A systematic review: Road infrastructure requirement for Connected and Autonomous Vehicles (CAVs)

Yuyan Liu1,2, Miles Tight2, Quanxin Sun1 and Ruiyu Kang3

1School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China
2School of Engineering, University of Birmingham, Birmingham B15 2TT, United Kingdom
3Drycoolers Inc, Oxford MI 48371, United State
E-mail: 15531189909@163.com

Abstract. There is currently a significant worldwide interest in Connected and Autonomous Vehicles (CAVs), not least for the reason that their realisation and implementation would transform the nature of transportation and provide new impetus for social and economic change. However, the road to support CAVs has not been well prepared, at the risk of leaving potential barriers to CAVs deployment. This paper, therefore, focuses on the gap between current status and future requirements of CAV-compliant road infrastructures, summarizes the possibilities of upgrades, and proposes a three-phase road infrastructure upgrade plan that evolves over time. The first phase is maintenance, followed by a segregated-infrastructure expansion phase leading to phase three which involves the application of simplified standard. The paper is based on an extensive literature review and evidence synthesis and is intended as a stimulus for future study and further debate. For objectiveness, the proposal is general but would need to be refined, when put into practice, to cater for specific implementation contexts.

1. Introduction

Connected and Autonomous Vehicles (CAVs) use a variety of devices including radar, lidar, cameras as sensors, to perceive their surroundings [1]. However, current shortcomings in the perception process may need to be overcome through well-prepared road infrastructure [2]. Otherwise, the realisation of a future with increased mobility for disabled people, a reduction of road accidents caused by human error and the mitigation of pollution as well as congestion could remain but a distant aspiration.

Currently, the research into road infrastructure to support CAVs is still in its infancy. Even though some reports and white papers containing ‘scattered views’ are slowly being released along with today’s CAVs testing projects (e.g. TSC in the UK), the planning and guidance documents used by the highway authorities (e.g. DMRB and WebTAG in the UK) have not taken CAVs into account yet [3]. Therefore, the aim of this paper is to assess the requirement for existing road infrastructure to support CAVs, and the review question is proposed as:

- How should the road infrastructure be upgraded to accommodate and support CAVs?

Following on from the Introduction, the paper is laid out as follows: Section 2 provides essential background information of both CAVs and the road. Section 3 is the detailed literature review process, followed by Section 4, which summarises the literature findings into two categories, namely the aspect
of infrastructure considered to be upgraded and the upgrade standard for different scenarios. A discussion is conducted in Section 5 to give an upgrade plan, whilst Section 6 concludes the paper.

2. Background

2.1. Taxonomy of driving automation
To know how roads should be upgraded, it is firstly needed to clarify the difference between different levels of AVs and the conventional cars. The SAE International [4] published a six-level definition for automation, see in table1. With each higher level of automation, the responsibility for performing driving task will increasingly shift from the driver to the vehicle.

| No | Level Name | Driving task | Response to failure | Operation area |
|----|------------|--------------|---------------------|----------------|
|    |            | Lateral & longitudinal control | Monitor surroundings |               |
| 0  | No driving automation | Driver | Driver | Driver | N/A |
| 1  | Driver assistance | Driver & System | Driver | Driver | Limited |
| 2  | Partial driving automation | System | Driver | Driver | Limited |
| 3  | Conditional driving automation | System | System | System &Driver | Limited |
| 4  | high driving automation | System | System | System | Limited |
| 5  | Full driving automation | System | System | System | Un-limited |

Table 1. Taxonomy of driving automation

Figure 1. Prediction of AVs implementation timeline.

2.2. CAVs implementation timeline
The time when different levels of CAVs will be implemented in fleet is another essential topic when considering upgrades. There are a number of factors that impact the prediction of the implementation timeline [5–6].
The Automation level 2 is widely proved available now by many automobile manufacturers, including: Maserati MY 2018, Nissan Leaf 2018 and Audi A8 2019. But when the vehicle manufacturers will produce higher levels of AVs is less certain. For example, Ford is planning to jump-over Level 3 and directly produce Level 4 vehicles in 2021 [7]. The same year, 2021, for producing level 4 vehicles is also mentioned by BMW, who also predicts that the fully AVs will be available between 2025 and 2030 [8]. However, even after full automation is proved to be reliable, it does not mean that people are happy with it and ready to buy. Additional time will also be needed for regulatory approval by the government.

