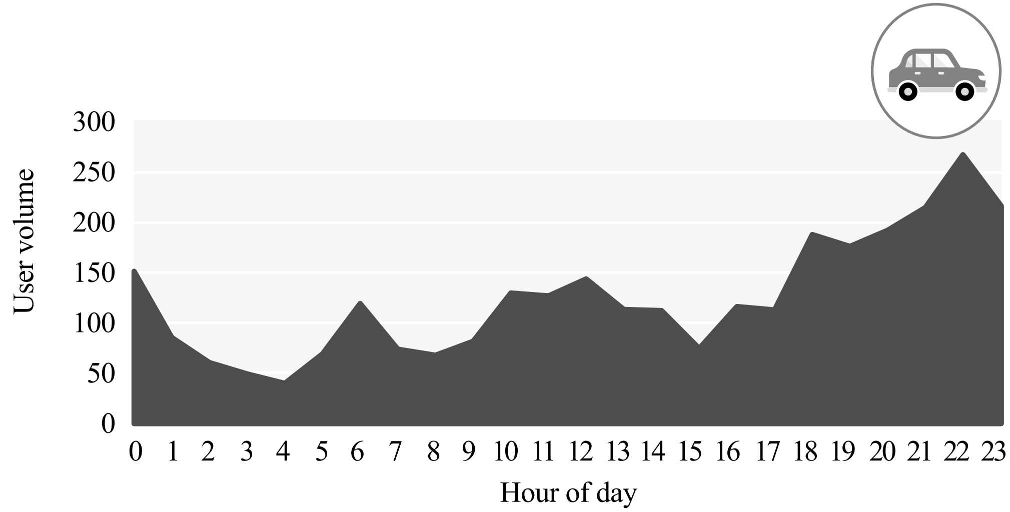


Figure 18: Cheapside demand profile - cars

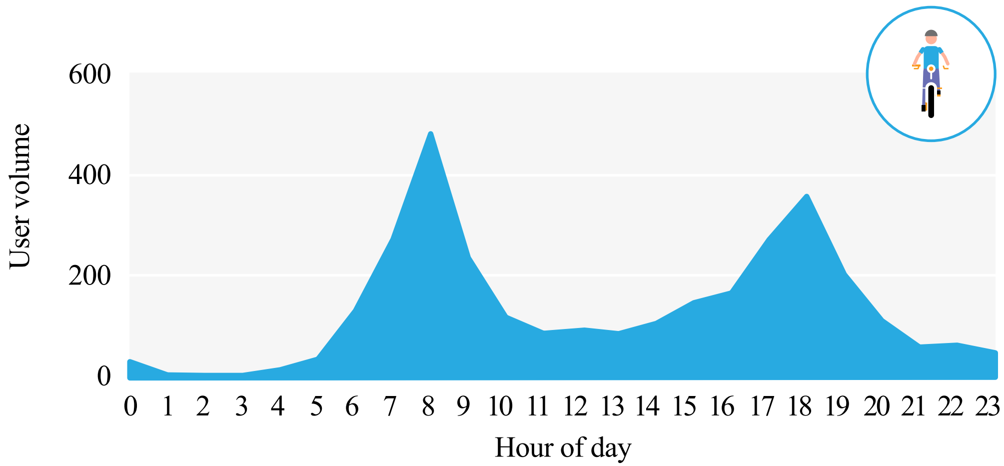


Figure 17: Cheapside demand profile - cyclists

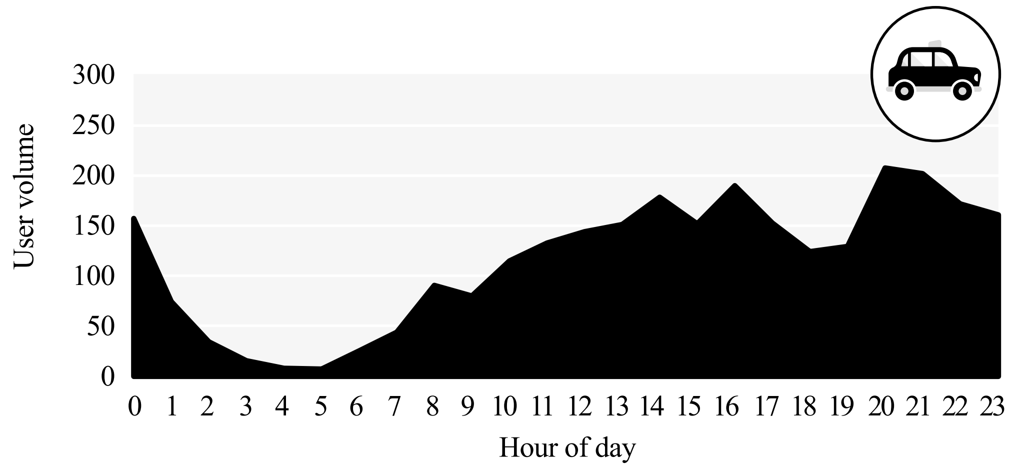


Figure 19: Cheapside demand profile - taxis

Light Goods Vehicles (LGVs)
More than 1,500 LGVs pass through Cheapside in 24 hours, with volumes highest (approximately 120 per hour) between 6:00 and 11:00 and steadily declining over the course of the day.

Buses
With four bus routes passing through, including one night bus, Cheapside sees a relatively steady flow of buses throughout the course of the day. Between 7:00 and 23:00, about 50–60 buses pass per hour, though this figure drops to 30–40 in the overnight hours.

Other Goods Vehicles (OGVs)
Finally, a comparatively lower volume of OGVs passes through Cheapside. These larger lorries peak at 8am with about 32 per hour, then steadily decrease in volume over the course of the day.

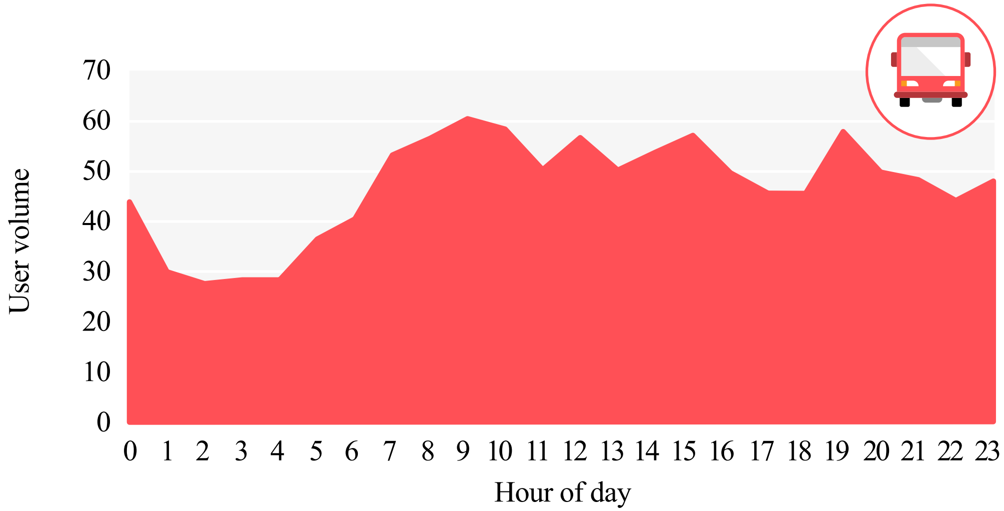


Figure 21: Cheapside demand profile - buses

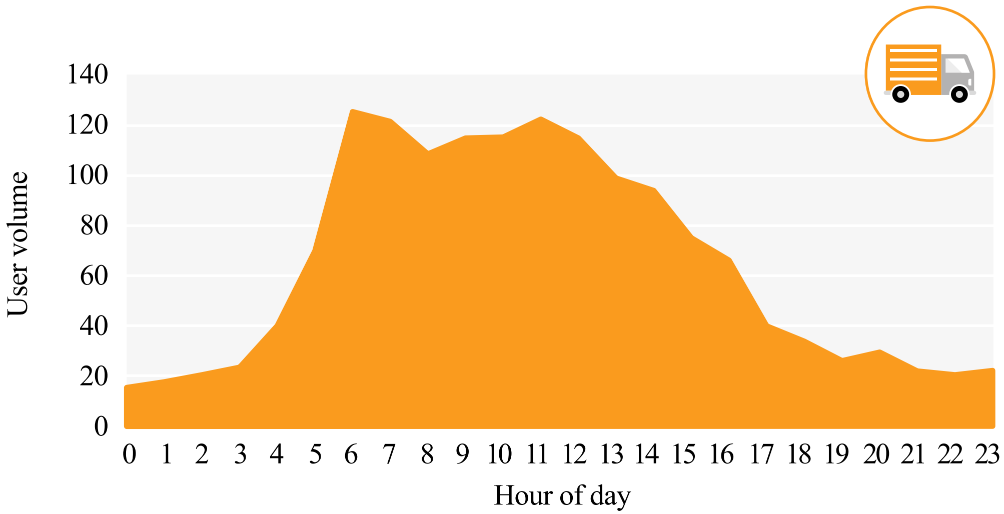


Figure 20: Cheapside demand profile - LGVs

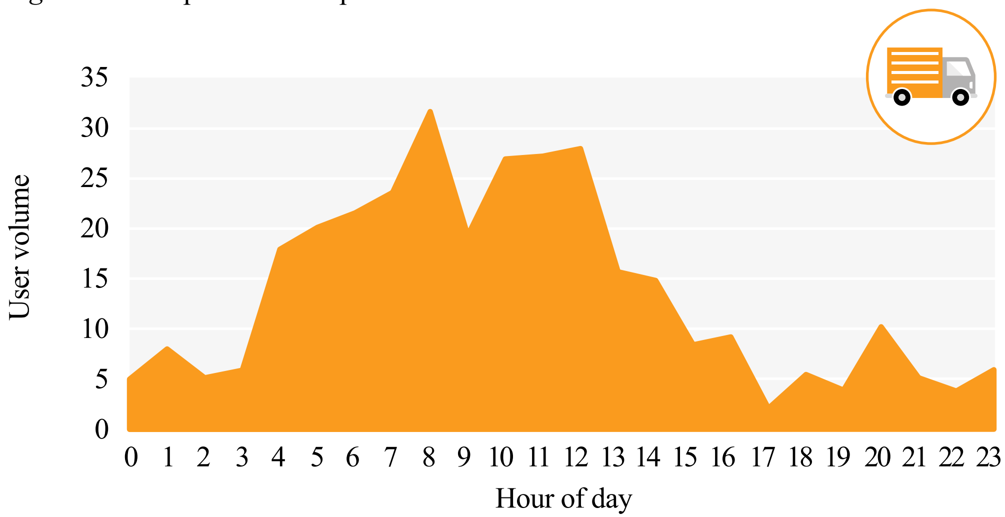


Figure 22: Cheapside demand profile - OGVs

FlexKerb schedule development

> Automated vehicles and other new transport technologies and services will work for the City, supporting efforts to reduce motor traffic and deliver inclusive, safe, attractive and vibrant streets.
>
> City of London: Transport Strategy, Vision, Aims and Outcomes (2018)

In the absence of TDMC technology for automatically fusing local policy with demand data, we have developed a robust methodology for manually mimicking this algorithmic process to develop an illustrative weekday FlexKerb schedule for the Cheapside study area for one weekday. While a true FlexKerb would respond to demand and kerbside reservations, the schedule produced for The Study represents a static snapshot of how a typical weekday's FlexKerb could look. This section describes our methodology in detail, then explains the nuances of the finalised schedule.

