Estimating Road Traffic Capacity

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ABSTRACT This paper proposes a novel passenger car equivalent and capacity estimation methods that determine the effect of deceleration and acceleration performance of heavy goods vehicles on the traffic flow and estimate the capacity to facilitate rescheduling container carriers. The development of the new methods considers the driver's perception of time and braking competency level, and the out of the box vehicle displacement approach. The safety gap between the following and leading vehicle should provide sufficient time and space for the driver to bring the vehicle safely to a standstill, to prevent accidents and facilitate enough space for maneuvering. As a case study, the authors have collected and utilized the automatic traffic counters data and the average annual daily flow data from manual counting for the road connecting the Liverpool containership port with North-West England and the rest of the UK. However, the capacity estimation method is suitable for all urban roads and streets that have controlled intersections in the UK and the USA. The authors have found that the passenger car equivalent method is directly proportional to the vehicle's speed, and gross mass and the capacity method is inversely and directly proportional to perception time and braking competency level, respectively. Also, building an extra lane will allow meeting the ports targets.

INDEX TERMS Driver's performance, heavy goods vehicle, road capacity, road congestion vehicle's performance.

I. INTRODUCTION

The expansion of the Liverpool container terminal increases the demand for road freight, and roads that connect the shipment container terminal with the city and the nearby cities will suffer from congestion. Therefore, local authorities try to overcome this problem by choosing one or a combination of solutions, such as building new roads, tunnels, adding extra lanes to existing roads, establishing urban consolidation centers, increase the utilization of other modes of transport for freight transportation. To reach a feasible solution, the planners would require an accurate and efficient method of estimating the effect of heavy goods vehicles (HGVs) on the road traffic flow.

The authors have chosen the Dunnings Bridge road as a case study because of the ongoing demand increase in the container terminal of Liverpool in the UK. The authors have collected data from the department for transport (DfT), and there are two types of data, the automatic traffic counters (ATC) and the average annual daily flow (AADF). The ATC

provides average speed and the traffic flow rates for four types of vehicles for every 15 minutes. The classification of the vehicle type is according to the vehicle's length {≤5.2m, 5.21-6.6m, 6.61-11.6m, and ≥11.6m} [1]. The AADF provides average daily flow by manual counting, and the data contains the actual types of vehicles, and the categorization of HGVs is by type and their number of axles [2].

In order to increase road freight transportation, we need to reschedule container carrier HGV (CC HGVa) without causing further congestions. Therefore, we must estimate the capacity of the road, and to achieve this, we need to estimate the impact of the CC HGVs on the traffic flow operation. Two of the crucial issues affecting the accuracy of traffic flow analysis are the vehicular types and proportions of the traffic flow [3]. The traffic flow proportions of various vehicle types have an adverse effect on the capacity and level of service of roads, especially for roads near container ports or industrial areas, due to the relatively high percentage of HGVs in traffic flow volume.

Typically, the Passenger Cars (PC) (private car or taxi up to eight-seater) comprises of over 85% of the traffic volume, unless the road is close to an industrial area or container

ports where the PC's percentage in the traffic volume over 75%. Therefore, to determine the impact of a non-passenger car vehicle on the traffic flow by estimating the Passenger Car Equivalent (PCE[1]) of these vehicles in comparison to passenger cars.

The PCE value is the equivalent effect of a Light Goods Vehicle (LGV[2]), Rigid HGV (HGVr), or Articulated HGV (HGVa) on traffic flow in comparison to a PC. The determination of the effect of HGVs requires the estimation of the PCE of the various vehicle types that make the traffic flow composition at different hours of the day. It is essential to determine an accurate and realistic PCE of HGVs.

Researchers who developed methodologies of PCE estimation over the last 80 years rely on either vehicle's proportion, flow volume, length, speed, delay, travel time, engine power, or a combination of two to three of these variables. In this paper, we will discuss these methods and the capacity estimation method in a literature review and propose novel methods for the PCE and capacity estimation.