Although the narrative about AVs fleet proportion is uncertain. However, an S-curve theory or Gal’s Insight [4], which was usually used as innovation deployment prediction can be adopted, see in figure1. The prediction shows that around 2030s, the AVs fleet proportion will reach 20%, while in 2050s, it will account 50% of vehicles on the road. Similar ideas were mentioned by KPMG [9], which predicted that in 2035, AVs in the fleet will reach 25%, and in 2050, the figure will exceed 50%.

2.3. Classification of the road infrastructure assets
To avoid any missing or making fragmented review, the road assets classes needs to be defined to ensure the upgrades are considered in a systematic level. This paper referred the Network Management Manual published by the Highway Agency [10] and defined five classes of road infrastructure assets: 1) Communications; 2) Road pavement; 3) Structures; 4) Geotechnical and 5) Drainage.

3. Methodology
A literature review can be a good starting point for an academic article that investigates relatively new fields of academic study [11]. This paper generally followed the methodological framework of a systematic review, as developed by Gough et al [12].

During key terms searching, synonyms of the keywords and Boolean operator are applied, see in table2. In order to identify existing articles potentially answering the review questions, 5 bibliography databases, 19 organizational databases were used, see in table3. Among the extensive databases, 7252 studies match the initial search. By filtering out those not written in English, published before 2012, and not transportation related papers, 1831 results were left. Then, based on a quick review of title and abstract, 57 results remained. After removing duplicates and no full text available, 29 papers made it through the first-round screening. The author then applied a Quality of Evidence (QoE) standard to the first-round results for evidence appraising, see in table4. 7 literatures are defined as “high quality” results thus were directly obtained, while the references list from the rests were reviewed for the second-round, and 6 articles were adopted, which gives a total amount of 13 results for the final synthesis of evidence. Figure2 shows a flowchart of the acquisition process.

![Flowchart of literature acquisition process](image-url)
### Table 2. Key searching terms.

| Key words          | Search strings                                                                 |
|--------------------|--------------------------------------------------------------------------------|
| CAVs               | (Connect* OR Autonomous OR automated OR self-driv* OR auto-pilot OR driverless) AND (Vehicle* OR car* OR automobile* OR driv*) |
| Upgrade            | AND (upgrad* OR chang* OR design OR maintain* OR construct*)                    |
| Road infrastructure| AND (Road* OR facilit* OR infrastructure)                                       |

### Table 3. Academic and non-academic databases.

| Types                | Name                                                                                                                                 |
|----------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Bibliography Database| TRID/ Scopus/ Web of Science/ GeoBase/ Compendex                                                                               |
| Organization Database| TRL/ OECD/ CAR/ CACC/ DiT/ KPMG/ SAE International/ TSC/ ITF/ Atkins/ RAND Corporation/ GATEway/ USDOT/ UKAutodrive/ Infrastructure Partnership Australia/ iRAP/ MARGE Greenwich/ RAC Foundation/ VENTURER/ Victoria Transport Policy Institute |

### Table 4. The Quality of Evidence (QoE).

| Standard                        | Description                                                                                                |
|---------------------------------|-------------------------------------------------------------------------------------------------------------|
| Soundness of the studies        | The study itself have explicit and effective evidence with reliable conclusion.                            |
| Relevance of review scope       | Studies focus both on the field of AVs and the likely road infrastructure changes.                         |
| Appropriateness for the review needs | Provides at least one aspect of upgrade suggestions from either the problems emerged in real situation or the critical thinking through engineering experience. |

Notes: Any literature meets at least two of the standards will be defined as “high quality” studies.

The acquisition results are shown in table5. The evidence was synthesized and summarized into 15 infrastructure relevant topics, which consists of 12 topics of infrastructure aspects (belongs to the five classes of road assets), and 3 topics of road upgrade standards.