Schedule-building methodology

The ultimate goal of the FlexKerb schedule is to serve local policy by accommodating or managing demand.

We achieved this for Cheapside through the following five-step methodology:

1 Locate potentially flexible spaces

Many London carriageways are flanked with two continuous kerbsides, which would allow for uninterrupted FlexKerbs along the entire length of street. However, Cheapside, as described in Section 3.2, consists of two moving lanes and two multifunctional kerbside "flex spaces", each located between a moving lane and the footway. These flex spaces contain an array of public amenities that must remain fixed, interrupting potential FlexKerb continuity.

Working within these constraints, we visited Cheapside to map which segments of the study area can be flexed and which cannot. Table 1 describes the restrictions within the flex spaces, and Figure 23 shows the unconstrained segments of Cheapside that are suitable for conversion into FlexKerbs. This information was compiled through consultation with the City of London, and Arup produced the final results of Table 1.

Amenity	FlexKerb Policy	Flexible?
Trees	May not be moved.	No
Pedestrian crossing	May not be moved.	No
Bus shelter	May be moved to a nearby location but cannot be removed.	No
Cycle stands	May be moved to a nearby location but cannot be removed.	No
Cycle hire docks	Assumed to be less reliant on fixed docks in the future. Can be removed and replaced with cycle racks nearby.	Yes
Loading/taxi bays	Policy-driven, function can change in future.	Yes

Table 1: FlexKerb policies around public amenities located within flex spaces

2 Assemble kerbside matrix

Next, to distil Cheapside's kerbs into a manageable and finite set of spaces, we divided the study area into 58 five-metre bays and assembled them in a matrix. We then plotted the existing north-side and south-side kerb uses found within each bay to determine, based on the information in Table 1, which could be flexible and which could not. In total, approximately 60% of Cheapside's kerb space could be converted into FlexKerb bays.

3 Define FlexKerb parameters

To understand how each FlexKerb bay could function on Cheapside and assign space accordingly, we used the following parameters to inform the schedule:

- As pedestrians sit atop the modal hierarchy pyramid, space should always default to pedestrians when possible. Even a single pedestrianised FlexKerb bay can improve the walking environment when Cheapside's footways become heavily congested during peak hours.
- Delivery vehicles require at least two adjacent bays (a minimum of 10 metres total).
- Passenger CAVs will likely be smaller than non-autonomous cars today, so one bay should be sufficient to accommodate CAV pickup and drop-off.
- Passenger CAV ranks should be situated toward the end of the street segment, closer to the London Underground stations.
- Since public amenities preclude continuous kerbside uses on Cheapside, cycle lanes would be interrupted and therefore are not recommended. However, to improve safety and comfort for the high volume of cyclists on Cheapside during peak hours, the FlexKerb could be used to create extra-wide cycle lead-in lanes approaching the junctions to provide extra space for cyclists to wait.
- Similarly, a continuous kerbside bus lane would not be possible along Cheapside. Thus, while other high streets could allocate FlexKerb space to buses when appropriate, for the purposes of The Study, buses are not included in the Cheapside FlexKerb schedule.

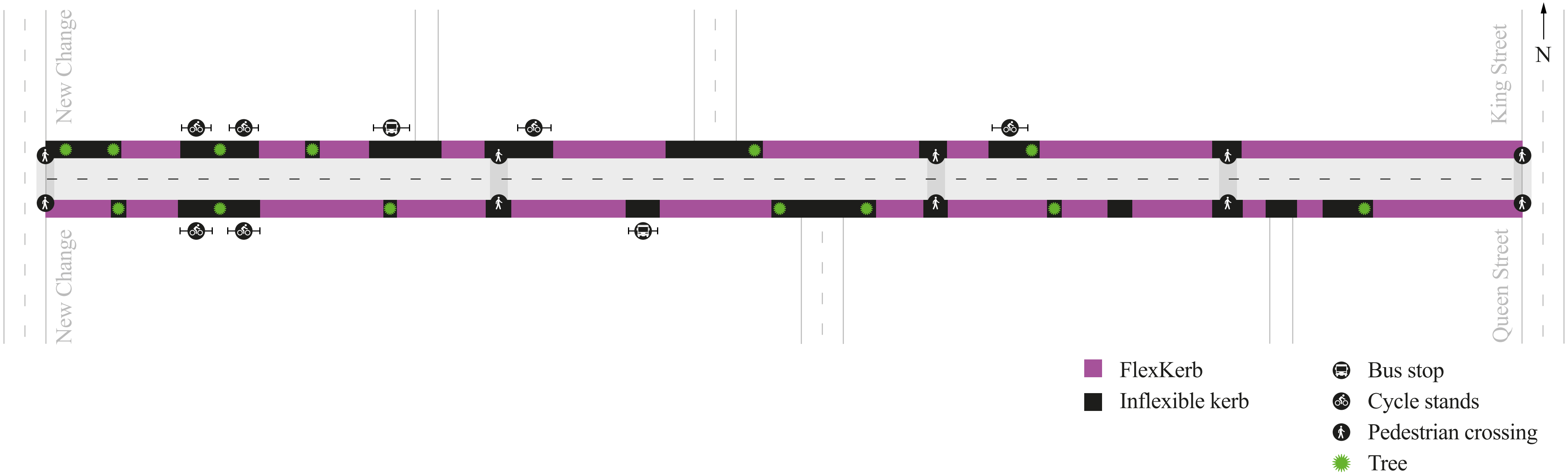


Figure 23: Segments of Cheapside suitable for conversion into FlexKerbs

4 Determine optimal kerbside uses
Determining the optimal uses for each segment of kerbside space and populating the matrix accordingly constituted the core of the schedule-building process. Completing this stage required carefully consulting both the modal hierarchy and the demand data for Cheapside, as well as the parameters defined above.

First, we divided the day into 24 one-hour increments, assuming that, for simplicity and illustrative purposes only, kerb uses would remain constant for at least one hour. Within each hour, we referred first to demand data for each mode to determine how and when each mode uses Cheapside. We then consulted relevant policies to determine whether demand should be accommodated (allocated extra space) or mitigated (allocated minimal space or restricted entirely) at that time of day.

We repeated this iterative process for each five-metre bay to fill out an entire day's worth of FlexKerb programming.

While the entire 24-hour schedule can be found in Appendix C, this section shows the schedules for four highly distinct time periods and explains the rationales behind each (Figures 24-31).

5 Define exceptions
While the FlexKerb schedule governs permitted uses of the kerb, exceptions exist that will allow certain users and uses to override regulations. Some exceptions include the following:

- While pedestrians occupy the highest rung of the modal hierarchy pyramid, emergency vehicles always take priority over all other users. When an ambulance, fire engine, or police car needs to pass quickly, FlexKerbs can switch to emergency operation mode and prohibit all other users. This feature would require a built-in warning period, indicated to street users through visual cues such as flashing lights, akin to a railway level crossing, or audible indicators like sirens and/or other recognisable tones.
- FlexKerbs can also support London's accessibility aspirations. To help disabled travellers to safely and comfortably reach their destinations, FlexKerbs can allow CAVs carrying disabled passengers to use any available bay currently accepting vehicles. Similar to Blue Badge parking regulations today, in future, disabled travellers may apply for an "e-placard", which will allow them to reserve any unused kerb space allocated to loading, buses or CAVs.

FlexKerb schedule *Morning Peak*

Demand	High pedestrian volumes
Policy	Pedestrians top priority, particularly when footways are most congested
Allocation decision	Nearly 80% of FlexKerb space to pedestrians

Demand	High cyclist volumes
Policy	Cyclists second-highest priority
Allocation decision	FlexKerb space adjacent to cycle lead-in lanes to cyclists, making extra-wide lanes

Demand	High LGV and OGV volumes
Policy	Limit deliveries during Morning Peak
Allocation decision	Manage demand—no bays for deliveries/ servicing

Demand	Low volume of taxis (proxy for shared CAVs)
Policy	Low on modal hierarchy, but small supply of kerb space needed to support attractiveness of CAVs and shared mobility
Allocation decision	Small CAV/taxi bays at junctions near Tube stations

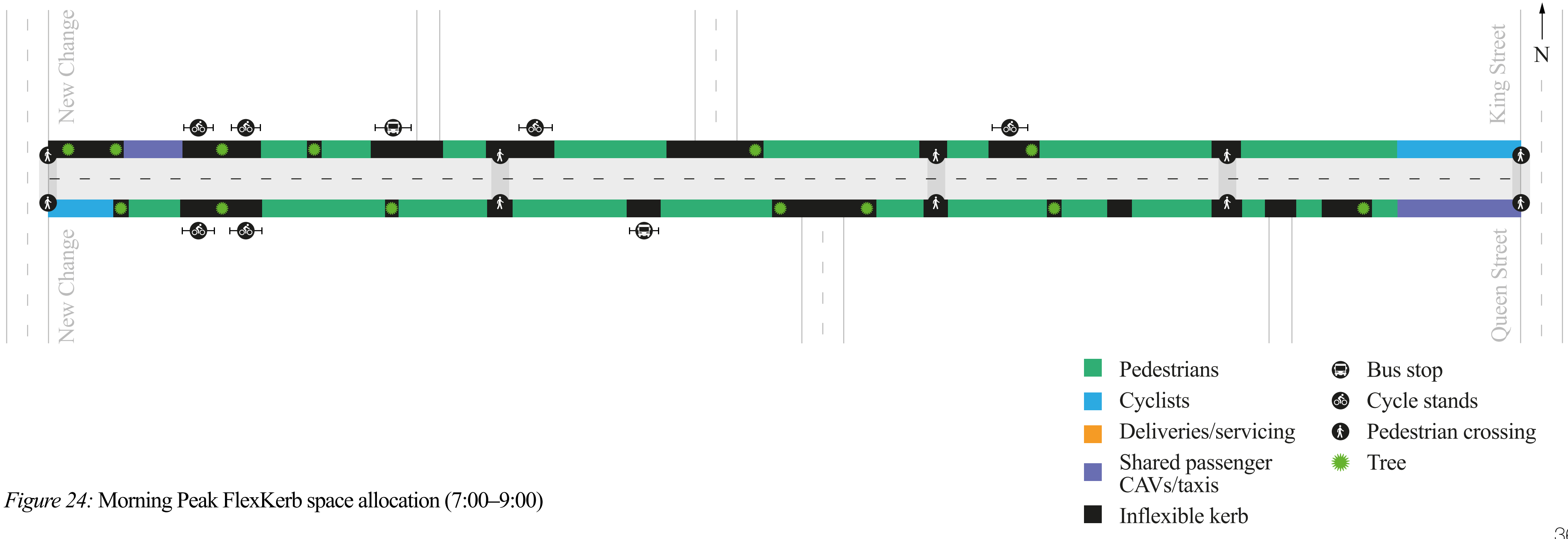


Figure 24: Morning Peak FlexKerb space allocation (7:00–9:00)