By estimating the HGVa's PCE value, we can estimate the dynamic capacity of the road and determine the available space to accommodate the maximum number of TEUs[3] without causing or increasing congestions or affecting the safety of the road. The target of the proposal for expanding Merseyside ports aims for processing an annual 2MTEU by the year 2020, and 3MTEU by the year 2030. The proposed targets by Merseyside ports are that the freight rail and inland waterway would transport 10% and 5% of these containers, respectively [4].

The number of existing annual TEUs processed in the year 2017 was 760kTEU, and the TEUs entering the UK through the port account for 48.5% of the yearly TEUs in both directions. Therefore, we can assume that the annual TEUs that leave the container terminal to the UK mainland by utilizing intermodal transportation is 369kTEU.

Of all the road freight TEUs going to the UK through Liverpool container terminal, 22% go to Liverpool while 78% go to Manchester, North West Region, and the rest of the UK [5]. By deducting the TEUs transported by rail and inland water modes [6], [7], the TEUs transported by road passing through the port's inland access (Dunnings Bridge Road) was 278kTEU in the year 2017, 732kTEU by 2020, and 1097kTEU by 2030.

However, for the year 2017, the inland waterway freight transported only 2.39% of TEUs, and freight rail transported

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TABLE 1. Literature review variables, definition, and units.

Variable	Definition	Units
f_{HV}	Heavy vehicle factor	vehicle/PC
PCE_T	Passenger car equivalent for all trucks	PC/Truck
PCE_R	Passenger car equivalent for recreational vehicles	PC/Rec
P_T, P_a	The proportion of trucks in traffic flow (TF) and proportion of articulated HGVs in traffic flow	Truck/TF, HGV$_a$/TF
PR	The proportion of recreational vehicles in traffic flow (TF)	Rec/TF
TF_{PCE}	PCE traffic equivalent volume	PC/h
TF_{total}	Total traffic flow volume	vehicle/h
D_{PC}	Delay caused by passenger car (PC)	s
ΔD_i	The additional delay caused by a vehicle of type (i)	s
AD_{pc}	Acceleration Distance of a PC	m
PCE_i	PCE based on delay for vehicle type (i)	PC/vehicle
D_T	Delay caused by a truck	s
TT_{Av}	Average travel time of all types of vehicles in the traffic flow	s
TT_T	Travel time of trucks traffic flow	s
S_{PC}	Mean speed of passenger cars	m/s
S_T	Mean speed of trucks	m/s
L_{PC}	Passenger car length	m
TF_{PC}	Traffic flow rate of PCs	vehicle/h
H_{pp}	headway between a PC and another PC	m
H_{PC}	Passenger car's headway	m
ΔH	Total increased headway of the queue caused by the truck	m
DT_T	The total discharge time of a truck queue	s
DT_{PC}	The total discharge time of a PC queue	s
HT_{pc}	Time Headway for PC vehicles	s
P_{PC}	Passenger Car Proportion in traffic flow	PC/TF
H_{Total}	The total headway due to vehicle composition	s
H_{pt}	Headway between a passenger car and a leading truck	m
H_{tp}	Headway between a truck and a leading passenger car	m
H_{tt}	Headway between a truck and a leading truck	m
TF_T	The traffic flow rate of trucks	vehicle/h
A_{PC}	The rectangular area occupied by passenger cars on the road	m^2
A_T	The rectangular area occupied by trucks on the road	m^2
H_T	Headway for trucks	m
L_T	Average Trucks' length	m

only 1.642% of TEUs, which leaves 95.97% of TEUs that utilize road freight transportation by CC HGVa. Therefore, we should set the target for road freight according to the actual intermodal share, and that is 726kTEU and 1089kTEU for the years 2020 and 2030 targets, respectively, for UK inbound road freight to the north-west and the rest of UK.

II. LITERATURE REVIEW

In this section, we will review the existing Passenger Car Equivalent (PCE) methods, vehicle's acceleration performance effect, the effect of the perception time, and the vehicle's braking performance effect on stopping distance. The literature review's variables and formulas are available in Table 1 and Table 2.