### Table 5. Summary of literature acquisition results.

| Ref  | Author(s)  | Year | Outlet type | Upgrade aspect | Upgrade standard | Location |
|------|------------|------|-------------|----------------|------------------|----------|
| [13] | Johnson    | 2017 | Report      | TR/DC/PS/RS/P/S/R/B/G/DS | M/SE/SI        | UK       |
| [14] | Lyon et al.| 2017 | Report      | TR/IRC/DC/P/B/G    | M                | Australia|
4. Summary of findings

4.1. Aspect of infrastructure considered to be upgraded

4.1.1. Traffic signs and road markings. CAVs require highly visible road edges, curves, speed limit and other signages to complete the task of locating [24], navigating [13], and parking [3]. However, the design and maintain of signs and markings are far away from accommodating CAVs. For example, faded road markings have discontinuous issues in North America [25]; low maintenance priority (e.g. dirty) cause signs unreadable in the UK [26]; non-standard road signs confused users in the EU [27].

In order to adopt CAVs, governments and organizations should call for uniform road marking across EU members, or even suggest global standardization [3], and also improve maintenance criteria and establish monitoring systems [3,14]. To complement the “readability” maintenance of roads, upgrades could also enhance the brightness of street lights [16] and frequently control roadside vegetation.

4.1.2. Incident and roadworks communications. Incidents and roadworks will change the road layout, which require CAVs to interpret real-time changes, such as merging-lanes suggestions provided by temporary signs and cones. Currently, two websites provide real-time information on traffic accidents and roadworks in the UK (roadworks.org and www.waze.com). Even though, both websites provide the cause and time of accidents, the lack of accurate on-site layout imaging still makes it difficult for CAVs to distinguish real-time changes from historical maps, thus hard to navigate.
Two suggestions for the future: establish uniform CAV-readable emergency signs, barriers or cones [3]; establish digital roadside communications to replace static facilities to provide real-time data [14].

4.1.3. Digital communications. The successful deployment of CAV requires not only vehicle-mounted instruments, but also road-side digital infrastructure to meet various forms of connectivity requirements (V2X communication) [1]. Sensors and Internet connectivity are required here for applying digital infrastructures:

- Substantial amounts of sensors including in-roadway sensors (such as loop detectors and magnetic detectors), and over-roadway sensors (cameras, radars and ultrasonic etc.) [14]. These sensors could help the road management center monitoring traffic demands and allocating transportation resource through I2V communications [1] to achieve smoother traffic flow.
- Internet connectivity can be implemented either via mobile network (4G/5G) or wifi-based facilities (ITS-G5) [3]. Some articles also mentioned fitting new roads and major junctions with the fiber-optic-cable beforehand to make future digital infrastructure easier to realize in the future [3,13].

4.1.4. Pavement structure. CAVs are more likely to operate continuously in the middle of the carriageway by using Lane-Keeping-system (LKS) [28], which will accelerate the appearance of rutting and other pavement deteriorations (e.g. potholes, cracking) [21]. So, certain areas beneath the CAV operation track need to be strengthened consequently [13].

In AV-dedicated lanes, higher stiffness and more deformation-resistance materials (e.g. asphalt concrete) can be considered for the surface layer. The maintenance frequency for the remaining pavement layers can also be increased in the future.

4.1.5. Road surface. CAVs can adjust vehicle speed more predictively through V2V and V2I communications to avoid sharp braking [13] thus reducing the stopping distance design standard. The requirement for the coefficient of friction (represented by the PSV and the texture depth) can therefore be relaxed, so that less skid-resistance materials are possible for use in the surface course in the future.

4.1.6. Parking. Multiple researchers have foreseen that Automated-Valet-Parking (AVP) can significantly reduce future parking demands [14,19,29], especially in the context of shared CAVs — shared cars can serve different customers at different times, eliminating the needs for long-term parking [30]. Once arrived the parking lot, the AVP will enable them parking more closer with each other to save more space. But current carparks are not yet able to support self-parking, as most parking spaces are made of concrete and are located underground where GPS signals are not strong, causing difficulties in navigation. Aiming at this, some researchers suggested solutions by digitally fitting those areas with Bluetooth and near field communications [18]. However, it is still uncertain when the retrofitting of existing carparks and the building of new ones will start [31].

It is expected that more flexible design approaches are obtained to meet the parking needs during transition phase [3]. A case study was provided by an architecture design firm from Boston, US [32], whose design could support both AVs and conventional vehicles in transition, see in figure3.
Figure 3. Garage adapts to AVs (left) and to full AVs and new uses (right).

The top floor of the building was originally designed as only a CAV-compatible parking for efficiency, whilst the remaining floors were retained as traditional parking spaces. As the amount of CAV increases, the lower floors are expected to be converted into CAV parking or even charging spaces, and the top layer then becomes a recreation area to avoid construction-waste.