FlexKerb schedule *Lunch Rush*

Demand	High pedestrian volumes
Policy	Pedestrians top priority, particularly when footways are most congested
Allocation decision	More than 80% of FlexKerb space to pedestrians

Demand	Low cyclist volumes
Policy	Cyclists second-highest priority
Allocation decision	With minimal cyclist demand, cycle bays reallocated to pedestrians

Demand	High LGV and OGV volumes
Policy	Limit deliveries during Lunch Rush
Allocation decision	Manage demand—no bays for deliveries/ servicing

Demand	Taxi volumes increase from Morning
Policy	Low on modal hierarchy, but small supply of kerb space needed to support attractiveness of CAVs; additional cycle or loading space not needed
Allocation decision	Slightly increased provision of CAV/taxi bays

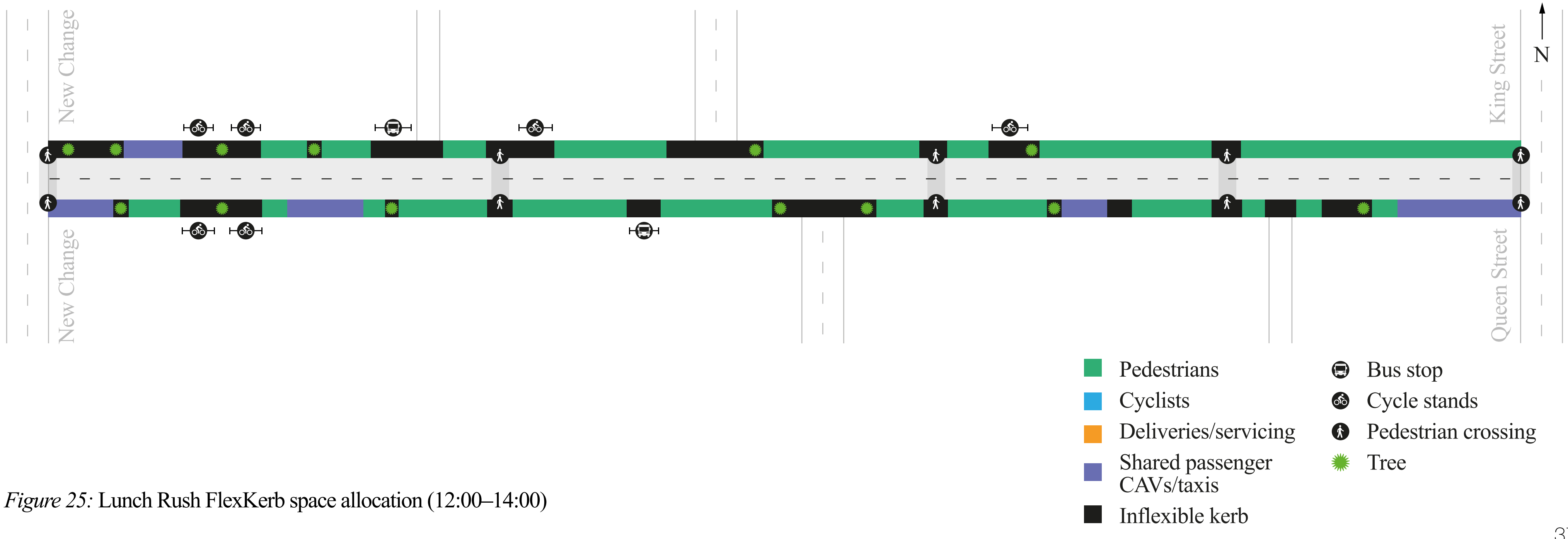


Figure 25: Lunch Rush FlexKerb space allocation (12:00–14:00)

FlexKerb schedule *Dinner Rush*

Demand	Moderate pedestrian volumes
Policy	Prioritise pedestrians; push for more nightlife in City of London
Allocation decision	Lower share of pedestrian space than Morning or Lunch, but still more than half of FlexKerb space dedicated to walking

Demand	Moderate cyclist volumes
Policy	Cyclists second-highest priority
Allocation decision	Small segments of FlexKerb adjacent to cycle lead-in lanes allocated to cyclists, providing extra-wide lanes at the junctions

Demand	Low LGV/OGV volumes
Policy	Encourage off-peak deliveries
Allocation decision	About one-fifth of FlexKerb space to deliveries/servicing

Demand	High taxi volumes
Policy	Push for more nightlife in City of London
Allocation decision	Increase in CAV/taxi bays across the study area

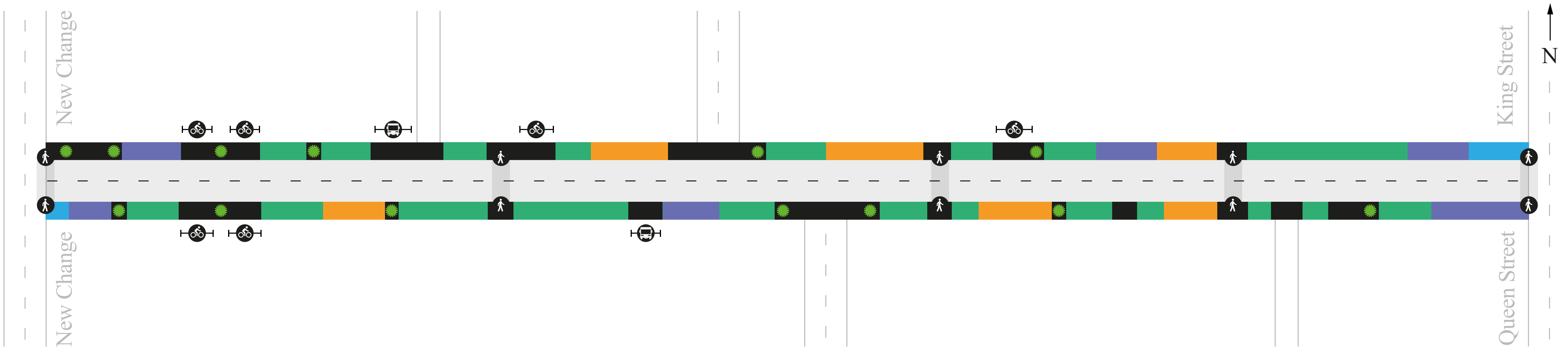


Figure 26: Dinner Rush FlexKerb space allocation (19:00–21:00)

FlexKerb schedule *Overnight*

Demand	Low pedestrian volumes
Policy	Footways can accommodate low demand
Allocation decision	Pedestrian space reduced to about half of all FlexKerb space

Demand	Low cyclist volumes
Policy	Carriageway can accommodate low demand
Allocation decision	With minimal cyclist demand, cycle bays reallocated to CAVs/taxis

Demand	Low LGV/OGV volumes
Policy	Encourage off-peak deliveries
Allocation decision	Delivery/servicing bays increased to about one-third of FlexKerb space

Demand	Low taxi volumes
Policy	Push for more nightlife in City of London; public transport reduced
Allocation decision	Increase in CAV/taxi bays across the study area

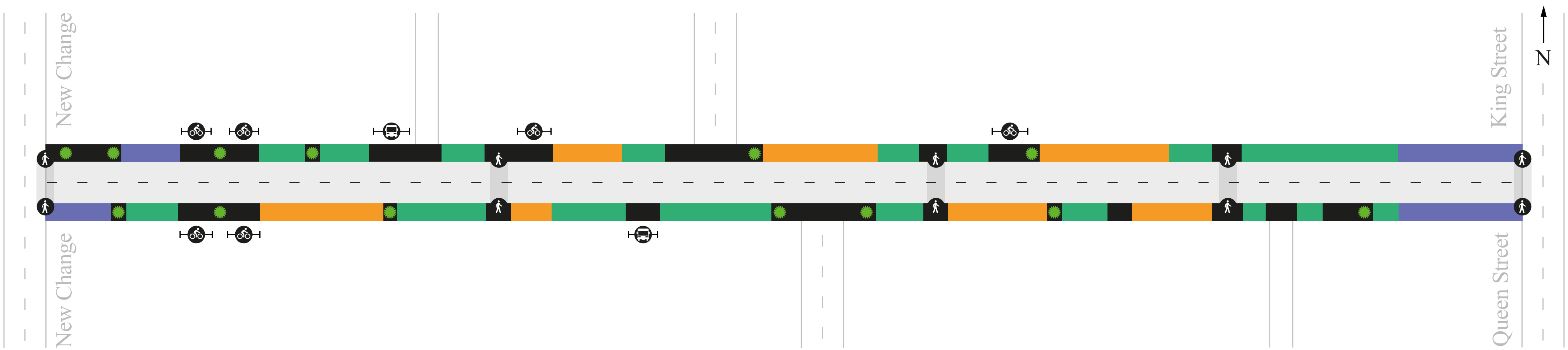


Figure 27: Overnight FlexKerb space allocation (2:00–4:00)

Figure 28: Morning Peak

Figure 29: Lunch Rush

Figure 30: Dinner Rush

Figure 31: Overnight

Testing and validating FlexKerbs

To demonstrate the technical feasibility of FlexKerbs and the proposed 24-hour schedule, and to test FlexKerbs' effectiveness at dynamic kerbside management on a CAV-enabled street, we built a VISSIM microsimulation model of the Cheapside segment. VISSIM, a modelling software developed by PTV Group is widely used across the transport industry to test the impacts of new developments and transport schemes on a road network.

Microsimulation modelling is effective at replicating a range of modes and behaviours on the transport network, enabling detailed observations of the impact of the FlexKerbs schedule. However, microsimulation modelling for CAVs is a relatively new field of study, calling for a set of informed assumptions around anticipated CAV behaviours, described in more detail in this section.

Modelling Assumptions
Microsimulation modelling is often used to replicate existing conditions and test an intervention's impacts across a city, town or neighbourhood's entire street network. This usually requires extensive time and data to calibrate and validate the existing conditions model before any testing can be carried out. However, the purpose of the modelling for The Study was to capture existing demand and test kerbside activity for just a short segment of Cheapside, somewhat simplifying the model's early background work. The next phase of work could include the development of a network validated base-year model to test FlexKerbs' effectiveness across a wider, integrated network.

For The Study's microsimulation model, we developed three scenarios to test and assess FlexKerbs:

· Existing conditions
· CAV Future No FlexKerbs
· CAV Future With FlexKerbs

For each of these scenarios, we modelled the four distinct time periods identified in Section 3.4: Morning Peak, Lunch Rush, Dinner Rush and Overnight.

The following section explains the logic behind each scenario and the underlying assumptions used to develop them.

Existing conditions
As discussed in Section 3.3, we first processed the data for Cheapside to create hourly demand inputs, segmented by each mode found within the study area. While this demand data formed a strong basis for the existing conditions model, we made several assumptions to fill gaps that this dataset did not capture.

For instance, while PHV trips have increased in Central London in recent years, largely driven by the growth of Uber in London, the observed data does not differentiate between private cars and PHVs. We felt this differentiation was important for Cheapside and its kerbside activity, as PHVs require pickup and drop-off space. Informed by a literature review and consultation with the City of London, we assumed that PHVs constitute 60% of cars on Cheapside.