A. PCE BASED ON TRAFFIC FLOW AND VEHICLE PROPORTION

One of the most common methods of assessing the impact of HGVs on the traffic flow operation in the saturation flow method [8], [9]. The HCM adopted a method called the heavy

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[1]The passenger car equivalent represents the equivalent effect of non-passenger car vehicles on the traffic flow and the value of PCE is expressed as the effect of a non-passenger car vehicle as equivalent to the effect of number of passenger cars on the road, e.g. if a truck has three times the effect of passenger cars on the road, then one truck is said to have a PCE equal to 3 PC/Truck

[2]We utilized the classification of vehicle types according to the categorization of vehicles in the AADF data set of the UK. Therefore, the LGV stands for light goods vehicles and not large goods vehicles as in some other countries such as the USA.

[3]TEU stand for Twenty feet Equivalent Unit and a 1 TEU is equivalent to a 20ft shipment container

TABLE 2. Literature review formulas and their description.

Author	Formulas
Transportation Research Board (TRB) (HCM)	$f_{HV} = \dfrac{1}{1 + P_T * (PCE - 1)} = \dfrac{TF}{TF_{PCE}}$
St John	$PCE = \left(\dfrac{1}{P_T}\right) * \left(\dfrac{TF_{PCE}}{TF} - 1\right) + 1$
Cunagin & Messer	$PCE_i = 1 + \dfrac{\Delta D_i}{D_{PC}} = \dfrac{D_{PC} + \Delta D_i}{D_{PC}}$
Benekohal & Zhao	$PCE_T = 1 + \dfrac{D_T - D_{PC}}{P_T * AD_{PC}}$
Keller	$PCE_T = \dfrac{TT_t}{TT_{Average}}$
Huber	$PCE_T = \dfrac{S_{PC} * L_T}{S_T * L_{PC}}$
Sumner	$PCEt = \dfrac{TF_{PC} * TF - TF_T * TF_{PC}}{TF_T^2} + 1$
Chandra	$PCE_T = \dfrac{S_{PC} * A_T}{S_T * A_{PC}}$
Molina	$PCE_T = 1 + \dfrac{DT_T - DT_{PC}}{HT_{PC}}$, $PCE_T = \dfrac{H_T + \Delta H}{H_{PC}}$
Gwynn, Werner	$PCE_T = \dfrac{\frac{H_{Total}}{H_{PC}} - P_{PC}}{P_T}$
Krammes	$PCE_T = \dfrac{(1 - P_T) * (H_{pt} + H_{tp} - H_{pp}) + P_T * H_{tt}}{H_{pp}}$
Greenshields, Seguin, and Cunagin & Chang	$PCE_T = \dfrac{H_T}{H_{PC}}$

vehicle factor (f_{HV}) that considers the impact of trucks on the traffic flow capacity according to the HGV proportion and its PCE value, and the f_{HV} is inversely proportional to the HGV proportion and PCE value, as in Table 2. Equation (1) shows that the PCE for non-passenger car vehicles is dependent on the value of f_{HV}, as in Table 2.

$$PCE_T = \frac{1 + f_{HV} * (P_T - 1)}{f_{HV} * P_T} \qquad (1)$$

where,

f_{HV}	is the heavy vehicle factor
P_T	is the proportion of trucks in traffic flow
PCE_T	is the PCE for trucks in PC/Truck

The HCM assumes a constant value of two for trucks PCE when applying the f_{HV}. The f_{HV} showed direct proportionality to the volume of PCs in traffic flow. Some PCE estimation methods utilized the flow volume and HGVs proportion.

St. John [10] utilized traffic flow volume, and vehicle proportion and results were proportional to traffic volume. Hence, the vehicle proportion does not reflect the actual effect of HGVs unless the traffic flow is at a capacity level, while the HGV traffic flow volume demonstrates the impact of HGVs at any traffic composition flow, as in Table 2. Webster and Elefteriadou [11] found that HGVs' PCE of St John's method is directly proportional to the traffic flow volume, free flow speed (FFS), and grade length, and inversely proportional to the truck's proportion and the number of lanes.

B. PCE BASED ON SPEED, TRAVEL TIME AND DELAY

Benekohal [12], Wiley and Cunagin [13], and Eric and Keller [14] utilized the non-passenger car vehicle's delay. Benekohal [12] demonstrated high values at off-peak hours indicate no correlation with flow volume, and it is due to the integration of HGVa proportion, e.g., the PCE value for an

HGVr is twice as high as that for an HGVa while the HGVr proportion is lower than the HGVa proportion.

