Novel mathematical model to determine geo-referenced locations for C-ITS communications to generate dynamic vehicular gaps

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Abstract: The study aims at determining geo-reference locations for dynamic cooperative communications to be established, allowing the generation of dynamic vehicular gaps between the Dangerous Goods Vehicles and their surrounding vehicles, such that they could travel via a tunnel as a plate and in isolation. This will ensure the safety of other road users in line with check-and-allow procedures at the road tunnel on Trans-European Transport Network, as per ADR regulations. The model is verified for different road layouts approaching a road tunnel in the UK, using varying traffic scenarios to determine if the identified geo-locations are at suitable distances for gap generation. The results are compared against the simulated real-world tunnel traffic flow with conventional vehicles involving escorting of Dangerous Goods Vehicles via human operators. The mixed traffic and connected vehicles traffic flow scenarios are simulated for dynamic gap generation and compared against real-world tunnel scenario to analyse the improvements in travel time, queues and congestion.

1 Introduction
To travel via a tunnel, Dangerous Good Vehicles (DGVs) require additional regulations and risk assessment checks before they can make a journey through a road tunnel network [1]. Such checks are based on special characteristics such as underwater tunnels, aged tunnels and tunnel with high traffic density and restrictions vary ranging from in-vehicle gaps, speed limiting and escorting [2–4]. The reason for this complex process is a wide range of hazardous goods they can carry, which if not dealt with care, could lead to fatal road accidents. As a reminder, the tragedies of 1999 in Mont Blanc [5] and Tauern [6] road tunnels, highlight the paramount importance of tunnel safety. Such incidents have, and can lead to high fatalities, damage to tunnel infrastructure, environment and long closures which could have significant socio-economic impacts [7].

Thus to monitor and control the flow of tunnel traffic, advanced sensors and surveillance cameras are used and in addition with traffic flow regulations as per The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) [8]. In the UK, various check-and-allow procedures are used to control the flow of DGV and Abnormal Load Vehicles (ALVs) either by using tolls boots prior to the tunnel, or by using sensors to detect the physical dimensions of vehicles, and orange plate sensors identifying UN numbers for identification of hazardous goods carried, as used at Dartford-Thurrock River Crossing Tunnel, Kent, UK [4, 9, 10]. Although the importance of such measures could not be undermined, their control behaviours put a stain on road networks with ever increasing traffic flow and limited infrastructure leading to congestion and delays, in turn compromising road safety.

With the advancements in the fields of Connected and Autonomous Vehicles (CAVs) and Connected Intelligent Transportation Systems (C-ITSs) solutions, many previous studies [11–13] have adopted such them in improving tunnel safety and road traffic conditions in and around the road tunnels. This paper aims to expand on prior knowledge by providing a novel mathematical model for identifying optimal geo-locations for C-ITS communications, enabling safe and secure movements of hazardous vehicles via a road tunnel.

The structure of the paper is defined as follows, Section 2 deals with comparing the proposed model with existing solutions to improve the traffic flow in general and specifically near the tunnels. Sections 3 and 4 define the methodology of the mathematical model and simulation setup, followed by Section 5 evaluating the results. Finally, the paper concludes by discussing the pros and cons of the proposed model.

2 Literature review
The previous study [11] has discussed the tunnel safety improvements using CITS solutions. The study mentions cooperative systems, such as Cooperative Vehicle-Infrastructure Systems (CIVS) and SMARTFREIGHT projects which helped develop Cooperative Tunnel Management application, targeting at the road tunnel safety. The application details how V2I would be used in determining the compliant and non-compliant DGVs aiming to travel via a tunnel. This information could then be displayed on in-vehicle human–machine interface (HMI) for the driver to take appropriate actions, such as drive-through, hold or bypass. The application uses centralised or decentralised approaches in effectively monitoring and coordinating DGVs in the tunnel. Another tunnel safety report [12] focusing on Heavy Goods Vehicles (HGVs) in the tunnel studies the benefits of using C-ITS communications in providing safe travel via a tunnel.

Another report on the Stockholm Bypass Tunnel [13] also mentions the use of C-ITS solutions for emergency management, avoiding standstill vehicles and managing DGV when travelling through a road tunnel environment. The paper proposes dynamic truck lanes for DGVs to improve their movement and safety in the tunnel, with a prerequisite of established V2I communications. Similar to the SMARTFREIGHT project, the movements of DGVs at Dartford-Thurrock River Crossing Tunnel are also controlled and monitored as per ADR and additional regulation [9, 14]. The DGVs arriving at the tunnel are inspected for their carriage and only complaint vehicles are allowed to travel via the tunnel. They queued and multiple vehicles are escorted together in isolation of other road vehicles via the tunnel, for cost-effective measures. The system does not use dynamic coordination between DGV and other road vehicles to optimise their movement, but is based on semi-
automated sensors to detect and monitor road traffic. The two separate papers [15, 16] focused on improving the traffic flow at the Dartford Crossing Tunnel using CAV DGVs and freight vehicles and highlighting the benefits on reducing congestion and delays which would, in turn, have socio-economic benefits.

Another study [17] based on the Stockholm Bypass Tunnel presented the global and local dynamic coordination approaches being used for managing traffic using C-ITS communications. This would be enabling them to negotiate and plans their arrivals at the tunnel to mitigate accident scenarios by determining safer headways when they approach the tunnel from different road sections. Although the above study mentions about dynamic coordination of DGVs by utilising real-time vehicles speed, GPS location, etc., it was limited to synchronising DGVs to avoid crashing but still travelling alongside other vehicles. The study does not cater to a vehicle which would need escorting and determines the control area arbitrarily for global coordination.

The above-mentioned studies and tunnel management procedures do point out the benefits of dynamic and coordinated movements of DGVs in improving the efficiency and safety of travel via a road tunnel but lack the solution which would mathematically help identify:

(i) Geo-reference locations for C-ITS communications to enable the dynamic coordination of DGVs’ approaching a tunnel.
(ii) Vehicular gaps between DGVs and other road vehicles such that DGV platoons could travel via the tunnel in isolation.