In addition, we developed a set of assumptions around how different modes interact with the kerb. These parameters were largely informed by a detailed loading survey that the City of London carried out in this area over two weekdays in early 2017, before the closure of Bank Junction to cars during daytime hours. This meant that we could broadly infer some of the stopping and loading activity to inform the model. Table 2 summarises the kerbside assumptions by mode in the Existing scenario.

Mode	Kerbside activity	Percentage of vehicles that stop	Dwell time
Buses	Fixed bus stops	All	20 seconds[29]
Deliveries/ servicing	Fixed loading bays	Varies by hour according to loading survey	Variable (1 min - 30 mins)
PHV	Stopping on street	10%	Variable (0 secs - 90 secs)
Taxi	Fixed taxi bay	10%	Variable (0 secs - 90 secs)
Private cars	No parking/stopping	-	-

Table 2: Kerbside activity assumptions by mode for Existing scenario

Assumptions around the CAV Future

Building on the existing conditions model, we developed a CAV Future model. What makes this particular model unique is that it tests the interactions and behaviours of CAVs, a new mode of transport that does not currently operate on today's roads. Consequently, as laid out in Section 3.1, we developed a set of assumptions for this scenario, which we based on existing research and reputable industry expert opinion. Of the existing vehicle fleet, we used the following assumptions about 2050:

- 95% of the freight fleet is operating at CAV Level 5 autonomy (fully autonomous);
- 50% of the PHV fleet is operating at CAV Level 5 autonomy;
- 50% of the private car fleet is operating at CAV Level 5 autonomy; and
- 100% of the black taxi fleet is operated by human drivers.

VISSIM allows for the modelling of some finite nuances of vehicle behaviour, such as vehicle following distance and visibility radius. To better replicate anticipated CAV behaviours, we varied some of the traditional parameters assigned to conventional cars. Table 3 shows the comparison of the traditional vehicles vis-à-vis CAV parameters used in The Study, which are based on ongoing Arup research. In general, CAVs can safely drive closer to other vehicles than conventional cars can.

Of greater relevance to this study are the assumptions on shared mobility and the CAV kerbside and stopping behaviour. Based on the City of London's loading activity survey data and the assumption that all the passenger CAVs will operate as part of a shared mobility system, we assumed that 30% of shared CAVs will stop to pick up or drop off passengers on Cheapside. Table 4 (overleaf) summarises the share of CAVs by mode and the stopping assumptions by mode in the CAV future, which applies to both the With and No FlexKerbs scenarios.

This Study does not uplift demand for 2050. Our aim is to test the FlexKerb concept with existing levels of demand on an already busy street. Rather, CAVs have been apportioned across existing levels of demand. Further studies could explore the extent to which FlexKerbs could contend with changes in demand volume.

Parameters	Conventional cars	CAVs
Car following		
Look-ahead distance (m)	250	600
Look-back distance (m)	150	300
Observed vehicles	4	10
Average standstill distance (m)	2	1
Lane change		
Minimum headway (m)	0.5	0.4
Safety distance reduction factor	0.6	0.5
Lateral behaviour		
Minimum lateral distance		
Distance standing (m)	0.2	0.15 - 0.2
Distance driving (m)	1.0	0.75 - 1.0

Table 3: CAV parameters used in VISSIM compared to conventional vehicles

CAV Future scenarios: No FlexKerbs and With FlexKerbs

After establishing what the future fleet may look like for this illustrative test on Cheapside, we developed two separate future scenarios:

- CAV Future No FlexKerbs
- CAV Future With FlexKerbs

Testing the CAV future model under both scenarios helped us to identify the true benefit FlexKerbs could deliver and explore how a future street would function without the deployment of FlexKerb technology. The key kerbside behaviours are summarised in Table 5.

Mode	% CAV	Reasoning	Percentage of vehicles which stop	Dwell times
Buses	-	For this illustrative example, TfL buses are assumed continue to perform as in the existing scenario.	All	20 seconds
Deliveries/ servicing	95%	Numerous studies predict that the freight industry will be one of the first modes to switch to full autonomy.	Varies by day according to loading survey	Variable (1 min - 30 mins)
PHV	50%	The predictions and forecasts for these vary widely across different studies. For this illustrative example, 50% L5 CAV by 2050 is assumed for shared cars/PHVs.	30%	Variable (0 secs - 90 secs)
Taxi	0%	For this illustrative example, black taxis are assumed to continue as non-autonomous cars.	10%	Variable (0 secs -90 secs)
Private cars	50%	The predictions and forecasts for these vary widely across different studies. For this illustrative example, 50% L5 CAV by 2050 is assumed for private cars.	-	-

Table 4: Future fleet and stopping assumptions by mode for the CAV future

Mode	Behaviours and regulations in a 'No FlexKerbs' future	Behaviours and regulations in a 'With FlexKerbs' future
Buses	Same as existing	Same as existing
Deliveries/ servicing	Permitted to use existing loading bays throughout the day	Permitted to use the bays shown in yellow (travel demand management is required)
PHV	Not permitted to stop in loading bays and must stop on the carriageway	Permitted to use the bays shown in purple
Taxi	Permitted to use existing taxi bay	Permitted to use the bays shown in purple
Private cars	No kerb access on Cheapside	No kerb access on Cheapside

Table 5: Future kerbside activity behaviours

Microsimulation model results

Overall the models show that FlexKerbs offer a wide range of benefits to all street users on a future CAV-enabled street. Comparing the No FlexKerbs and With FlexKerbs future scenarios, FlexKerbs offer dramatic reductions in vehicle delay, a safer and more comfortable experience for cyclists when and where they need it, a more efficient use of kerb space and an extra-wide footway to accommodate high pedestrian volumes.[30] For this particular analysis we focussed on the two busiest time periods of the day: the Morning Peak and the Lunch Rush. Table 6 and Table 7 describe the VISSIM model results in more detail.

Morning Peak

Model	General observations	Average delay*
Existing Conditions	A fairly busy segment, the peak demand for all modes clash, which slows down the overall throughput. Cyclist demand struggles to move effectively through the segment.	157 seconds
CAV Future No FlexKerbs	Shared CAVs cause additional delays on the carriageways and blocks cyclists, buses and cars. Taxis can use the taxi rank successfully but often the kerb is left unused by those who most need it.	192 seconds
CAV Future With FlexKerbs	The introduction of FlexKerbs allows buses, cyclists and other motorists to flow through the network smoothly. The assumed increase in pickup and drop-off CAV or PHV trips is easily accommodated within the kerb space provided by the FlexKerb schedule. The pedestrian peak means extra kerb space is available for walking and social activity. Cyclists have a wider and safer lane at each junction, which comfortably accommodates the high demand in the Morning Peak.	51 seconds

Table 6: Morning Peak model results
*Average delay is the delay across all vehicles across the model

Lunch Rush

Model	General observations	Average delay*
Existing Conditions	Fairly quiet carriageway, mainly buses and delivery vehicles.	76 seconds
CAV Future No FlexKerbs	Shared CAVs causes additional delays on the carriageways and blocks buses and cars. Taxis can use the taxi rank successfully, but often the kerb is left unused by those who most need it.	67 seconds
CAV Future With FlexKerbs	The introduction of FlexKerbs allows buses, cyclists and other motorists to flow through the network smoothly. The pedestrian peak means extra kerb space is available for walking, street vendors and social activity. There are shared CAV bays, which are utilised, and no delivery bays, which means deliveries would need to be retimed or relocated.	54 seconds

Table 7: Lunch Rush model results

[30] The VISSIM models do not incorporate actual pedestrian data. Therefore, pedestrian activity depicted in the model is illustrative only, and volumes shown are far below actual demand. FlexKerb space designated to walking is identified by green bays.

Figures 32 and 33 show screenshots from the VISSIM model in 3D view, which depict the No FlexKerb CAV Future scenario for the Morning Peak and Lunch Rush.

Morning Peak (No FlexKerbs)

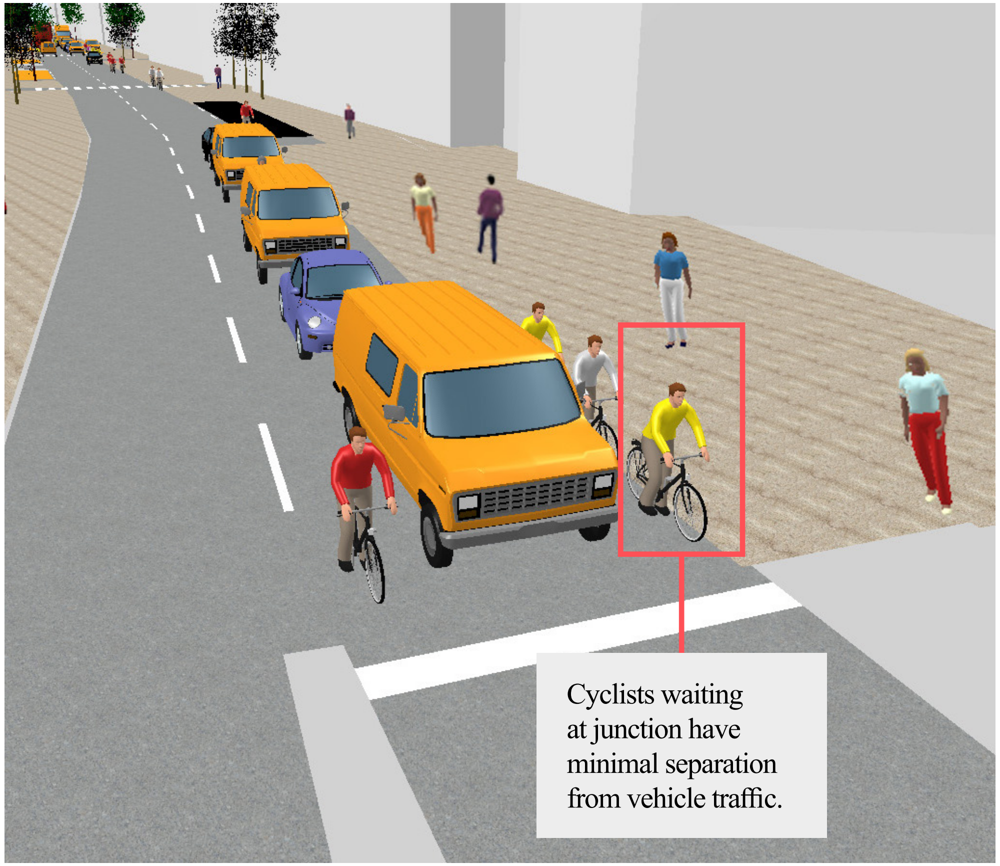


Figure 32: Morning Peak (No FlexKerbs) model screenshot

Lunch Rush (No FlexKerbs)