Wiley and Cunagin [13] and Eric and Keller [14] utilized non-passenger vehicle extra-delay and travel time, respectively. The HGVa could be 10-22 times the passenger car in weight and over three times the passenger car in length and engine power. The average PCE value is 2.87 a day and ranges 1.01-8.55 for the method by Wiley and Cunagin [13], and the results showed unstable PCE values up to 8.55 during morning peak hours, and down to 1.01 during the afternoon and evening peak hours.

Keller's method [14] resulted in an unrealistic PCE value for HGVa of 1, and both of Wiley and Cunagin [13] and Keller's [14] methods do not correlate with speed and traffic flow rates. Methodologies that depend on time delay or travel time, such as Wiley and Cunagin [13] that evaluated the PCE of 14 different vehicle types under various conditions of traffic and roadway geometry. Wiley and Cunagin [13] estimated PCEs at signalized intersections and found that PCE values range from 1-1.37 for HGVr and from 1-2.18 for HGVa, as in Table 2.

Benekohal [12] concluded that the percentage of trucks has a nonlinear relationship with the PCE value, while the traffic flow volume is proportional to PCE value, as in Table 2. Keller [14] developed a method of PCE that depends on the ratio of a truck's travel time to the average of all vehicles' travel time, as in Table 2.

Michel Van Aerde [15] developed a method based on speed reduction caused by traffic in the opposite direction in two-lane rural highways and explored the effect of platooning. The values that they estimated were relatively high. The PCE for trucks ranged from 3.8-11.4, and recreational vehicles ranged from 2.6-3.9. Platooning followers' PCE values for trucks and recreational vehicles at high traffic volumes are 1.20, 1.07, respectively, and 1.23 for both at low traffic volumes. While platooning leaders' PCE for trucks and recreational vehicles are 2 and 1.55, respectively.

Huber [16] developed a method based on the vehicle's length and speed, as in Table 2, and proved that his formula is equivalent to St John's [10] formula. Chandra [17] estimated PCE based on the vehicle's speed and footprint, as in Table 2. Huber [16] and Chandra [17] combined speed and vehicle dimensions to estimate the PCE. The Huber [16] method provided an HGVa PCE value of 3.81, given that an HGVa is over three times longer than a PC. Chandra [17] integrated the width of vehicles to determine the effect of a vehicle's footprint on the PCE and resulted in a relatively acceptable PCE value of 5.51, given that an HGVa is only up to 44% wider than a PC.

C. PCE BASED QUEUE DISCHARGE

A method developed by Molina [18] depended on its position in a traffic queue. The method estimated the PCE values to be 1.6, 2, 2.3-2.5, and 3.1-4.1 for two-axle, three axles, four-axle, and five-axle trucks, respectively, where the value of the height of five-axle trucks PCE is for trucks in the first position

in the queue. Molina [18] proposed modifying the headway ratio by adding an extra headway behind trucks and developed a relationship between passenger cars' headway and time of discharge of passenger cars' queue and time of discharge of trucks' queue, and the method is dependent on the extra delay caused by longer trucks, as in Table 2.

Molina [18] suggested that the positions of vehicles in the queue do not significantly affect the PCE values for the two to three-axle trucks. The acceleration performance of these types of trucks is close to that of passenger cars. Thus, their position in the queue has minimal effect on the PCE value. Al-Kaisy [19] and Al-Kaisy [20] methodologies consider congested conditions and represented by queue discharge flow (QDF) and vehicle's weight to power ratio, respectively.

Al-Kaisy's two methods work during congested traffic where the volume to capacity ratio is equal to one and dependent on a vehicle's manufacturing characteristics that vary according to the HGV's load. For instance, a fully loaded truck acceleration time is not the same as an empty truck, and the QDF method only considers traffic flow at full capacity. Different factors involve the estimation of the effect of HGVs, such as grade, grade length, and lane restriction by vehicle type.