The motivation for the first objective is that, to the best of the author's knowledge, no work is carried out in identifying optimal reference locations for C-ITS communications when trying to dynamically coordinate movement of vehicles. Although Marilisa et al. [18] provide an insight on the various C-ITS communications projects in European Union (EU), highlighting services ranging from Emergency electronic Braking Light (EBL) to Connected and Cooperative Navigation (CNN), and Directive 2010/40/EU [19] layout guidelines for deployment of Intelligent Transportation Systems (ITSs) in the field, none of these can determine the distance or location for optimal communications to be established for coordinating the movements of similar groups of vehicles, in this case, DGVs, travelling on same or separate road sections.

Another important point to consider is that all of the various C-ITS communication services are implemented using standardised V2V and V2I messages using Cooperative Awareness Message (CAM) [20], Decentralised Environmental Notification Message (DENM) [21], Signal Phase and Timing (SPaT) and Map Data (MAP) [22–24] and using suitable communication technologies, such as ETSI ITS G5 [25] and cellular LTE [26] and 5G [27]. They are independent of communication protocols. Similarly, the mathematical model proposed in this study is considered independent of the communication protocols and the architectural details for the model are beyond the scope of this paper. The pros and cons of using V2V and V2I communication strategies were highlighted in [28]. The study assumes standardised methods should be used based on current and future best practices of message delivery and communication technologies and by using a combination of V2V and V2I, where former could be used, e.g. to maintain safe distances amongst vehicles, and latter could be used to confirm vehicles passage by verifying dimensional and carriage compliance with the approaching tunnel.

The motivation for the second objective is based on, firstly the tunnel safety and DGVs movement restrictions detailed in ADR regulations [8] and Directive 2004/54/EC [1], and secondly the cost associated to parking and escorting procedures for both the tunnel and freight management systems. As an example, by assessing the data in the Dartford-Thurrock River Crossing tunnel, for which the permission was obtained from Highways England, it was observed that escorting of DGV was a regular occurrence with an average of four escorts per hour. The total average time spends for inspection and the escorting of DGV was 30 min with an upper bound of ~5 h. During this time cost associated with parking and holding, vehicles could be high for both tunnel operators and freight companies. The studies suggest [14, 15, 29] that while escorting is in progress, the traffic stopped from travelling via tunnel could lead to an increase in congestion, delays and socio-economic impacts.

In another study, The GOOD ROUTE project [30] aimed at developing a coordinated system for DGVs routing, monitoring, enforcement and driver support using dynamic and real-time data via V2V and V2I communications. One of the project's pilot sites was 17 km long Gotthard Road Tunnel in Switzerland, which was used to demonstrate basic routing decisions and clearance to pass. The main difference between this study and GOOD ROUTE project is that the latter provided the coordinated information to the DGV drivers or the operations to follow the prescribed route or course of action, whereas in this study focuses on dynamically controlling the coordinated movements of DGV by modulating the traffic speeds.

To ensure CAV enabled freight transportation can manage the safe passage via a road tunnel network, it is imperative that the vehicles and infrastructure behave symbiotically and V2V and V2I communications are relayed at the appropriate time and at the appropriate location to optimise the coordination. The traffic control using Variable Speed Limits (VSLs) and Coordinated ramp metering was studied [31] to create a discharge section upstream of the congested section to support efficient traffic flow. Another study in Wang et al. [32] placed 25 at scenarios of mixed traffic using CAV to improve traffic capacity but was limited by smaller vehicle counts and using platoons on a single lane.

In addition to improving tunnel safety and communication protocols, controlling the flow of traffic and congestion prevention is also necessary. Measures such as Active Traffic Management [33] systems, Ramp Metering [34, 35], Dynamic Ramp Metering [36] for controlling traffic on slip road based on near real-time Motorway Incident Detection and Automatic Signalling (MIDAS) data [37] to merge on the main carriageway during rush hours. VSL [38, 39], ITS [40] etc. are widely used as traffic control measures by transport authorities to control and monitor the traffic flow. The evaluation of different smart motorway schemes was conducted [41, 42] and it was shown that they are effective in controlling the traffic flow than non-managed motorways. The Smart Motorways CALibration and Optimisation (SMCALO) toolkit [43–45] is used by smart and managed motorway schemes in the UK in determining the flow threshold in near-real-time based on MIDAS historic data, to set VSL on motorways controlling congestion and traffic shockwaves. Additionally, other studies have discussed the path-planning and collision avoidance measures for autonomous vehicles [46–49].

By reviewing different traffic control and C-ITS techniques for conventional and connected vehicles, to the best of the authors’ knowledge, no study has so far proposed a model to appropriately identify a geo-reference location for C-ITS communication to let platoons to travel in isolation or buffer safety gap via a tunnel.

3 Methodology

The objective of the study is to allow a safe passage to the platoon of Connected and Autonomous Dangerous Goods Vehicles (CA-DGVs), referred to as the ‘convoy’ in the paper, via a road tunnel in an isolation. The proposal is to create vehicular gaps between the convoy and its preceding and following vehicles without stopping the road traffic, but by dynamically modulating the speeds of preceding, convoy and following vehicle groups. Here the preceding vehicles are defined as vehicles travelling in-front or alongside the convoy, and the following vehicles are defined as vehicles travelling behind the convoy.

To achieve the desired objective, a novel mathematical model is detailed to identify geo-reference point locations (rP) at which the V2I communication would be established to dynamically coordinate DGVs by adjusting their speeds, such that desired vehicular gaps are created between the preceding, convoy and following vehicle groups. The calculations for generating vehicular gaps are categorised into two categories based on the tunnel's length:
For accurately identifying primary and subsequent georeferenced locations, it is important to determine the number of slip roads and the mandatory speed limit between $r_{\text{primary}}$ and the destination tunnel. On their basis, a suitable mathematical formulation would be applied. The UK motorways design and junction road layouts were briefly reviewed [53, 54] but as the model is only concerned with approaching road(s) and speed limit(s) downstream of $r_{\text{primary}}$, detailed analysis of the design is beyond the scope of this paper.