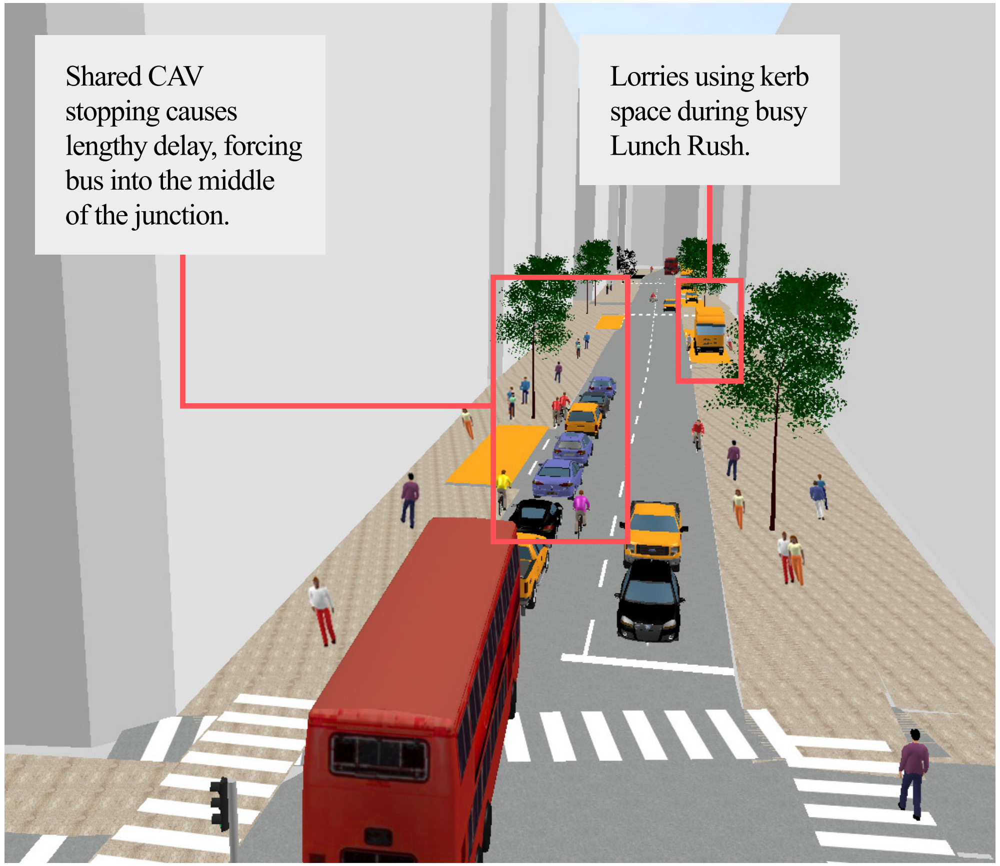


Figure 33: Lunch Rush (No FlexKerbs) model screenshot

Figures 34 and 35 show screenshots from the VISSIM model in 3D view with the introduction of FlexKerb technology. The microsimulation models demonstrate the benefit of a flexible kerbside schedule for both CAVs and other street users during the busiest times of day.

Morning Peak (With FlexKerbs)

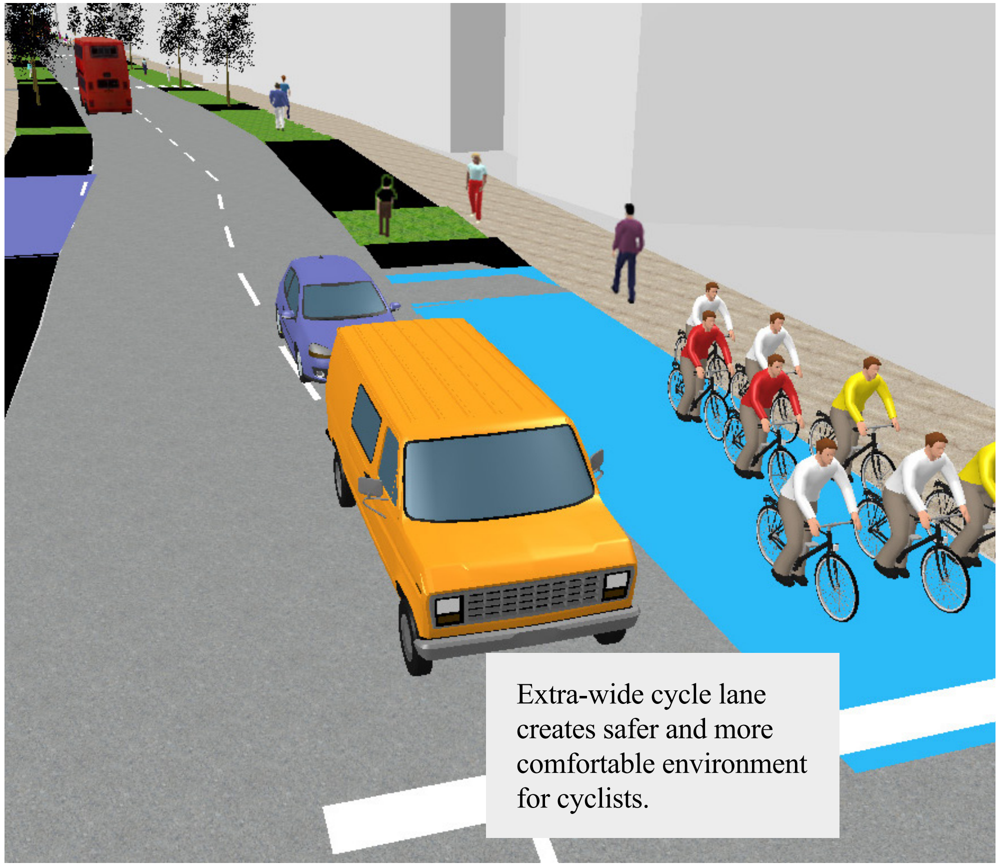


Figure 34: Morning Peak (With FlexKerbs) model screenshot

Lunch Rush (With FlexKerbs)

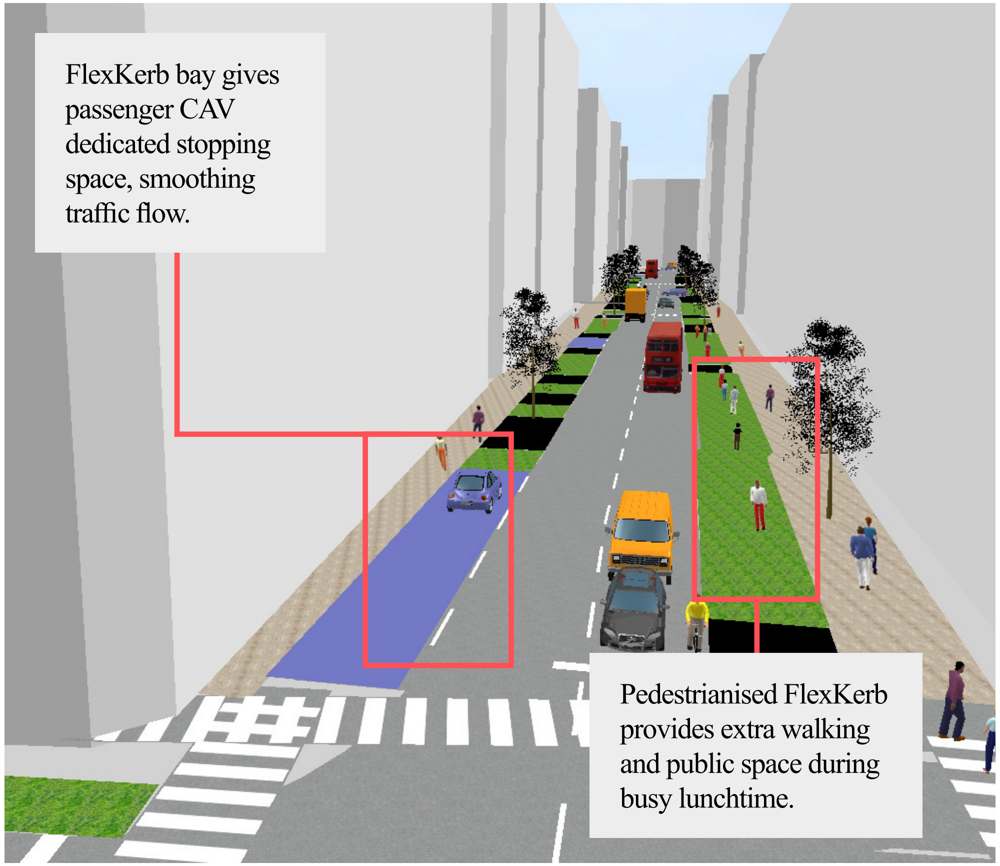


Figure 35: Lunch Rush (With FlexKerbs) model screenshot

Conclusions and next steps

> The specific balance between the different functions of any one space, such as its place-based activities and its function to facilitate movement, should be at the heart of how the space is designed and managed.
>
> Draft New London Plan (2017)

Conclusions and next steps

This study has demonstrated that FlexKerbs can effectively maximise the benefits and mitigate the risks of a CAV-enabled city. If implemented, FlexKerbs could viably adapt UK streets for the introduction of CAVs, while simultaneously enhancing streets for walking, cycling and public transport. We have substantiated the following key points:

1 FlexKerbs are technologically feasible
A range of existing and future technologies could be employed to build and implement the various components of a FlexKerb network as described in this report.

2 FlexKerbs would balance the needs of all road users
While other CAV mobility solutions tend to prioritise the experience of vehicle passengers, FlexKerbs would be unique in their ability to enhance an urban environment for people walking, cycling and using public transport.

3 FlexKerbs would give councils proactive agency in achieving local objectives
With local policy driving their regulations, FlexKerbs would allow cities to shape street uses in a fashion that could achieve a cross-cutting set of goals.

4 FlexKerbs would enable efficient use of street space
By allocating kerb space to specific users only when they need it most and when local policy supports it, FlexKerbs would ensure that streets are consistently used in the most efficient manner possible.

5 FlexKerbs would work
As our microsimulation model demonstrates, FlexKerbs would successfully achieve their primary aims of supporting CAV deployment while enhancing public realm and active mobility.

To achieve this range of benefits, FlexKerbs must extend beyond words and images on a page into a real-world setting. To that end, the FlexKerbs concept has already generated a significant amount of interest and conversation in the media (see Appendix D), across the Arup world, and amongst a range of potential collaborators from the public, private and academic sectors who are interested in working to make FlexKerbs a reality.

For instance, WestTrans, a transport planning consortium of six West London boroughs, contacted and discussed with Arup to explore FlexKerbs as a practical approach to integrated, cross-borough freight management. Additionally, Arup met with several technology providers—including Umbrellium, Grid Smarter Cities and Humanising Autonomy—who expressed interest in partnering with Arup to build FlexKerb technology on streets. Moreover, a team of professors and researchers from University College London (UCL) reached out to Arup regarding collaboration on a multi-year study of dynamic road space allocation. Following the conclusion of the Roads for the Future competition, Arup will maintain these contacts and continue to pursue opportunities for partnership with a long-term goal of FlexKerb implementation.

The intelligence gathered through these conversations has revealed that the world is beginning to actively gear up for the introduction of Connected and Autonomous Vehicles. Various transport and technology practitioners and researchers are exploring a broad scope of interventions to pave the way for an autonomous fleet. What sets FlexKerbs apart from other infrastructure concepts is their capacity to allow public realm to evolve in tandem with changes to towns and cities and their residents. As built form changes, populations grow, and human behaviours adapt, FlexKerbs respond by optimising the use of existing spaces. This unique feature confers FlexKerbs with the singular power to enable seamless roadway adaptation toward higher CAV penetration without compromising the role of streets as cities' greatest public spaces.