Al-Kaisy [21] investigated the effect of HGVs that ran on roads with upgrade or downgrade (non-level terrain) and suggested that the HCM PCE recommended values may have a considerable error. Due to the acceleration and deceleration experienced during congestion, Al-Kaisy [21] utilized the QDF method, and Al-Kaisy [19] derived the PCE from simulation experiments based on grade lengths of 0.2-2km, grades of +2-6% and HGV percentage of 2-25%. Al-Kaisy [21] concluded that the effect of HGVs on upgrade roads would not depend solely on the length of the truck and its' headway (unlike the case on level terrain), but also on acceleration performance, which is mainly dependent on the power to weight ratio (PWR) of the HGV.

D. PCE BASED ON VEHICLE HEADWAY

The headway methodology adopted by Greenshields [22] and Molina [18] showed a correlation to length and speed if the calculation of headway is dependent on stopping distance. However, if the calculation of the headway considers only the vehicle flow rate as in TRB [8], [9], then the Greenshields [22] and Molina [18] methods showed HGV PCE values of an average of 6.88 with a range of 4.06-14.65, and an average of 7.88 with a range of 5.06-15.01 respectively. However, the results of the latter two methods showed unrealistic values that reach their highest values at off-peak hours, and they do not correlate with vehicles' flow rate, proportion, a vehicle's length, and the available gap between following and leading vehicles.

The Gwynn's [23] and Krammes's [24] methods used headway and proportion to estimate the PCE, and the results showed the same pattern that appeared in the Greenshields [22] and Molina [18] methods. Additionally, the Gwynn's [23] and Krammes's [24] methods' PCE results

showed no correlation with flow volume. The Gwynn's [23] method shared the same inconsistent results in, where it provided PCE values for an HGVr 5-6 times higher than the PCE for an HGVa even though an HGVa is longer and heavier than an HGVr.

Gwynn [23] and Werner [25] developed similar methods for estimating PCE for low levels of service on a level terrain that considers headway distance and vehicular proportions, as in Table 2. Krammes [24] evaluated the merits of three approaches of constant volume to capacity ratio, equal density, and spatial headway, as identified by Roess [26] to estimate PCE. Krammes utilized truck's flow volume's proportion, and passenger car and truck headways, as in Table 2.

Krammes [24] stated that trucks are larger than passenger cars and have lower operating capabilities than passenger cars and concluded that the spatial headway approach was the most suitable method for primary freeway segments. Greenshields [22], Seguin [27], and Cunagin [28] based their estimation only on headway distance, as in Table 2. Cunagin [28] stated that the presence of HGVs reduced the road capacity during the peak period and found that the increase of HGVs in traffic flow would increase the mean headway.

Fan [29] found that the PCE values are higher in Singapore than the ones recommended in the HCM [8], and stated that it is due to lower speed limits for HGVs and LGVs and higher capacity per hour per lane in Singapore. Also, Fan [29] concluded that HGVs and buses have higher PCE values than LGV's PCE even though they have the same speed limit due to the smaller size of LGVs and because LGV drivers exceed speed limits in high proportions.

Obiri-Yeboah [30] showed that PCE values were higher at intersections with roadside friction than those without roadside friction. The values obtained in Obiri-Yeboah [30] study were larger than values adopted elsewhere, and it showed PCE values for cars, medium vehicles, and trucks of 1, 1.65, and 3.05, respectively, with roadside friction and 1, 1.35, and 2.25 respectively without roadside friction.

Elefteriadou [31] stated that variables such as the percentage of trucks do not always have the expected effect on PCEs, whereas other variables, such as vehicle type, PWR ratio as well as vehicle length could be vital to the estimation of PCE, especially on roads with steep upgrade or downgrade.

E. PERCEPTION TIME AND BRAKING COMPETENCY LEVEL

1) PERCEPTION TIME

The determination of the stopping distance (SD) should consider the worst-case scenario, and the SD value is a combination of braking distance and perception time distance during unanticipated emergencies. The UK's Highway Code [32] stated that the safety spacing between a passenger car and the leading vehicle should be from 1.34s for 32.2km/h (20mi/h) to 4.69s for 112.7km/h (70mi/h). As stated by the Highway Code of the UK, the thinking time for driver's perception is

a minimum of 0.67s, although the braking distance varies in proportion to vehicle type, speed, and braking efficiency.