Depending on the position of $r_{\text{primary}}$ following road layout scenarios are identified:

(i) $r_{\text{primary}}$ is positioned before the first nearest approaching junction to the tunnel and without further downstream mandatory speed changes, as shown in Fig. 1a.
(ii) $r_{\text{primary}}$ is positioned before the first nearest approaching junction to the tunnel and with additional downstream mandatory speed limits, as shown in Fig. 1b.
(iii) $r_{\text{primary}}$ is positioned on the main road which has one or more approaching junctions between it and the tunnel. No additional mandatory speed limits are identified downstream of $r_{\text{primary}}$ on the main road and $r_{\text{subsequent}}$ on associated junctions but have different speed limits on individual road sections, as shown in Fig. 1c.
(iv) $r_{\text{primary}}$ is positioned on the main road which has one or more approaching junctions between it and the tunnel. Also, additional
mandatory speed limits are identified downstream of $rP_{\text{primary}}$ on the main road and $rP_{\text{subsequent}}$ on associated junctions, as shown in Fig. 1a.

Furthermore, for road layouts with additional slip roads, there are two different driving scenarios, where

- A single convoy is travelling on the main road.
- Multiple convos are travelling on different roads and should be merged as one before entering the tunnel.

For the mentioned two tunnel categories, four road layout scenarios and two driving scenarios, mathematical formulas are derived to ensure the convoy travels via a tunnel with appropriate gaps between the preceding, convoy and following vehicle groups, irrespectively.

4 Mathematical model

A mathematical model is detailed below to identify appropriate $rP$ at the distance $d$, at which the speeds would be adjusted to achieve desired gaps.

4.1 Primary reference location (all road layouts)

The first $rP$ identified to be termed as $rP_{\text{primary}}$. This reference point is crucial in determining if there will be a need for subsequent reference points ($rP_{\text{subsequent}}$) or not. For a road layout scenario whichRequest a call or leave a message. I'll be happy to help! at which the speeds would be adjusted to achieve desired gaps. In cases where there are additional mandatory speed change, junctions or both between the $rP_{\text{primary}}$ and the tunnel, then $rP_{\text{subsequent}}$ locations will be required to ensure the gaps are appropriately generated when the speeds vary or additional traffic is merged with the main road.

The desired gap is defined as

$$ g = \left( L_{\text{dial}} + L_{\text{convoy}} + d_{\text{safe}} \right) $$

where $L_{\text{dial}}$ is the length of the destination tunnel, $L_{\text{convoy}}$ is the length of the convoy and $d_{\text{safe}}$ is the safety distance between the convoy and two other groups. The detailed analysis of $d_{\text{safe}}$ parameter is beyond the scope of this paper and should be identified using methods such as quantitative risk analysis for tunnels [55–57]. Although, at the Dartford Crossing tunnel, to optimise the escort and minimise traffic disruptions, the Highways England traffic officers (HATO) communicate to start escorting as the last of preceding vehicles exit the tunnel and release of the normal traffic into the tunnel as the last of escorting vehicles exit the tunnel.

$L_{\text{convoy}}$ is calculated as

$$ L_{\text{convoy}} = \sum_{j=1}^{n} (l + d_{\text{saop}}) $$

where $l$ = length of the vehicle in the convoy of size $n$, $d_{\text{saop}}$ = safe stopping distance between $j$ and $j-1$ within the convoy.

It is important to consider the convoy’s length in calculating the desired gap $g$, to ensure the preceding vehicle travelling alongside the last vehicle in the convoy (on multi-lane road network), could safely overtake the convoy before further speed changes are applied at $rP_{\text{subsequent}}$ (where applicable).

Using (2), the time $t$ required to generate a gap $g$ is calculated for $b \in B$ as

$$ t_b = \frac{g}{v_{\text{diff}}} \quad \begin{cases} \text{if} \quad \left( v_{\text{diff}} - (v_j - v_f) > 0 \right) \\ \text{and} \quad v_i = v_f \end{cases} $$

where $v_i$ = velocity of leading vehicle group, $v_f$ = reduced velocity by $\%$ of $v_i$.

Additionally, deceleration time take by vehicles to reduced speed is calculated as

$$ t_a = \left( \frac{(v_i - v_f)}{a} \right) $$

where $t_a$ = deceleration time and $a$ = average acceleration.

Adding (5) into (4)

$$ t_b = \left( \frac{g}{v_{\text{diff}}} \right) + t_a $$

The distance $d$ at which $rP_{\text{primary}}$ would be positioned for $b$ is calculated as

$$ d_b = (v_i \times t_b) + \delta $$  (7)

where $\delta$ is the latency for C-ITS communications.

Using (7), $rP_{\text{primary}}$ is calculated as

$$ rP_{\text{primary}} = \max \{d_b\} $$  (8)

where primary geolocation is selected by choosing the maximum of distance values for the convoy and the following groups. This is to ensure that vehicles slow down safely and faster-moving vehicles are not blocked by slower traffic.

4.2 Subsequent reference locations

The subsequent reference locations ($rP_{\text{subsequent}}$) are required in addition to the $rP_{\text{primary}}$ for all other road layouts except for the layout defined in Fig. 1a.

4.2.1 Multiple speed limits on a single road: For the layouts with no junctions but with additional mandatory speed changes between $rP_{\text{primary}}$ and the tunnel, $rP_{\text{subsequent}}$ are required such that when the group of preceding vehicles enter a new speed limit zone, the convoy and following vehicles’ speeds are adjusted accordingly, to ensure the gaps keep expanding at a determined rate. The $rP_{\text{primary}}$ for this layout is calculated using (8).