4.1.7. **Service stations.** Traditional service stations providing drivers places to stop, to refresh, and to refuel. With the British government’s announcement that pure petrol/diesel-powered vehicles will be banned from 2040 [33], and the ultimate goal is making Electric Vehicles (EVs) account for at least 9% of the total fleet by 2020 [18], it can be expected that future service stations are likely to provide more chargers [3,23]. A bolder idea can even be replacing charging points completely by a more efficient charging road [34]. In fact, the first electrified road in Sweden has already been put into use so that vehicles on this road can be charged while driving [35].

4.1.8. **Safe harbour area.** Safe harbour area is essential for AVs, since the level 3-4 vehicles require safe places to stop or restart in an emergency or when reaching the exit of an automated operation areas [4].

The traditional safe harbour area in the UK is a hard shoulder along the motorway but a number of these have recently been converted into running lanes. The former definition of safe harbour referred to an emergency refuge area (ERA), see in figure 4, which is 100m long and located at intervals of 2.5km. These were sometimes misused by drivers, leading to serious consequences (for instance, if the ERA is occupied by other cars, a driver is forced to stop in a busy lane when broken down).

Figure 4. Example of hard shoulder (left) and ERA (right).

In the future, the frequency and the design standard of safe-harbours needs to be reconsidered to accommodate CAVs and may also need the introduction of regulations to avoid misuse [3].

4.1.9. **Roundabout.** There are two opposite considerations about the future of roundabouts:

- At present, roundabouts essentially reduce the severity of accidents by transforming dangerous side-collisions into passing-collisions. However, with the advent of AVs, signalized intersections may be safer because of their more predictable elements [15].

- In terms of achieving smoother traffic flow, roundabouts may be preferred due to shorter delays and queuing times [36]. This benefit is predicted to extend as the merging action is easier to achieve with the AV’s computer programmers [23].
4.1.10. Bridges. As the amount of CAV increases, the segregated infrastructures, including bridges [23], tunnels and underpasses [13] are also needed to be provided to reduce conflicts between different traffic flows. The current bridge designs, particularly long-span bridges, has not catered for the ‘platooning’ needs of heavy trucks. Therefore, the inadequate design standard needs to be updated [3].

4.1.11. Geotechnical. With the technique of LKS, many researchers advocate the possibility of narrower carriageways [14], extra lane(s) based on existing road width [22], and tighter corners [13] in the future. Besides, reduced road gradients with more cuts and fills, embankments and tunnels are also preferred in response to the needs of platooning, since the vehicle speed can be easily-controlled on flat slopes [13].

4.1.12. Drainage. According to the Annual Assessment of Highways England’s performance [37], 69% of road network drainage data in the UK is unknown. Since severe surface water accumulation may cause the CAV systems becomes ‘paralysed’ [15], improving the design and maintain of drainage infrastructure (e.g. culvert, channels and gullies) should be given higher priority [13].

4.2. Upgrade standards for different scenarios
Instead of simply combining the upgrade aspects together to develop a retrofit plan for the uncertain future, it is better to determine more targeted plans for different scenarios. A comprehensive review of three different upgrade standards is given below, considering different CAV proportions on the road.

4.2.1. Maintenance. No matter how rapidly the CAVs evolves, it is better to update the infrastructure through maintenance rather than being radically changed at an early stage [17]. This is not only to meet the needs of CAV development [13], but also to meet the safety requirements of conventional vehicles [15]. Maintenance work can be considered from:
- Establishing enhanced standards and shorten maintain intervals of communication facilities.
- Increase the frequency of pavement maintenance (e.g. grading, sealing and patching) [21].
- A broader maintenance range of drainage system is also worth considering.

4.2.2. Segregation. As the automation level evolves and the market penetration of CAV increases, the road may be shared by different levels of AVs, which requires not only the preservation of the current facilities for lower-level AVs [13], but also the construction of additional infrastructure for full AVs. However, the co-existing infrastructure will undoubtedly bring about road right issues, which prompts further consideration of the expansion needs of the AV-segregated facilities [16]. Including:
- Specific routes [17,38,39] with reinforced surface materials.
- Safe harbour areas with devices that prevent head-on-collisions (e.g. central barriers) [15].
- Other structures like shared-CAVs gathering stations, service stations or even charging roads.