References

1 National Infrastructure Commission. *National Infrastructure Assessment.* 2018.

2 Greater London Authority. *Mayor's Transport Strategy.* London: Greater London Authority, 2018.

3 Greater London Authority. *A Growing Population.* 2018. <https://www.london.gov.uk/what-we-do/planning/london-plan/current-london-plan/london-plan-chapter-one-context-and-strategy-0>.

4 Greater London Authority. *Mayor's Transport Strategy.*

5 Pavegen. *Dupont Circle, Washington, DC.* 2018. <http://www.pavegen.com/washington>.

6 Pavegen. *Dupont Circle, Washington, DC.*

7 Umbrellium. *Starling Crossing: Responsive Road Infrastructure.* 2018. <http://umbrellium.co.uk/initiatives/starling-crossing>.

8 Grid Smarter Cities. *Kerb: A New Way to Manage the Kerb Space.* 2018. <https://www.kerbuk.com>.

9 Grid Smarter Cities. *Kerb: A New Way to Manage the Kerb Space.*

10 Coord. *The future of mobility starts at the curb.* 2018. 08 August 2018.

11 Schroter, Regina. *Popup City.* August 7 2018. Website. 9 August 2018.

12 Sidewalk Labs. *307.* 2018. https://sidewalktoronto.ca/get-involved/307-landing.

13 Microsoft. *Microsoft Soundscape: A map delivered in 3D sound.* 2018. Website. 23 August 2018.·

14 Bloomberg Aspen Initiative on Cities and Autonomous Vehicles. T*aming the Autonomous Vehicle: A Primer for Cities.* Long Island City, NY: Bloomberg Philanthropies, 2017.

15 Bloomberg Aspen Initiative on Cities and Autonomous Vehicles. *Taming the Autonomous Vehicle: A Primer for Cities.*

16 Greater London Authority. *The London Plan: The Spatial Development Strategy for Greater London, Draft for Public Consultation*. London: Greater London Authority, 2017.

17 Littman, Todd. *Autonomous Vehicle Implementation Predictions: Implications for Transport Planning*. Victoria, BC: Victoria Transport Policy Institute, 2018.

18 Bloomberg New Energy Finance, McKinsey & Company. *An Integrated Perspective on the Future of Mobility.* London: McKinsey & Company and Bloomberg, 2016.

19 Burns, Lawrence D., William C. Jordan and Bonnie A. Scarborough. *Transforming Personal Mobility*. New York City: Earth Institute, Columbia University, 2013.

20 Isaac, Lauren. *"Driving Towards Driverless: A Guide for Government Agencies."* 2016.

21 Wikipedia. *Cheapside*. 2018. Website. 10 August 2018.

22 City of London. *Transport Strategy: Vision, Aims and Outcomes.* London: City of London, 2018.

23 Greater London Authority. *The London Plan: The Spatial Development Strategy for Greater London, Draft for Public Consultation.*

24 Greater London Authority. *Mayor's Transport Strategy.*

25 Transport for London. *Healthy Streets for London.* London: Transport for London, 2018.

26 City of London. *Transport Strategy: Vision, Aims and Outcomes*.

27 While the contents of this hierarchy were gleaned from the four policy documents, it is not officially endorsed by the City of London or any other public entity. It is meant to serve as a conceptual input into illustrative FlexKerb functionality.

28 City of London. *City Streets: Transport for a Changing Square Mile*. London: City of London, 2018.

29 Arhin, Stehen A., et al. "Predicting Dwell Time by Bus Stop Type and Time of the Day." *Journal of Civil & Environmental Engineering 5.5 (2015)*. Document.

30 The VISSIM models do not incorporate actual pedestrian data. Therefore, pedestrian activity depicted in the model is illustrative only, and volumes shown are far below actual demand. FlexKerb space designated to walking is identified by green bays.

Appendices

Street	Cheapside	Tottenham Court Road	Marylebone High Street	Fleet Street
Segment	New Change to Queen St	Windmill to Howland	Nottingham to New Cavendish	Fetter Ln to Farringdon St
Borough	City	Camden	Westminster	City
Diversity of uses				
Cycle facilities				
Bus stop / shelters				
Bus lane				
On-street parking				
Freight loading / unloading zones				
Pedestrian crossing				
Taxi bays				
Other				
High street feel				
Active frontages				
Mixture of uses				
Retail				
Employment				
Data availability				
Car counts				
Pedestrian counts				
Cycle counts				
Taxi counts				
Bus counts				
Freight activity (counts, timing, etc.)				
Kerb usage (timing, circulation)				
Other				
Varied weekday weekend use patterns				
Proximity / ease of access to Arup office				
Kerbside activity on both sides of street				
Average				

← Does not satisfy criteria — Strongly satisfies criteria →

Document	Page	Policy commitment
Mayor's Transport Strategy *(Mar 18)*	13	London's streets should be for active travel and social interaction, but too often they are places for cars, not people.
	13	Cars take up a lot of space relative to the number of people they can move around, and reliance on this space-inefficient mode of transport has made London's streets some of the most congested in the world.
	15	Currently, road transport is responsible for half of the main air pollutants.
	21	80 per cent of all trips in London to be made on foot, by cycle or using public transport by 2041.
	23	The Mayor's aim is, by 2041, for all Londoners to do at least the 20 minutes of active travel they need to stay healthy each day.
	23	The Mayor aims to reduce freight traffic in the central London morning peak by 10 per cent on current levels by 2026, and to reduce total London traffic by 10-15 per cent by 2041.
	25	Growth is good for London, and it is important that all of the city's current and future residents feel its benefits. As the city grows, it must also become a better place to live in – London's growth must be 'Good Growth'.
	25	Using new public transport links and better walking and cycling environments to help areas develop will create a future of reduced car dependency and increased active travel. Planning streets and places around walking, cycling and public transport will increase active, efficient and sustainable travel for short trips around new town centres.
	25	Changing the transport mix will put people back at the heart of the transport system, prioritising human health and experience over traffic dominance.
	29	Given the fundamental importance of efficient movement to the continuing success of such a limited geographical area, the future of central London must involve a steady reduction in car use. Walking, cycling and public transport use must continue to increase and deliveries must be consolidated, rescheduled and switched to more efficient and sustainable vehicles, including making more use of the Thames. All of these changes will reduce the congestion that inefficient travel causes, freeing up space for essential freight trips and more reliable bus journeys.
	29	Central London sees the most concentrated mix of demands for public space, so it is vital that this area is properly planned in a strategic way that makes it work well for people.
	29	The challenge of improving the efficiency of London's streets is especially acute in central London where space is at a premium. The elements of this strategy will need to be managed carefully by TfL and the central London boroughs to ensure they all work together to deliver this vision.

Document	Page	Policy commitment
Mayor's Transport Strategy *(Mar 18)*	37	Eighty per cent of Londoners' trips are entirely on streets, and all Tube and rail journeys rely on good street access to stations.
	37	Streets are where Londoners spend their time and meet other people – they make up 80 per cent of the city's public space.
	37	The Healthy Streets Approach provides the framework for putting human health and experience at the heart of planning the city.
	43	Attractive street environments encourage active travel, as little as 20 minutes of which a day is enough to stay physically and mentally healthy. Reducing car use will lower harmful emissions, and the trees and other greenery that make streets pleasant places to be improve the city's resilience to climate change. Streets that are busy with people, rather than cars, are safer.
	43	To realise all the benefits of improved street environments, the uses of the whole street, from building line to building line, must be considered when making any changes at street level.
	43	Walking, cycling, and public transport should be prioritised, taking space from less efficient general traffic where required to minimise conflicts between complementary active, efficient and sustainable modes.
	43	Individual street improvements can change local environments, but to achieve this strategy's ambitious aims, it will be vital to consider how the wider street network operates as a whole.
	43	The way street space is allocated for these purposes will vary between different places in London, and by time of day and week. The appropriate use of street space will be considered while the policies and proposals within this strategy are used to deliver the healthy Streets Approach throughout London.
	51	Creating 'Liveable Neighbourhoods' to improve the public's experience of walking, cycling and using public transport and to increase opportunities to use streets as public spaces and for play, and to encourage fewer trips by car.
	51	Ensuring any scheme being undertaken on London's streets for any reason improves conditions for walking and cycling.
	75	Advanced traffic management techniques are already used extensively to manage the streets more efficiently, and it is essential that these traffic control systems continue to be improved to ensure better outcomes for all road users, prioritising people who are walking, cycling and using buses.
	75	The longer-term solution must therefore be to better manage the way in which goods are delivered in London and to significantly reduce car use in favour of more space-efficient means of travel. A reduction in traffic of about 10-15 per cent (6-7 million kilometres per day) by 2041 is required to keep congestion in check, while also achieving the aims of this strategy.

Document	Page	Policy commitment
Mayor's Transport Strategy *(Mar 18)*	75	Over time, reallocating space to more efficient modes, combined with improvements to public transport, measures to manage demand, and applying the principles of Good Growth for new development, will create streets that function better not only for people who are walking, cycling and using public transport, but also for taxis and essential delivery, servicing, car and motorcycle journeys.
	75	The Mayor, through TfL and the boroughs, and working with stakeholders, will prioritise space efficient modes of transport to tackle congestion and improve the efficiency of streets for the movement of people and goods, with the aim of reducing overall traffic levels by 10- 15 per cent by 2041.
	75	Congestion has different causes and impacts in different parts of the city and so the approach to dealing with it must vary across London. In central London, where congestion is worst, constrained street space and rising levels of freight and private hire traffic are the main issues to be tackled.
	75	To allow London's businesses to continue to receive the goods and services they need to flourish, while ensuring that London's streets become better places for people, all aspects of freight and servicing activity must be actively managed in an integrated way.
	79	Currently, lorries and vans account for around one fifth of road traffic in London and about one third in central London during the morning peak. As London grows, the volume of freight and servicing trips is also forecast to grow unless action is taken. This would place further pressure on street and kerb space. The majority of freight trips are made by vans – of which there are almost four for every HGV – and these have been growing since the 1970s.
	83	Many freight and servicing trips are time-critical or time-constrained, and some need to be conducted in peak time for this reason. However, at present, many trips that could be made at times where they would have less impact on streets are also made at peak times, because of out-dated or inappropriate restrictions and regulations. The Mayor will work with TfL and the London boroughs, retailers and stakeholders to better understand the barriers to delivering outside the busiest times and to make recommendations for updating and changing regulations and local restrictions.
	85	Thoughtful design and management of the kerbside is key when designing new streets and transforming places. As part of all street schemes, TfL, working with the boroughs, will review loading provision and ensure delivery and servicing facilities are designed in a way that allows streets to be attractive places in which to walk or cycle.
	85	Improving the design and management of loading and servicing activities at the kerbside and off-street
Mayor's Transport Strategy *(Mar 18)*	85	Re-timing goods and services to the times where they will have least impact on streets.
	99	Using street space more efficiently to encourage more walking, cycling and public transport should be considered. This could include creating vehicle-free zones, introducing 'filtered permeability' (using physical restrictions to prevent motorised vehicles from using certain streets) or creating space for cycle parking, greening or seating.
	155	Using buses to support these changes will allow public transport links to be added where they are needed now, and potentially reviewed as cycling and walking become more common options in the future.
	159	TfL will start by making the best use of existing bus priority by reviewing the hours of operation and reducing interference from general traffic. The Mayor will review whether lanes that do not currently operate in off-peak hours, late evening or on Saturdays and Sundays, should be extended to operate at these times or on these days. This can be delivered quickly and at low cost.
	207	Cultural events involving street closures will also be used to activate the night time economy, helping Londoners and visitors to see how streets can be used differently at night, as well as during the day.
	279	If autonomous vehicles make car use more appealing and easier to do, people may walk around their neighbourhoods less.
	281	Creating a safe, attractive environment on our streets: new services and technology should help create a safer, quieter and more pleasant environment on London's streets, where it is more attractive to walk or cycle, and should not lead to existing active trips being made by nonactive modes. There must always be an emphasis on the safety of passengers, people walking and cycling, and other road users. Where this involves introducing technology directly into the street, it should be done in a co-ordinated way that enhances the overall character of the street, reduces clutter, and does not prevent future potential re-allocation of space for walking, cycling and public transport.
	281	Using space efficiently: new services must make efficient use of road and kerb space, be appropriate for the area of London in which they operate and support opportunities to re-allocate space for walking, cycling and public transport.
	281	However, providing that the supply of, and demand for, shared/low-occupancy services is appropriately managed, they could play a role in reducing car ownership by providing connectivity where public transport is harder to provide or for those who are not able to walk or cycle.
	281	It will be important to provide walking and cycling environments and public transport services that make active, efficient and sustainable travel options more appealing than 'shared mobility' services.