To calculate the $rP_{\text{subsequent}}$ first, calculate the time $t_{\text{prec}}$ to determine how long it will take for the preceding vehicles to reach the next speed change for $\forall j \in SN$, where $SN$ is the number of additional speed changes between $rP_{\text{primary}}$ and the tunnel as

$$ t_{\text{prec}} = \left( \frac{d_{\text{speedChng}}}{v_{\text{prec}}} \right) $$

where $d_{\text{speedChng}}$ = distance between $rP_{\text{primary}}$ (or immediate previous $rP_{\text{subsequent}}$ location) and the next mandatory speed change, $V_{\text{prec}}$ = current speed of preceding vehicles.

Using (9), the distances $d$ at which $rP_{\text{subsequent}}$ are positions for $b \in B$ and $\forall j \in SN$ are calculated as

$$ d_{j} = (v_i \times t_{\text{prec}}) + (l + \epsilon) + \delta $$

where $l$ = length of the last vehicle in convoy, $\epsilon$ = small constant added to the length $l$ to ensure if a vehicle from preceding group was travelling alongside vehicle $l$, has enough time to cross the subsequent mandatory speed limit before it is been adjusted by the vehicle $l$.

Using (10) $rP_{\text{subsequent}}$ for $\forall j \in SN$ is calculated as

$$ rP_{\text{subsequent}} = \max \{d_j\} $$
4.2.2 Multiple junctions with the single speed limit and single convoy: For the road layout with multiple junctions between \( r_{P_{primary}} \) location and the tunnel, \( r_{P_{subsequent}} \) locations will be required for \( V_j \in JN \), where \( JN \) is a number of junctions between \( r_{P_{primary}} \) location and the tunnel. Two \( r_{P_{subsequent}} \) locations per junction are required to be determined for a scenario where a single convoy is travelling on the main road. The first reference point will be on the main road where the convoy is travelling, as the dynamic speed changes will only be triggered by the last vehicle in the convoy. This reference point is referred to as \( r_{P_{updateSlip}} \). The second reference point (\( r_{P_{subsequent}} \)) will be positioned on the slip road, where the speed changes would be applied when trigged via \( r_{P_{updateSlip}} \) reference point.

The aim is for the preceding vehicles on slip roads to merge with the preceding vehicles on the main road and following vehicles on slip roads with the following vehicles on the main road, with an appropriate gap for the convoy to squeeze in between two groups, maintaining generated gaps.

To determine the \( r_{P_{subsequent}} \) on the slip roads, first, calculate the time \( t_{precend} \) taken by preceding vehicles on the main road to reach the junction \( j \) for \( \forall j \in JN \) as

\[
\text{where } d_{junc} = \text{distance between } r_{P_{primary}} \text{ and junction } j.
\]

Once \( t_{precend} \) is calculated, determine the distance travelled by the following vehicles \( d_{follow\text{Travelled}} \) on the main road in \( t_{precend} \) as

\[
\text{where } v_{follow} = \text{current speed of the following vehicles.}
\]

Using (13), calculate the gap \( g \) developed between the convoy and the following vehicles for \( \forall j \in JN \) as

\[
\text{The distance } d \text{ for } b \in B, \forall j \in JN \text{ is calculated as}
\]

\[
\text{Using (15) } r_{P_{subsequent}} \text{ is calculated as,}
\]

Now \( r_{P_{updateSlip}} \) locations for all the junctions are calculated by adding deceleration distance and subtracting the time lag distance \( d_{lag} \) (caused due to differences in mandatory speed limits between main and slip roads) to the \( r_{P_{subsequent}} \) distance for individual slip roads. First, calculate the time lag between the main road and subsequent junctions as

\[
\text{where } \mu_{main\text{Road}} = \text{mandatory velocity on main road}, \quad \mu_{slip\text{Road}} = \text{mandatory velocity on the slip road for junction } j. \quad \text{Note, for scenarios where all road sections have exact mandatory speed limits, } t_{lag} = 0.
\]

Using (17), distance \( d_{lag} \) is calculated as

\[
\text{Deceleration distance is calculated as}
\]

\[
\text{where } \mu = \text{number of times speed is reduced on the slip. Here this value will be equal to 2 as on the slip with the single mandatory speed limit, vehicles will slow down at } r_{P_{subsequent}} \text{ and at merging junction, in a normal traffic flow.}
\]

Adding (19) to (16) and subtracting (18) gives

\[
\text{The calculated } r_{P_{updateSlip}} \text{ in (20) is positioned on the main road at distance measured downstream from the respective junctions.}
\]

4.2.3 Multiple junctions with single speed limit but multiple convoys: The road layout with multiple junctions has an alternate scenario whereby separate convoys would be travelling on different roads throughout the network, and to be merged as one before travelling through the road tunnel. To ensure all separate convoys coalesce as one platoon at their respective junctions, it is important to satisfy the following conditions:

- The coalesced convoy length must not exceed the predetermined maximum limit of vehicles in a platoon. The vehicle groups on main and slip roads must be travelling such that each of the groups on the main road must arrive at the junction at the same time as their counterparts on the slip. This should consider the speed differences between the main road and slip road, and of any speed changes applied at \( r_{P_{primary}} \) and \( r_{P_{subsequent}} \).

  - The \( t_{start\text{TimeLag}} \) for \( \forall j \in JN \) is calculated as

\[
\text{where } n = \text{number of speed changes between the start location of the convoy and the respective junction } j, \quad d_{speed\text{Change}} = \text{distance between two speed changes, starting from the depot or last holding location before arrival at the junction } j \text{ for respective convoys}.
\]

- The \( t_{start\text{TimeLag}} \) is added to the start time of convoy’s journey. This information could be identified beforehand and relayed prior to the start of the journey, between different depots or holding locations around the region such that the vehicles depart at a pre-determined time. Furthermore, by utilising connected infrastructure, the movement of different convoys could be monitored to ensure the smooth passage of vehicles through the road network.