4.2.3. Simplification. Some existing road infrastructure may become redundant when full automation is proven efficiency. Therefore, new standards for different classes of infrastructure are expected to be developed to simplify road facilities [13].
- In terms of communications: Use simplified road markings [16] in AV-specific areas; Replace the static roadway-signs with digital in-vehicle devices [17] or establish single communication beacons to replace several traffic signals [13]; Remove the speed cameras since CAVs are programmed to obey traffic rules [20].
- In terms of structures: Roundabouts and some crash countermeasures (e.g. speed bumps) can be reduced [20]; The layout of carparks can be unified into a more concise standard; Service stations can be considered as a proper safe harbour areas for faulty AVs [3].
- Road geometry can be simplified, making future roads less confusing and more attractive [13].
5. Discussion

5.1 A general description of the upgrade plan for the transition phases

Based on the timeline prediction in section 2.2 and the upgrade standard in section 4.2, a three-phase transition plan is proposed. For each phase, it assigns different road infrastructure upgrade work considering the status of each stakeholder (manufacture, road users, and the government), shown in Table 6.

Table 6. The upgrade plan for transition phases.

| No. | Start time | CAVs proportion | Automation level | Manufacture (techniques) status | Road users (market) status | Government (policy) status | Upgrade standard |
|-----|------------|----------------|-----------------|-------------------------------|--------------------------|--------------------------|-----------------|
| 1   | Now        | <20%            | Level 0         | Mature                        | Dominant                 | Early adopter            | Release CAVs testing standards Maintenance |
|     |            |                 | Level 1-2       | Prove to be efficiency        | Early adopter            |                          |                 |
|     |            |                 | Level 3-4       | Prove to be reliable          | Turn-out                 |                          |                 |
|     |            |                 | Level 5         | Testing                      | Rarely seen              |                          |                 |
| 2   | 2030s      | 20–50%          | Level 0         | Mature                        | Gradually eliminate      | Road division            | Segregation     |
|     |            |                 | Level 1-2       | Mature                        | Dominant                 |                          |                 |
|     |            |                 | Level 3-4       | Prove to be efficiency        | Faithful adopter         |                          |                 |
|     |            |                 | Level 5         | Prove to be reliable          | Turn-out                 |                          |                 |
| 3   | 2050s      | >50%            | Level 0         | Mature                        | Nearly disappear         | Ownership change, Energy substitution Simplification |
|     |            |                 | Level 1-2       | Mature                        | Gradually eliminate      |                            |                 |
|     |            |                 | Level 3-4       | Mature                        | Dominant                 |                            |                 |
|     |            |                 | Level 5         | Prove to be efficiency        | Faithful adopter         |                            |                 |

5.1.1 Phase 1. Phase 1 is essentially underway and should continue until sometime in the 2030s when Level 2 automation will be dominant. Current, techniques are established, the market is dominant, and all road policy is suitable for automation level 0, which is no driving automation. However, researchers and vehicle OEMs are trying to prove the efficiency of Level 1-2 and reliability of Level 3-4, and testing Level 5. Therefore, the government along with other highway agencies need to publish a certain level of new road standards for supporting the testing of AV technologies.

The current upgrade standard includes: 1) Maintaining the existing road infrastructure (including certain types of communications facilities, pavement structure and drainage systems) to ensure the safe operation of conventional vehicles. 2) Building certain types of digital communication facilities for vehicles with partial automation functions at the same time.

5.1.2 Phase 2. Phase 2 is the key and the most complicated stage. Although Level 2 vehicles account for vehicles on the road, the market share of Level 3-4 vehicles can no longer be ignored. Also, Level 5 vehicles may become available on the market as well. This mixed-level operation will certainly be a problem for road-rights campaigners. Therefore, new laws and regulations must be released by the government to highlight the separation of responsibilities, for example, in accidents that involve AV.
Furthermore, the transportation sector needs consequently adjust the upgrade standard to build some road facilities that are able to reduce conflicts. Investing in AV-segregated infrastructure like AV-specific routes, gatherings and service stations are all possible ways for further investigation. Flexible design, such as building CAV-compatible parking lots, is also needed. In addition, since lower-level vehicles are still available on the market, the existing facilities such as road signs and traffic signals should not be abandoned in this phase immediately [15,39].