Document	Page	Policy commitment
Mayor's Transport Strategy *(Mar 18)*	281	Managing the way people pay for road use could play a key role in ensuring that these services do not cause major increases in congestion or emissions.
	281	How kerb space is used by shared vehicles will be an important issue to consider if they become more widespread.
	281	The Mayor, through TfL, will explore and monitor the relationship between access to kerb space, including for car parking, and the level of demand for all forms of car use to inform assessment of how demand management measures should evolve over time.
	285	The interactions of connected and autonomous vehicles with people walking, people cycling and conventional vehicles will also need to be made in a safe, predictable and manageable way, while any connected and/or autonomous vehicles should be secure from 'cyber-attack'.
Healthy Streets for London *(Feb 17)*	6	Cars take up 19 per cent of street space in central London, but account for only 11 per cent of journey kilometres.
	6	Providing more appealing walking, cycling and public transport options is the best way to reduce car use.
	8	To deliver appealing local street environments, wider action is required to manage our transport networks and to plan the Capital better.
	10	This will include considering different uses of our streets across the day so that more street space is available for walking, cycling and leisure purposes, while ensuring our shops and services continue to thrive.
	10	The interaction between the need to create attractive places and the need to move goods and people varies from street to street.
	11	Flexible use of space on Lower Marsh (Lambeth) enables this local market to receive deliveries in the mornings, provide a lively food market at lunchtimes and a pleasant space for visiting shops and bars in the afternoons and evenings.
	16	Over time, reallocating space will create streets that function better not only for people who are walking, cycling and using public transport, but also for taxis and essential delivery, servicing and car journeys.
	13	Promote the crucial role town centres have in the social, civic, cultural and economic lives of Londoners, and plan for places that provide important opportunities for face-to-face contact and social interaction during the daytime, evening and night time.
	14	To accommodate growth while protecting the Green Belt, and for this growth to happen in a way that improves the lives of existing and new Londoners, this Plan proposes more efficient uses of the city's land. The key to achieving this will be taking a rounded approach to the way neighbourhoods operate, making them work not only more space efficiently, but also better for the people who use them.

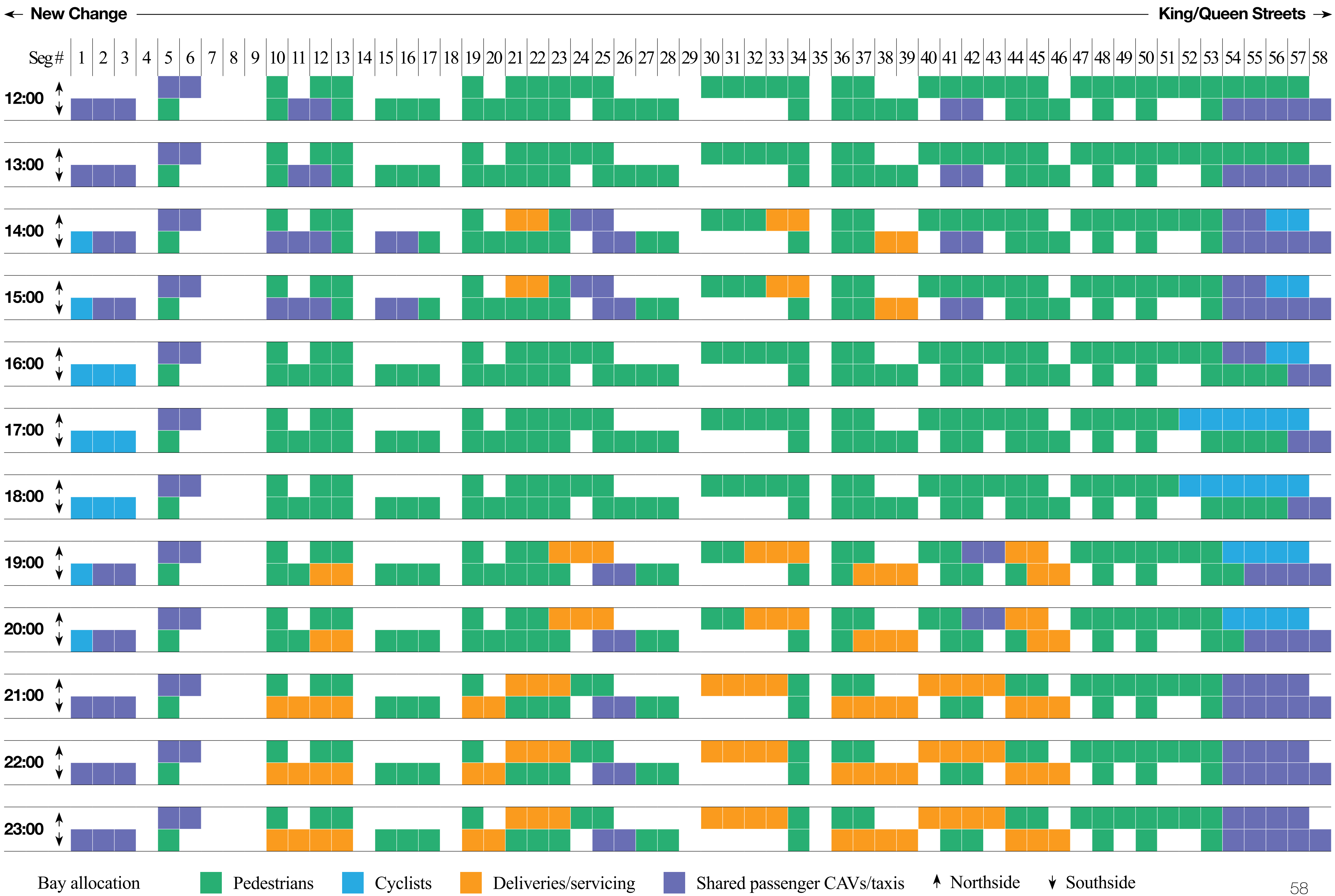
Document	Page	Policy commitment
Healthy Streets for London	14	Making the most efficient use of the existing and future public transport, walking and cycling networks.
	16	Maximise opportunities to use infrastructure assets for more than one purpose, to make the best use of land and support efficient maintenance.
Draft New London Plan *(Dec 17)*	122	Maximise the contribution that the public realm makes to encourage active travel and ensure its design discourages travel by car and excessive on-street parking, which can obstruct people's safe enjoyment of the space.
	122	Be based on an understanding of how the public realm in an area functions and creates a sense of place, during different times of the day and night, days of the week and times of the year. In particular, they should demonstrate an understanding of the types, location and relationship between public spaces in an area, identifying where there are deficits for certain activities, or barriers to movement that create severance for pedestrians and cyclists.
	122	Ensure both the movement function of the public realm and its function as a place are provided for and that the balance of space and time given to each reflects the individual characteristics of the area. The priority modes of travel for the area should be identified and catered for, as appropriate.
	123	Explore opportunities for innovative approaches to improving the public realm such as open street events.
	124	The specific balance between the different functions of any one space, such as its place-based activities and its function to facilitate movement, should be at the heart of how the space is designed and managed. The Mayor's Healthy Streets Approach, explains how the design and management of streets can support a wide range of activities in the public realm as well as encourage and facilitate a shift to active travel.
	402	A shift from car use to more space-efficient travel also provides the only long-term solution to the road congestion challenges that threaten London's status as an efficient, well-functioning globally-competitive city. Reliable deliveries and servicing, and easy access to workplaces and key attractions are dependent on an increasingly-efficient transport network. Roads will continue to play a vital role in this, and greater priority needs to be given to making them more efficient for those activities that depend on them the most.
	402	Rebalancing the transport system towards walking, cycling and public transport, including ensuring high quality interchanges, will require sustained investment including improving street environments to make walking and cycling safer and more attractive, and providing more, better-quality public transport services to ensure that alternatives to the car are accessible, affordable and appealing.

Document	Page	Policy commitment
Draft New London Plan *(Dec 17)*	403	Development plans should identify opportunities to improve the balance of space given to people to dwell, walk, cycle, and travel on public transport and in essential vehicles, so space is used more efficiently and streets are greener and more pleasant.
	404	Enough space for dwelling, walking, cycling and public transport use must be provided.
	404	Measures which improve Londoners' experience of individual streets, including greening, to encourage them to live active lives should be embedded within new development.
	404	Development which facilitates opportunities to improve route choice and capacity for walking and cycling as well as linking to bus networks.
	405	Considering different uses of London’s streets across the day so that more street space is available for walking, cycling and leisure purposes, while ensuring shops and services continue to thrive.
	422	Parking provision should be flexible for different users and adaptable to future re-purposing in the context of changing requirements, including technological change.
	432	Developments should be designed and managed so that deliveries can be received outside of peak hours and in the evening or night time.
City of London: Transport Strategy, Vision, Aims and Outcomes *(Jun 18)*	2	The number of people working in the Square Mile is expected to grow by 90,000 in the next decade.
	2	90% of on-street journeys that start or finish in the City are entirely or partially walked, including to and from public transport.
	2	14% of Londoners consider themselves to have a disability that impacts their day to day activities ‘a lot’ or ‘a little’ This is expected to rise to 17% by 2030.
	2	Four in five people think traffic levels in the City are too high.
	2	The number of motor vehicles using the Square Mile’s streets has halved since 1999, while the number of people cycling has grown by 292%.
	2	Lorries and vans make up over a quarter (27%) of motor traffic on the City’s streets between 7am and 7pm.
	3	84% of people think pavements are overcrowded.
	3	60% of people think that people walking are given too small a share of street space.
	3	65% of people think the needs of people walking are underprioritised.
	3	25% of global new vehicle sales in 2035 will be connected and autonomous vehicles.
	8	People walking will have their needs prioritised.