To calculate the \( r_{P_{subsequent}} \) location for the slip roads with travelling convoy, first, calculate the time taken by preceding vehicles to reach individual junctions from the \( r_{P_{primary}} \) as

\[
\text{where } \Delta L_{convoy} = \text{currently merged convoy length for approaching a junction}, \quad \mu_{main\text{Road}} = \text{current velocity of preceding vehicles on the main road.}
\]

Adding (19)–(22), the \( r_{P_{subsequent}} \) is calculated as
\[ r_{P_{\text{subsequent}}} = (v_{\text{slipRoad}} \times t_{\text{preced}}) + d_i^t + \delta \]  

(23)

where \( v_{\text{slipRoad}} \) = velocity of preceding vehicles on the slip.

The calculated \( r_{P_{\text{subsequent}}} \) location in (23) would be sufficient to generate an appropriate gap between the preceding, convoy and following vehicle groups on the slip roads to merge with their respective counterparts on the main road.

### 4.2.4 Multiple junctions with multiple speed limits:

For scenarios with single or multiple convoys on the roads with multiple mandatory speeds limits and multiple junctions \( r_{P_{\text{primary}}} \) will be calculated as (8), additional \( r_{P_{\text{subsequent}}} \) locations for all road sections as (23), and additional mandatory speed changes for individual road sections as (11).

### 5 Simulation setup

This section details the simulation setup using PTV Vissim traffic micro-simulation software, version 2020. The simulations are aimed at proving two hypotheses in two phases. Phase I tests the first hypothesis that \( r_P \) as calculated by the mathematical model are appropriately placed for the dynamic generation of desired gaps by modulating traffic speeds and the convoy can travel via a tunnel independently or with sufficient gaps. The evaluation is visual by analysing the stepwise flow of traffic simulation. Phase II tests the second hypothesis and analyses the effectiveness of dynamic gaps and speed variations in improving overall traffic flow. The evaluations are measured on basis of travel time, queue reductions and vehicle occupancy, which are captured at 5 min interval during simulations.

In Phase I, simulation results are compared for four road layout scenarios mentioned in Section 3. Mixed traffic scenarios are simulated for this hypothesis where the convoy is simulated as CA-DGV and Cars (combined cars and Light Goods Vehicles (LGVs) vehicles types) and HGV as conventional vehicles. In PTV Vissim, the conventional vehicles are defined using Wiedemann 99 [58] car following behaviour and connected vehicles are defined as per the CoExist project [59]. In Phase II, the simulations are focused on only one road layout, the one with the single main road and two slip roads and the convoy travelling on all three sections. For evaluations, three traffic scenarios are identified as:

- Simulation of conventional vehicles with no dynamic gap generations and following existing escorting procedures used at Dartford Crossing tunnel with traffic signals labelled as Baseline.
- Simulation of mixed traffic (conventional Cars and HGV but CA-DGVs) and achieving dynamic gap generation, labelled as MixedTraffic. This study assumes the dynamic speed updates for conventional vehicles via VMS and enforced using speed cameras, and for connected convoy via C-ITS communications and enforced using in-Vehicle Speed limits (VSPD) [18] and similar services.
- Simulation of all vehicles running as connected Cars, HGV and CA-DGV, labelled as CAV.

For this study, the simulation model simulates the real-world Annual Average Hourly Traffic flow (AAHT) and traffic compositions for Cars, HGV and DGV as analysed using Dartford Crossing tunnel data for which the appropriate permission from Highways England is obtained. The data is yearlong between March 2018 and February 2018. In addition to AAHT and composition, the waiting times for inspection, parking and escorting of DGV are also considered for travel time analysis.

A short tunnel of 200 m is used to demonstrate the effectiveness of the model in generating gaps. This is because the model is independent of the tunnel’s length and with a 200 m long tunnel the \( r_P \) points on main or slip road would be \( \sim 2500 \) m which would help accurately analyse the generation of gaps and traffic flow conditions during the simulations. The simulated road layouts are designed as a 4-lane main road with two 2-lane slip roads (where applicable).

Furthermore, the PTV Vissim’s platooning functionality [60] is enabled for the convoy vehicle category with the following parameters:

- Maximum number of vehicles = 6.
- Maximum desired speed = 50 mph.
- Maximum distance for catching up to a platoon = 250 m.
- Gap time = 0.20 s.
- Minimum clearance = 1.50 m.

The calculation, implementation and dynamic speed modulated as identified by the mathematical model are performed using PTV Vissim’s COM (Component Object Model) interface [61] with Python scripting language. The \( r_P \) locations are calculated and are placed at a measured distance from the tunnel entrance using Detectors (Vissim’s object) which are triggered when CA-DGV category vehicle a.k.a. the convoy passes over it. The simulation is configured to run for 350 s which is a suitable duration for vehicles to journey \( \sim 2500 \) m distance. The CA-DGV vehicles are dynamically added to the network after 90 s of a simulation run, to ensure road(s) are sufficiently saturated of vehicles. The number of convoy vehicles added on individual roads is based upon the road layout scenario. To ensure the modified speed limits at \( r_P \) locations were reset appropriately following the passage of the convoy. For the simulation scenarios in this study, the Desired Speed object of PTV Vissim mimicking the motorway gantries or VMS, is placed at the \( r_P \) locations, immediately after the junctions and before and after the tunnel. The \( r_{P_{\text{reset}}} \) locations were identified based on these Desired Speed objects as \( (r_P - 2) \), where \( r_P \) is the current geo-reference location of the Desired Speed object on which the convoy is travelling.

The \( r_{P_{\text{reset}}} \) locations should be calculated differently based on distances between two locations, the number of joining junctions between them, etc. The analysis for determining \( r_{P_{\text{reset}}} \) locations is beyond the scope of this paper.