5.1.3. Phase 3. Phase 3 will not start until Level 3-4 vehicles take the majority of market share and the automation level 5 are proved to be efficient and attracting customers. For phase 3, many articles envisaged the ‘ideal future’ with full AVs, for example, ‘middle-class’ families will be able to afford level 5 AVs which allow them to sleep or work during daily commute.

Also, during phase 3, the government could spare more attention to social or environmental issues that generated from phase 2 (e.g. the increasingly serious transportation pollution). New solutions can therefore be considered, such as ownership-model changes and the substitution of energy options. Two highly possible products that may be seen are unmanned buses and shared driverless taxis, which will take a significant number of privately-owned vehicles off the road [18]. EVs or other clean-energy-powered vehicles will grow rapidly. Also, road infrastructure could and will become simpler, making the road less complex and more attractive. For example, multiple road markings and traffic signals could be replaced by a single digital communication beacon, very few or none parking spaces appeared in the city center, most service stations replaced by charging stations, etc.

5.2. Assessment of impacts of the upgrade plan

It is worth noting that there may be gaps or overlaps among the 3 phases, as it is not an outcome of accurate prediction or calculations. However, a potential cost-benefit assessment is still needed to help estimate the worthiness of the upgrade.

To avoid any lengthy and fragmented analysis for the unconfirmed future, table7 provides a weighted framework to qualitatively assess the costs-benefits impact on the upgrade plans. The measuring indicators were developed from the Road Investment Strategy published by DfT [40].

| Indicators of cost and benefits | a | b | c | d | e | f | g | Av e |
|-------------------------------|---|---|---|---|---|---|---|-----|
| Maintain-oriented             |   |   |   |   |   |   |   |     |
| Unified design and enhanced maintain for road signs & markings | 2 | 5 | 3 | 5 | 5 | 3 | 3 | 3.7 |
| Setup readable incident roadwork signage | 2 | 5 | 3 | 5 | 5 | 3 | 3 | 3.7 |
| Enhanced maintenance standards for pavement structure | 2 | 4 | 3 | 5 | 4 | 2 | 3 | 3.2 |
| Enhanced maintenance standards for drainage system | 2 | 4 | 3 | 5 | 4 | 3 | 3 | 3.4 |
| Segregated-expansion          |   |   |   |   |   |   |   |     |
| Setup specific lanes with more bridges, tunnels & underpasses | 1 | 5 | 3 | 5 | 5 | 1 | 5 | 3.5 |
| Setup CAV-compatible parking lot | 1 | 5 | 5 | 5 | 5 | 1 | 5 | 3.8 |
| Setup safe harbour area with safe defence | 1 | 5 | 3 | 5 | 4 | 1 | 3 | 3.4 |
| Setup charging machine for service station | 1 | 5 | 3 | 4 | 5 | 5 | 3 | 3.7 |
| Simplified-standard           |   |   |   |   |   |   |   |     |
| Setup digital roadside communications | 1 | 5 | 5 | 5 | 5 | 1 | 5 | 3.8 |
| Reduce the number of roundabouts | 5 | 1 | 3 | 1 | 3 | 5 | 5 | 3.2 |
| Relaxed skid-resistance standards for road surface | 5 | 1 | 3 | 1 | 3 | 5 | 3 | 3.0 |
| Simplified geometry design standards | 3 | 2 | 3 | 2 | 4 | 5 | 5 | 3.4 |
Notes: Scores: 1=disadvantage; 2=possible disadvantage; 3=neutral; 4=possible advantage; 5=advantage.
Indicators: a=Construction & maintenance cost; b=Needs of extra CAVs techniques cost; c= Easy for future change; d= Improved road safety; e=Improved road efficiency; f=Less energy consumption and pollution; g= Better land use; ave=average score

In table 7, the average score is calculated under the assumption that each evaluating indicator has the same weight, and a score of more than 3 suggests that the upgrade option is cost-effective when applied appropriately.

Based on this assumption, most upgrade points are shown as very cost-effective, especially the “Setup digital roadside communications” and “Setup CAV-compatible parking lot”. (Both scored 3.8). However, “Relaxed skid-resistance standards for road surface” with score of 3.0 shows that it is not very desirable.