The thinking time varies depending on the driver's age, health, and state of mind, and it could reach up to 2.5s as recommended by [33]–[36]. [18], [35], [37]–[44] determined the perception time (PT) within a range of 0.3-3.0s, and Johansson [45] at unexpected situations, the PT would increase by a factor of 1.35 or up to one second more.

Consiglio [46] investigated the effect of PT in conditions where drivers listen to the radio, have a conversation with a passenger, have a conversation using hand-held the phone, and have a conversation using a hands-free phone, and found that the PT delay is 0.016s, 0.061s, 0.072s, and 0.073 s, respectively. Fiorentini [47] determined that the impact of ageing on the visual and decision responses had led to an increase in PT of up to 75ms.

[48]–[52] found that drivers with blood alcohol concentration (BAC) of 0.88g/l would require up to 0.274s more PT than drivers with no alcohol consumption and up to 0.419s more for information processing rate. TAC also stated that if a driver is continuously awake for 17 hours and 24 hours, and the effect tiredness has on the driver's PT is equivalent to a driver with a BAC of 5g/l and 1g/l, respectively, and this makes the driver twice and seven times likely to have an accident as a driver with zero alcohol intake. Drivers with fatigue are more likely to fall asleep during driving, and drivers with high fatigue at least close their eyes for 2s.

Guofa [53] determined that in the post-congestion period, drivers became more aggressive, more focused in the forward area, but less focused in the dashboard area. On the one hand, the more the driver focus in the forward area, the less perception time required to avoid crashing the leading vehicle. On the other hand, the driver's aggressiveness, and loss of attention to the periphery area will increase the risk of collision with motorcycles, bicycles, and crossing pedestrians.

2) BRAKING COMPETENCY LEVEL

Greibe [54] conducted braking trials for 172 emergency stops and 23 comfort-braking maneuvers, where the majority of test drivers were non-professional, and utilized a straight level terrain road and vehicles with fitted automatic braking system (ABS). Greibe [54] found that the time it takes for the pedal from being touched until the pressure reaches at least 10kg was 0.05s for professional test drivers and 0.83s for non-professional test drivers.

Greibe [54] stated that the maximum required pressure is 20kg, and some professional drivers applied pressure of up to 150kg. However, the deceleration was the same as if they applied pressure of 20kg because one the ABS activates, extra pressure on the brake pedal will not increase the deceleration. Also, Greibe [54] stated that the majority of non-professional drivers applied only 50% of the intended maximum pressure for the brakes.

The authors have presented perception time scenarios in Table 3 that shows six scenarios where driver's braking

TABLE 3. Various driver's scenarios and their effect on PT.

Driver's Behavior and Conditions	PTC in (s)	Scenarios of Driver's braking competency level, conditions, and behavior that contribute to the PT of drivers, and results are in (s)					
		One	Two	Three	Four	Five	Six
Radio	16m	-	16m	-	-	16m	-
CWP	61m	-	61m	-	-	61m	-
CHHP	72m	-	-	72m	-	-	72m
CHOP	73m	-	-	-	-	-	-
Y or E	0 or 7.5m	0	0	7.5m	0	0	7.5 m
ES	0	-	-	-	-	-	-
US	1	1	1	1	1	1	1
EM	0.63	0.63	0.63	0.63	0.63	0.63	0.63
BPL for NP or P	0.83 or 0.1	0.83	0.83	0.83	0.1	0.1	0.1
LF or BAC ≤0.5g/l	0.4	-	0.4	-	-	0.4	-
HF or BAC ≤1g/l	0.8	-	-	0.8	-	-	0.8
S_l	2	-	-	2	-	-	2
PT in (s)		2.46	2.94	5.41	1.73	2.21	4.61

Where,

PTC	Perception Time Component in second (s)
NPBCL	Non-professional braking competency level
PBCL	Professional braking competency level
Radio	Turning on the Radio
CWP	Having a conversation with passengers
CHHP	Having a conversation by hand-held phone
CHOP	Having a conversation by hand-off phone
Y or E	Driver's age is Young or Elderly
ES	Expected Situation
US	Unexpected Situation
EM	Driver's Eye Movement
BPL for NP or P	Braking Pressure level for Non-professional or Professional drivers
BAC	Drivers with Blood Alcohol Concentration
LF	Drivers at Low Fatigue
HF	Drivers at High Fatigue
S_l	Drivers close their eyes to sleep for at least 2 seconds

competency level, behavior, road conditions, age, health, and alcohol consumption change according to the literature review in section II.F.