To ensure the simulation results are not due to chance, each simulation scenario is configured for ten random runs using a random seed, defined using general simulation parameters “Random Seed” generator [62] in the software. The detailed list of parameters and their settings for different scenarios are listed in Table 1.

### 6 Results

The results are detailed in two phases. The first phase aims at verifying the mathematical model’s approach in generating dynamic gaps using PTV Vissim traffic simulation. In the second phase, the study analysis the impact of dynamic modulation of speed and vehicular gaps between the preceding, convoy and following vehicle groups with regards to travel time, traffic flow and queue formations.

#### 6.1 Phase I

In the first phase, the traffic was simulated for four road layout scenarios mentioned in Figs. 1a–d with the traffic parameters defined in Table 1. The \( r_P \) locations were calculated for each of the scenarios using the relevant mathematical equations and their respective locations are defined in Table 2. For all the scenarios, the velocity \( (v_f) \) was reduced as \( (v_f - 10) \) mph for \( v_f \geq 30 \) mph. For \( v_f \leq 30 \) mph, \( v_f \) was calculated as \( (v_f - 5) \) mph. The results illustrate dynamic gap generation between the preceding, convoy and following vehicles and isolated travel of convoy via a tunnel as stepwise flow sequences shown in Figs. 2a–d. From the sequences for all the simulated scenarios, it could be concluded that the geo-reference locations on the main road \( (r_{P_{\text{primary}}} \) and on the slip roads \( (r_{P_{\text{subsequent}}} \) were appropriately calculated and placed. The simulation scenario sequences show that by retaining the speed of preceding vehicles and adjusting the speeds of the convoy and following vehicles at \( r_P \) locations, the desired gaps were successfully generated, leading to isolated travel of DGV via the road tunnel. To ensure the adjusted speed limits were reset...
following the passage of the convoy, in the simulation the speeds at \( rP \) locations were reset periodically to ensure following vehicles were at \( \approx 50 \text{ m} \) \( \Delta \text{safe} \) distance from the tunnel, once the convoy has exited the tunnel, as observed in Figs. 2a–d. From the simulation, it was observed that once the speed limits were reset, the following vehicles now travelling at faster speeds were blocked by traffic in front and does not affect the generated gaps.

### 6.2 Phase II

In this section, the dynamic gap generation using the mathematical model is compared for traffic performance between the three scenarios simulated on a road layout with two junctions and the convoy travelling on all road sections. The simulation runs are 480 s and measurements were made every 30 s. The average of ten simulation runs per scenario was performed using random seeds [62] to ensure no two simulations of ten runs are exactly same as in a real-world. For simplicity of graphs Cars, HGV and DGV labels are used for both conventional and connected scenarios.

#### 6.2.1 Travel time analysis: Fig. 3 shows the travel time analysis for the three traffic scenarios comparing Cars, HGV and DGV vehicle groups. Here DGV vehicle group is used to represent conventional convoy for Baseline scenario and connected convoy for MixedTraffic and CAV scenarios. To compare the differences between the three scenarios and to determine if the average travel times were improved between the scenarios, One-Way ANOVA [63] with post hoc testing was conducted. No outliers were observed in the data as assessed by boxplots. Using Shapiro-Wilk’s test [64] (significant value \( p > 0.05 \)), the average travel time was normally distributed for all three categories and homogeneity of variances was satisfied, as assessed by Levene’s test. The average travel time for Cars was reduced from Baseline (sample size \( N = 37 \), mean \( M = 140 \), standard deviation \( SD = 19 \)) to MixedTraffic \( (N = 39, M = 112, SD = 13) \), to CAV \( (N = 39, M = 109, SD = 14) \) scenarios, in that order. For HGV the travel time reduced from Baseline \( (N = 36, M = 143, SD = 21) \), to MixedTraffic \( (N = 39, M = 113, SD = 14) \), to CAV \( (N = 39, M = 109, SD = 14) \) scenarios. And for DGV it was reduced from Baseline \( (N = 2, M = 2096, SD = 3) \), to MixedTraffic \( (N = 4, M = 116, SD = 7) \), to CAV \( (N = 5, M = 115, SD = 6) \) scenarios. The Tukey post-hoc analysis revealed that the travel time improvements for all three vehicle groups where statistically significant \( p = 0.000 \) from Baseline to MixedTraffic and CAV scenarios. On the other hand, the post-hoc test revealed that travel time improvements were not statistically significant between MixedTraffic and CAV scenarios for Cars \( (p = 0.771) \), HGV \( (p = 0.525) \) and DGV \( (p = 0.972) \) vehicle groups. Fig. 4 also compares the travel time on per road basis and highlights that MixedTraffic and CAV scenarios have significantly improved the travel time for Main Road, First Slip and Second Slip roads when compared with the Baseline scenario.

#### 6.2.2 Vehicle count analysis: This analysis is aimed to test the flow of vehicles through a network during an escort in the Baseline scenario and dynamic gap generation in MixedTraffic and CAV scenarios. Fig. 5 shows the average vehicle counts measurements at 30 s intervals, captured using PTV Visum’s Data Collection Points (mimicking MIDAS loops [37]) for the three traffic scenarios.