6. Conclusion
Through a wide-ranging literature review and in-depth evidence synthesis, this paper proposes a 3-phase road infrastructure upgrade plan in answer to the research question “How should the road infrastructure be upgraded to accommodate and support CAVs?” Phase 1 mainly comprises maintenance work, phase 2 involves the construction of CAV-segregation infrastructure, and phase 3 concerns a simplified design standard for constructing road infrastructure. Although the 3-phase plan has limitations largely associated with the immaturity of the CAVs market and the lack of collectable data, it should be regarded as a starting point, which can be used to stimulate further research in the field of road facilities upgrades during the CAVs transition time.

Future considerations, however, could be more accurately proposed based on, say more sophisticated data analysis. Appraising software (e.g. the HDM4) could be used for qualitative assessment. A limitation of the research is that the 3-phase upgrade plan did not consider the effects from different regions, countries or under different cultures. Future study could also create specific plans by considering different city sizes, populations, policies and even energy allocation constraints.

References
[1] Guanetti J, Kim Y and Borrelli F 2018 Control of connected and automated vehicles: State of the art and future Challenges. *Annual reviews in control*. Vol 45, pp. 18-40.
[2] Pendleton S D et al 2017 Perception, Planning, Control, and Coordination for Autonomous Vehicles. *MDPI, Machines*, Vol.5, Issue.1. DOI:10.3390.
[3] TSC 2017a Future Proofing Infrastructure for Connected and Autonomous Vehicles. Available: https://s3-eu-west-1.amazonaws.com/media.ts.catapult/wp-content/uploads/2017/04/25115313/ATS40-Future-Proofing-Infrastructure-for-CAVs.pdf.
[4] SAE 2018 *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. J3016_201806.
[5] Litman T 2018 *Autonomous Vehicle Implementation Predictions: Implications for transport planning*. Victoria Transport Policy Institute.
[6] TSC 2017b Market Forecast: for Connected and Autonomous Vehicles. Available: https://assets.pUBLISHING.service.gov.uk/government/uploads/system/uploads/attachment_data/file/642813/15780_TSC_Market_Forecast_for_CAV_Report_FINAL.pdf.
[7] Walker J 2018 *The Self-Driving Car Timeline– Predictions from the Top 11 Global Automakers*. Available: https://www.techemergence.com/self-driving-car-timeline-themselves-top-11-automakers/.
[8] BMW 2018 *Autonomous Driving: What You Need to Know in 2018*. Available: https://www.youtube.com/watch?v=x5Qv4wiUYU&t=126s.
[9] KPMG 2017 Impact of Autonomous Vehicles on Public Transport Sector. Available: https://home.kpmg.com/ie/en/home/insights/2017/07/impact-autonomous-vehicles-public-transport-sector.html.
[10] HA 2009 Network Management Manual: Standards for Highway. Available: http://www.standardforhighways.co.uk/ha/standards/nmm_rwse/docs/nmm_part_0.pdf.

[11] Wee B V and Banister D 2015 ‘How to Write a Literature Review Paper?’ Transport Reviews. 36:2, pp:278-288, DOI: 10.1080/01441647.2015.1065456

[12] Gough D, Oliver S and Thomas J (ed.) 2017 An introduction to systematic reviews. Los Angeles: SAGE. 2nd edn.

[13] Johnson C 2017 Readiness of the road network for connected and autonomous vehicle. London: RAC Foundation.

[14] Lyon B, Hudson N, Twycross M, Finn D, Porter S, Maklary Z and Waller T 2017 Automated vehicles: Do we know which road to take? Infrastructure Partnerships Australia.

[15] Lawson S 2018 Roads that Cars Can Read: Report III – Tackling the Transition to Automated Vehicles. Available: http://resources.irap.org/Report/2018_05_30_Roads%20that%20cars%20can%20read_FINAL.PDF.

[16] Shladover S E and Bishop R 2015 Road transport automation as a Public-Private Enterprise. Third EU-U.S. Transportation Research Symposium. Washington D.C: Transportation Research Board.

[17] McCarthy J, Bradburn J, Williams D, Piechocki R, and Hermans K 2016 Connected and Autonomous Vehicle: Introducing the Future of Mobility. London: Atkins Ltd.