Document	Page	Policy commitment
City of London: Transport Strategy, Vision, Aims and Outcomes *(Jun 18)*	8	The experience of walking and spending time on our streets will be improved through investment in high quality public realm, street greening and motor traffic reduction.
	8	Appropriate vehicle access will be provided for those that need it.
	8	People enjoy a relaxed cycling experience in the Square Mile.
	8	The design and management of streets will enable cycling at a pace that suits the City and make cycling a relaxing and enjoyable way to travel
	8	Carbon emissions and people’s exposure to air and noise pollution will be reduced.
	9	Delivery and servicing needs are met in ways that benefit the Square Mile.
	9	Future development and growth will be supported by changing the way that goods are moved around the Square Mile.
	9	The transport, delivery and servicing requirements of businesses and residents will be met in ways that maximise social, economic and environmental benefits.
	9	Street space is used more fairly and effectively.
	9	The use of streets will be better matched to the priorities of people and businesses.
	9	Street space will be used more flexibly, recognising that priorities can vary by time of day and seasonally.
	9	Transformational change will be accelerated through temporary interventions and trialling projects prior to making permanent changes.
	9	The impact of planned and unplanned disruption on the movement of people and goods will be minimised.
	9	Emergency services will be able to respond rapidly to incidents.
	9	Emerging transport technologies benefit the Square Mile.
	9	Automated vehicles and other new transport technologies and services will work for the City, supporting efforts to reduce motor traffic and deliver inclusive, safe, attractive and vibrant streets.

APPENDIX C: CHEAPSIDE FLEXKERBS SCHEDULE

Bay allocation: Pedestrians, Cyclists, Deliveries/servicing, Shared passenger CAVs/taxis, ↑ Northside, ↓ Southside


New Change
King/Queen Streets
Seg#
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Bay allocation
Pedestrians
Cyclists
Deliveries/servicing
Shared passenger CAVs/taxis
Northside
Southside

Following the issuing of the National Infrastructure Commission's press release, FlexKerbs received a high volume of media attention from a diversity of sources, ranging from transport and technology industry publications to national and international news outlets.

Auto Breaking News, "The 'smart' pavements that can move the kerbs and make city roads wider in peak hour", 30 May, 2018, https://www.autobreakingnews.com/2018/05/the-smart-pavements-that-can-move-the-kerbs-and-make-city-roads-wider-in-peak-hour/.

Bikebiz, "Pop-up protected cycleway to be trialled in London", 23 May, 2018, https://www.bikebiz.com/landscape/flexkerbs.

Building Design & Construction, "Smart pavements could be introduced in the UK", 29 June, 2018, http://www.bdcmagazine.com/smart-pavements-could-be-introduced-in-the-uk/.

Mirror, "Britain's first 'flexible kerb' could mean MOVING pavements with pop-up cycle lanes and space for pedestrians", 29 May, 2018, https://www.mirror.co.uk/tech/britains-first-flexible-kerb-could-12615540.

Daily Mail Online, " 'Flexible kerb' concept that provides pop-up cycle lanes and space for pedestrians at different times of the day to be tested on London roads", 29 May, 2018, http://www.dailymail.co.uk/sciencetech/article-5783139/Flexible-kerb-concept-provides-pop-cycle-lanes-tested-London-roads.html.

Dalby Herald, "Simple solution to controversial road rule", 5 June, 2018, https://www.dalbyherald.com.au/news/simple-solution-to-cycling-road-rule/3433420/.

Express, "Smart pavements that can make roads wider and move kerbs could be coming to UK cities", 30 May, 2018, https://www.express.co.uk/life-style/cars/967103/smart-pavements-UK-cities-traffic-pedestrians-cyclists.

FleetNews, "Adjustable kerbside markings could help traffic flow", 21 June, 2018, https://www.fleetnews.co.uk/news/car-industry-news/2018/06/21/adjustable-kerbside-markings-could-help-traffic-flow 1/.

Global Construction Review, "Arup's shrinking streets concept to be tested in London", 30 May, 2018, http://www.globalconstructionreview.com/news/arups-shrinking-streets-concept-be-tested-london/.

The Gympie Times, "Simple solution to controversial road rule", 5 June, 2018, https://www.gympietimes.com.au/news/simple-solution-to-cycling-road-rule/3433420/.

Highways Industry, "Smart pavements that can make roads wider and move kerbs could be coming to UK cities", 31 May, 2018, https://www.highwaysindustry.com/smart-pavements-that-can-make-roads-wider-and-move-kerbs-could-be-coming-to-uk-cities/.

ITS International, "Five Companies shortlisted for Roads of the Future project", 31 May, 2018, http://www.itsinternational.com/sections/events/news/five-companies-shortlisted-for-roads-of-the-future-project/.

Media Telecom, "Roads for the future busca ideas infraestructura de vehículos autónomos", 25 May, 2018, https://tecnologia.mediatelecom.com.mx/2018/05/25/roads-for-the-future-busca-ideas-para-la-infraestructura-de-vehiculos-autonomos/.

Metro, "'Smart' pavements could aid autonomous cars", 1 June, 2018, https://www.metro.news/smart-pavements-could-aid-autonomous-cars/1081186/.

New Civil Engineer, "Arup and Aecom shortlisted for future roads scheme", 23 May, 2018, https://www.newcivilengineer.com/latest/arup-and-aecom-shortlisted-for-future-roads-scheme/10031316.article.

News.com.au, "Simple solution to cycling road rule Australian drivers want banned", 5 June, 2018, https://www.news.com.au/technology/innovation/motoring/on-the-road/simple-solution-to-cycling-road-rule-australian-drivers-want-banned/news-story/e001bf72a0643bc7ef0d54a325c2f227.

Road.cc, "flexible kerb space idea could result in pop-up cycle lanes", 24 May 2018, https://road.cc/content/news/242371-flexible-kerb-space-idea-could-result-pop-cycle-lanes.

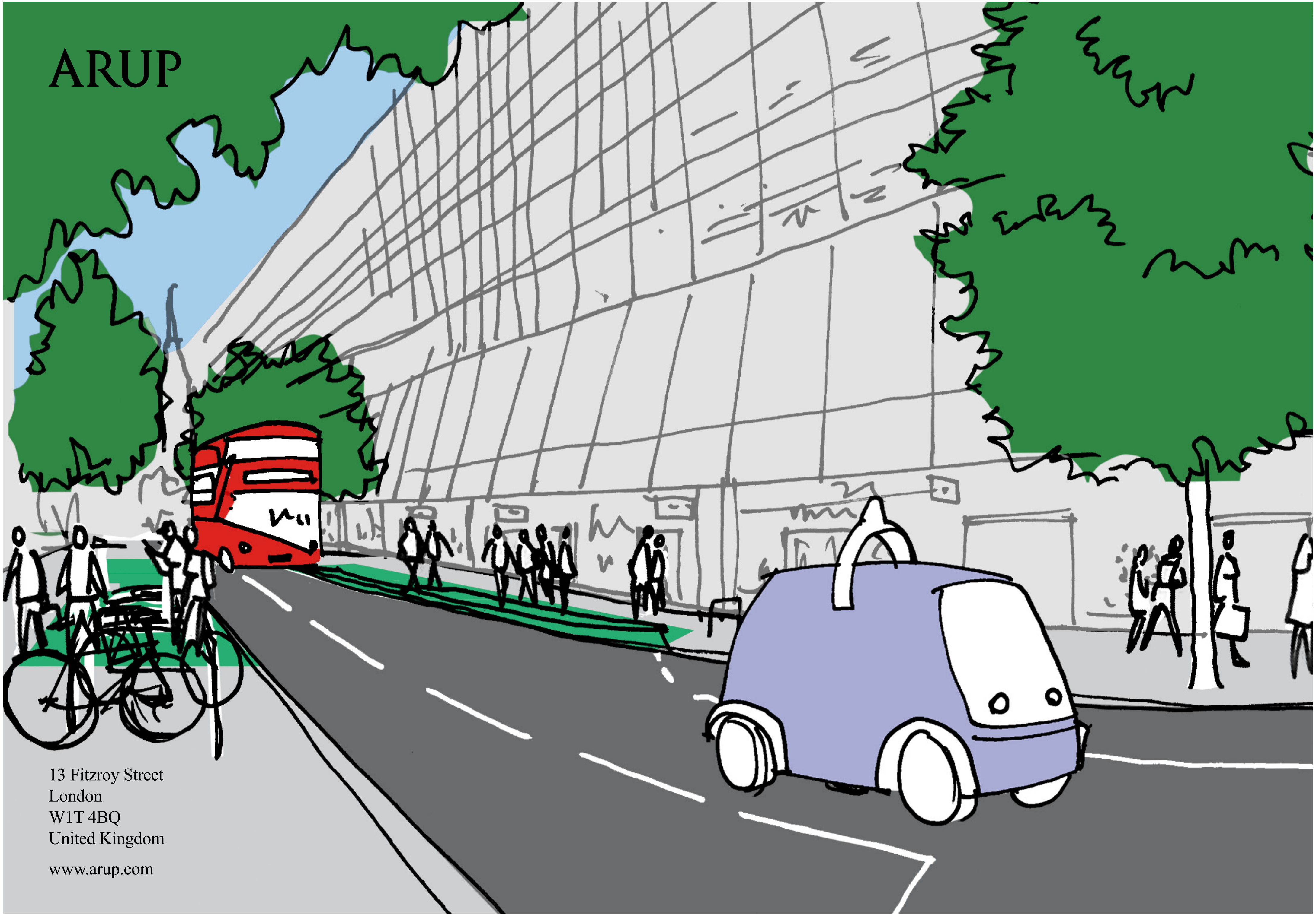
The Sun, "Kerb your enthusiasm: the 'smart' pavements that can move the kerbs and make city roads wider in peak hour", 30 May, 2018, https://www.thesun.co.uk/motors/6408635/the-smart-pavements-that-can-move-the-kerbs-and-make-city-roads-wider-in-peak-hour/.

The Sunday Times, "Smart 'FlexKerbs' widen and narrow to fit usage by drivers, cyclists and pedestrians", 29 May, 2018, https://www.driving.co.uk/news/smart-flexkerbs-widen-narrow-fit-usage-drivers-cyclists-pedestrians/.

The Times, "Look right, look left: it's the kerb that won't stay still", 29 May, 2018, https://www.thetimes.co.uk/article/look-right-look-left-its-the-kerb-that-wont-stay-still-fqv9cvjkt?#_=_.

World Highways, "Shortlist announced for UK's Roads for the Future competition", 6 June, 2018, http://www.worldhighways.com/categories/traffic-focus-highway-management/news/shortlist-announced-for-uks-roads-for-the-future-competition/.

The World News, "The 'smart' pavements that can move the kerbs and make city roads wider in peak hour," 30 May, 2018, https://theworldnews.net/gb-news/the-smart-pavements-that-can-move-the-kerbs-and-make-city-roads-wider-in-peak-hour.



ARUP

13 Fitzroy Street
London
W1T 4BQ
United Kingdom

www.arup.com