A one-way ANOVA was used to determine the statistically significant different traffic flow conditions for the three traffic scenarios. The data was observed to be moderately positively skewed and the outliers were observed using the boxplot. The data was square-root transformed to successfully deal with outliers. Using Shapiro-Wilk’s test \( (p<0.05) \), on the transformed data, the average vehicle counts were not normally distributed for all three categories. As one-way ANOVA is considered fairly robust to non-

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### Table 1 Simulation parameters for mathematical model and simulating conventional and connected vehicles

| Parameters                      | Conventional vehicles | Connected vehicles (CAV) |
|---------------------------------|-----------------------|--------------------------|
|                                 | Cars | HGV | DGV | Cars | HGV | CA-DGV |
| AAHT                            | 30001hr (Main road) | 10001hr (Slip roads) |
| average traffic composition     | 82%  | 18% | 5 h | 82%  | 18% | four (single lane) |
| average waiting time            | N/A  | N/A | 33 min | N/A  | N/A | N/A |
| platoon count                   | N/A  | N/A | N/A | N/A  | N/A | N/A |
| \( d_{\text{safe}} \)           | -21 m | -21 m | -21 m | -15 m | -5 m | 6 m |
| \( d_{\text{keep}} \)           | 5.21 m–11.6 m | >11.6 m | 8.85 m | 5.2 m–11.6 m | >1.6 m | 8.85 m |
| average desired acceleration    | 1.0 m/s² | 1.33 m/s² | 1.33 m/s² | 1.01 m/s² | 1.24 m/s² | 1.24 m/s² |
| average desired deceleration    | -2.75 m/s² | -1.25 m/s² | -1.25 m/s² | -2.75 m/s² | -1.25 m/s² | -1.25 m/s² |
| comms latency (\( \delta \))    | N/A  | 100 ms | 10 m | N/A  | 10 m | 10 m |
| length constant \( r \)         | +10% | +10% | +10% | +10% | +10% | +10% |
| Speed fluctuations              |        |        |        |        |        |        |

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### Table 2 Defining \( rP \) locations in meters for four simulated road layout scenarios

| Parameters | Single road, single speed | Single road, multiple speeds | Main road with two slip, single speed (DGV on the main road) | Main road with two slips, multiple speeds per road sections (DGV on all roads) |
|------------|---------------------------|-------------------------------|-------------------------------------------------------------|-----------------------------------------------------------------------------|
| platoon Count | 4 vehicles | 4 vehicles | 4 vehicles | 6 vehicles (2 per road) |
| \( r_{\text{Primary}} \)                    | 1447 m | 2000 m | 1457 m | 1585 m |
| \( r_{\text{MainRoadSlip1 preceding}} \)    | — | — | 765 m | — |
| \( r_{\text{MainRoadSlip2 preceding}} \)    | — | — | 1951 m | — |
| \( r_{\text{Slip1 preceding}} \)            | — | — | 1032 m | — |
| \( r_{\text{Slip1 subsequent}} \)           | — | — | 569 m | — |
| \( r_{\text{Slip2 preceding}} \)            | — | — | — | 581 m |
| \( r_{\text{Slip2 subsequent}} \)           | — | — | — | 1115 m |
normality for nearly equal sample size [63, 65], the results were continued to be analysed by this method. Variances were homogeneous, as assessed by Levene's test. The average vehicle count per interval was improved from Baseline \((N=145, M=20, SD=15)\), to MixedTraffic \((N=150, M=21, SD=16)\), but not for MixedTraffic to CAV \((N=150, M=21, SD=16)\) scenarios. The comparison showed that the traffic flow between the three scenarios was not statistically significant, \((F\text{-distribution } F(2, 442) = 0.091, p = 0.913)\).

6.2.3 Maximum queue length analysis: This analysis is aimed to test the queue formations due to stopping of traffic prior to a tunnel for escorting procedure in the Baseline scenario and due to dynamic speed modulations performed for dynamic gap generations in MixedTraffic and CAV scenarios. Fig. 6 shows the average queue formation throughout a simulation at 30 s interval for three traffic scenarios.

To compare the queue formations between the three traffic scenarios one-way ANOVA with post hoc testing was conducted. The data was observed to be moderately positively skewed and significant outliers were observed, as assessed using boxplot. The data was square-root transformed to successfully deal with outliers. Using Shapiro-Wilk's test \((p>0.05)\), on the transformed data, the average maximum queue lengths were normally distributed. The homogeneity of variance was violated, as assessed using Levene's test \((p = 0.000)\) and thus ANOVA with Games–Howell post-hoc test was conducted. The average maximum queue lengths were

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**Fig. 2** Dynamic gap generation in simulated stepwise sequence for four road layouts
(a) Single speed limit, (b) Multiple speed limits but no junctions, (c) Single speed limit with junctions, (d) Multiple speed limits with junctions

**Fig. 3** Average travel time comparison between different traffic scenarios

**Fig. 4** Average travel time for scenarios on per road basis
analysis revealed that queue reduction from queues were ever observed for three scenarios. By analysing the eliminated, but reduced significantly from MixedTraffic p = 0.20, 95% CI [−0.07, 0.98]) was not statistically significant (p = 0.004). Also, the queue reduction from MixedTraffic to CAV (0.45, 95% CI [−0.07, 0.98]) was not statistically significantly (p = 0.106).

Fig. 6 Average queue length analysis to measure traffic flow

reduced from Baseline (N = 48, M = 11.56, SD = 29.24), to MixedTraffic (N = 48, M = 2.33, SD = 8.08), to CAV (N = 48, M = 0.20, SD = 1.40) scenarios, in that order. Games–Howell post-hoc analysis revealed that queue reduction from Baseline to MixedTraffic scenario (1.05, 95% Confidence Interval (CI) [−0.11, 2.22]) was not statistically significant (p = 0.085) but from Baseline to CAV scenario (1.50, 95% CI [0.43, 2.58]) was statistically significant (p = 0.004). Also, the queue reduction from MixedTraffic to CAV (0.45, 95% CI [−0.07, 0.98]) was not statistically significantly (p = 0.106).

Fig. 7 compares the queue formation on Main Road and Second Slip at their respective junctions. The First Slip is not included in the analysis as being the farthest from the tunnel at ∼1000 m, no queues were ever observed for three scenarios. By analysing the graph, it was observed queues were significantly reduced and eliminated for MixedTraffic and CAV scenarios, respectively, for the Second Slip. On the Main Road, the queues were never eliminated, but reduced significantly from Baseline to CAV scenarios, leading to shorter clearance time, ensuring traffic kept moving smoothly.