[18] UK Autodrive 2018 Paving the Way: Building the Road Infrastructure of the Future for the Connected and Autonomous Vehicles. Available: http://www.ukautodrive.com/downloads/.

[19] KPMG 2012 Self-driving Cars: the Next Revolution. Available: https://faculty.washington.edu/jbs/itrus/self_driving_cars[1].pdf.

[20] Begg D 2014 A 2050 Vision for London: What Are the Implications of Driverless Transport. London: Transport Times. Available: https://www.transporttimes.co.uk/Admin/uploads/64165-transport-times-a-2050-vision-for-london_aw-web-ready.pdf.

[21] Chen F, Baileu R and Kringos N 2016 ‘Potential influences on long-term service performance of road infrastructure by Automated Vehicles’. Transportation Research Board. pp. 72–79. DOI: 10.3141/2550-10.

[22] CAVita 2017 Connected and Automated Technologies and Transportation Infrastructure Readiness. National Cooperative Highway Research Program Project 20-24(111).

[23] Godsmark P, Kirk B and Flemming B 2015 Automated vehicle: The Coming of the Next Disruptive Technology. The Conference Board of Canada.

[24] Kuutti S, Fallah S, Katsaros K, Dianati M, Mccullough F and Mouzakitis A 2018 ‘A survey of the state-of-the-art localisation techniques and their potentials for Autonomous Vehicle applications’. IEEE Internet of Things Journal. DOI 10.1109/JIOT.2018.2812300.

[25] Sage A 2016 Where’s the Lane? Self-driving Cars Confused by shabby US roadways. Available: https://www.reuters.com/article/us-autos-autonomous-infrastructure-insig/wheres-the-lane-self-drivingcars-confused-by-shabby-u-s-roadways-idUSKCN0WX131.

[26] DMRB 2015 Design Manual for Roads and Bridges. Part 2. TD 25/15. Vol 8 Traffic signs and road lighting, Sect 2. Traffic signs and road markings.

[27] EuroRAP 2013 Roads that Cars Can Read: A quality standard for road markings and traffic signs on major rural roads. Available: www.eurorap.org/wp-content/uploads/2015/03/roads_that_cars_can_read_2_spread1.pdf.

[28] Vine S L and Polak J 2014 Automated cars: A smooth Ride Ahead? Independent Transport Commission.

[29] West D M 2016 Moving forward: Self-driving vehicles in China, Europe, Japan, Korea, and the United States. Center for technology innovation at Brookings.

[30] Cavoli C, Phillips B, Cohen T and Jones P 2017 Social and Behavioural Questions Associated with Automated Vehicles, A Literature Review. London: Department of Transport.

[31] Wagner J, Baker T, Goodin G and Maddox J 2014 Automated Vehicles: Policy Implications Scoping Study. Texas A&M Transportation Institute. 600451-00029-1.
[32] Arrowstreet 2016 Available at: http://www.arrowstreet.com/portfolio/autonomous-vehicles/.
[33] BBC News 2017 New Diesel and Petrol Vehicles to Be Banned from 2040 in UK. Available: https://www.bbc.co.uk/news/uk-40723581.
[34] Kenny S 2017 Road Charging for Cars: What the European Commission Should Do? Freight & Rail Policy Officer. Transport & Environment.
[35] Boffey D 2018 World’s First Electrified Road for Charging Vehicles Opens in Sweden. Available: https://www.theguardian.com/environment/2018/apr/12/worlds-first-electrified-road-for-charging-vehicles-opens-in-sweden.
[36] DMRB 2007 Design Manual for Road and Bridges. Part 3. TD 16/07. Vol 6. Road geometry. Sec 2. Junctions.
[37] ORR 2017 Annual Assessment of Highway England’s Performance. ISBN 9781474145565.
[38] Bierstedt J, Gooze A, Gray C, Peterman J, Raykin L and Walters J 2014 Effects of Next-generation Vehicles on Travel Demand and Highway Capacity. Available: http://orfe.princeton.edu/~ala/ink/Papers/FP_NextGenVehicleWhitePaper012414.pdf.
[39] Glancy D J, Peterson R W and Graham K F 2016 A Look at the Legal Environment for Driverless Vehicles. Washington, D.C: Transport research board. DOI 10.17226/23453.
[40] DfT 2014 Road investment strategy. Summary leaflet. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/410877/ris-leaflet-accessible.pdf.