7 Discussion

By analysing Phase I results it could be stated that the C-ITS communication rP locations as calculated using the mathematical model were appropriately placed to generate dynamic vehicular gaps using dynamic speed modulations, effectively. It was noted that for all the different road layout scenarios the preceding, convoy and following vehicles travelled as anticipated, generating desired gaps to allow the convoy to travel in isolation. From the stepwise sequences, it was observed that preceding and following vehicles were at approximately d safe distance as the convoy entered and exited the tunnel. Using the model and appropriate reset techniques, ensured that following vehicles now travelling at higher speeds were held back by slower traffic in front, as shown in Fig. 2. It would suggest that too early a reset would let faster vehicle approach the convoy before it completes its journey and diminish the generated gap between the convoy and following vehicles, and too late a reset would impact on the efficiency of travel for following vehicles, leading to delays, queues and congestion build-ups.

By analysing the results for Phase II, it could be observed that the dynamic gap generation performed overall better than existing techniques of escorting of DGV via a road tunnel in isolation. By analysing the average travel time improvements, it was noted that the travel times were drastically improved by ∼21% for Cars, ∼22% for HGV and ∼94% for DGV vehicle categories from Baseline to MixedTraffic and CAV scenarios. Comparing the MixedTraffic and CAV’s scenarios, the improvement by ∼2, ∼4 and ∼1% was observed for Cars, HGV and DGV vehicle categories, respectively. The most benefited category was CA-DGV as they no longer required waiting for inspection, escort and hold procedures but was able to travel without stopping via a tunnel safely. This statement is also backed by [15] which studied the impact of connected freight vehicles travelling via a tunnel. By observing Figs. 4 and 7, it was noted that overall traffic flow on all road sections was significantly improved from Baseline scenario to the other two scenarios. Cross verification of travel time and queue formations on per road basis between the scenarios showed that MixedTraffic and CAV scenarios benefited considerably by using the dynamic gap generation model.

By observing the average vehicle counts, no statistically significant improvements were observed. Nevertheless, from Fig. 5, it was noticed that MixedTraffic and CAV’s scenarios were able to accommodate a comparatively higher volume of traffic than the Baseline scenario, for the exact same road layout. This could be because of smaller headway between connected vehicles or coordinated driving behaviour as simulated by PTV Vissim based on CoExist project in comparison to Wiedemann 99 model for conventional vehicles. This statement could be supported by another study [16] which analysed the impact of connected vehicles in improving the traffic throughput via a road tunnel network. Another interesting observation made was regarding the
recovery of traffic from perturbations caused by traffic closure or dynamic gaps. It was observed that it took ~3 min to recover from the disruptions for all the three traffic scenarios, but the highest congestion vehicles were observed for CAV scenarios, which could be due to shorter headways and standstill distances simulated than other two scenarios. Once the traffic was stabilised after ~3 min, the traffic flow remained stable till the end of the simulation. Additionally, by analysing the average maximum queue lengths, it was observed that the lengths of the queues were substantially improved by ~60% from Baseline to MixedTraffic scenario and by ~73% from Baseline to CAV scenarios. Between the MixedTraffic and CAV scenarios, the queues were improved by ~33%. These average queue reductions were significant even with the traffic volume for MixedTraffic and CAV scenarios were observed to be higher, especially when the dynamic gap generation was in progress. These queue reductions could be related to significantly improved travel times for these two traffic scenarios.

8 Conclusion

The novel mathematical model proved to be an effective and efficient way to escort DGV and similar vehicles such as ALVs which require secure and safe passage via a road tunnel. This would be particularly useful for DGV in a real-world scenario to benefit from platooning as they could be safer and efficient to travel as a group. This is currently a concern as in case of an incident involving a DGV platoon could be fatal or have a significant harmful impact of traffic and road infrastructure, especially in a road tunnel [66]. However, if the convoy is isolated for a relatively short period of time and with appropriate safe buffer gaps between its neighbouring vehicles, the benefits of DGV platooning could be realised. By merging more convoys together, especially for the individual vehicles travelling on slip roads, would help escort more vehicles through the tunnel, increasing the socio-economic benefits and improving the supply chain of the freight industry.

The results showed that the proposed model of dynamic gap generation is effective and efficient in improving travel times, queues and congestion, as compared to the existing practice of escorting and holding. The significant improvements in travel times would benefit the supply chain and logistics of transporting dangerous goods. The study would be useful for transport authorities in designing and planning phases of road infrastructure and tunnel development. Using the model and pre-planned road layouts, the reference point location could be identified proactively, and necessary sensors could be installed to ensure V2V and V2I communications are effective.

Having said so, the proposed model would struggle for vehicles with human drivers requiring higher speed tolerances (current UK acceptable tolerance is 10% ± 2 mph), which are difficult to control given the randomness of speed variations. Until stringent speed control measures using speed cameras, law enforcement measures and using connected services such as VSPD are applied the model would render unsuitable for conventional vehicles. The model would best be suited for the traffic conditions, where the majority of vehicles are connected or automated.

The current model is limited to identification of rP locations and is unable to determining of safety distances required between the preceding, convoy and following vehicle groups. This would be specifically applicable for longer tunnels greater than 3 km where complete isolated travel would be impracticable and costly. It is also limited in accurately identifying speed reset locations (rPreset) for larger road networks with long tunnels and should be investigated in future works.

Future works should also include the investigation of a proposed mathematical model in improving motorway and urban road network in easing congestion an alternative to existing ramp metering techniques.

9 Acknowledgment

The authors thank Highways England contacts for their assistance with the data. The authors would also like to thank PT/ V AG for permission to use PTV Vissim traffic simulation software for simulation purposes. This work was supported in part by the EPSRC, and in part by Costain Ltd. (Grant iCase Voucher 17100033).

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IET Intell. Transp. Syst., 2020, Vol. 14 Iss. 14, pp. 2010-2020

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