F. ROAD CAPACITY ESTIMATION

In this paper, the road capacity estimation only covers the roads with controlled intersections. Most countries adopt the Highway Capacity Manual's (HCM) [8] capacity estimation and level of service methods and [55]. The capacity estimation method utilized by the HCM starts by calculating the saturation flow (SF) for a single lane, as in (2):

$$SF = \frac{One\ Hour}{Saturation\ headway\ (h_s)} \quad (2)$$

Thereby, the definition of a saturation headway (h_s) in the HCM is "It is the average headway that can be achieved by a saturated, stable moving queue of vehicles passing through the signal", and the unit is s/vehicle. The HCM determined that the h_s is equal to 2s/vehicle, and since that one hour is equal to 3600s, the saturation flow should be equal to 3600/2 = 1800vehicle/h.

By calculating the SF for a single lane, we need to consider other factors, such as the number of lanes (NL), heavy vehicle

factor (f_{HV}), lane width correction factor (f_w), effective green ratio (EGR), and driver' population factor (f_p). The road under investigation is a one-way two-lane road with a speed limit is 64.4km/h (40mi/h) with a signalized intersection. Therefore, we will neglect the effect of the access ramp and two-directional flow.

The heavy vehicle factor is a measure of the impact of heavy vehicles on the capacity of the road, by utilizing the vehicle's PCE and vehicle's percentage of flow from the total traffic flow composition. The f_p is a measure of the familiarity of the driver with the road, e.g., and every weekday commuter has an f_p of 1 while unfamiliar drivers can have an f_p of 0.75-0.9 [56].

The f_w factor considers the width of the vehicle, lane, and the distance of obstruction from the sides of the road, and f_w varies from 0.66-1 depending on the lane's width, vehicle's width, and whether the obstruction on one side or both side. Therefore, the f_w for HGVs is 0.81-0.9, and for PCs is 0.94-0.97 [56]. The EGR definition is ''The green time that is used by traffic'' [57]. The calculation of EGR considers the cycle length, green period, yellow period, and lost time. Now, the capacity estimation formula for a multi-lane one-way road with signalized intersection (Interrupted traffic flow) is as in (3) [8], [58]:

$$Capacity = \left(\frac{3600}{h_s}\right) * NL * f_w * f_p * EGR * F_{HV} * EGR \tag{3}$$

Unlike most countries, Britain does not adopt the HCM methodology in estimating the road capacity. The road categorization in the UK is as follows:

- Motorways
- Built-up trunk roads with speed limit ≤ 64.4km/h
- Built-up principle roads with speed limit ≤ 64.4km/h
- Non-built-up trunk roads speed limit > 64.4km/h
- Non-built-up principle roads speed limit > 64.4km/h

In this research, the author is investigating the A5036 road, and it is a built-up trunk road with a speed limit of ≤64.4 km/h. The A5036 is also a dual carriageway with two lanes for each direction. In the UK, the capacity estimation methodology considers an approach based on empirical British research studies related to different discrete aspects of road operation and analysis. The result of this approach shows that the road under investigation has a capacity of 3250 vehicle/h, and with a reduction of 100 vehicle/h from every lane for traffic flows with15-20% HGVs, and a reduction of 150 from every lane for traffic flows with 20-25% HGVs [55], [56].

G. SUMMARY OF LITERATURE REVIEW

The above literature has highlighted the following gaps in the estimation of the PCE and capacity:

1) The utilization of vehicle proportion in PCE estimation does not reflect the actual effect of the vehicle on the road unless the traffic flow is at its full capacity.

2) The utilization of speed, delay, travel time, and queue discharge delay in PCE estimation requires the manufacturing details and speed for various vehicle types in the traffic flow composition.
3) The methods that utilize the vehicle's headway has not considered the effect of acceleration delay for non-PC vehicles.
4) All the existing PCE methods have not addressed the effect of the driver's perception time and braking competency that affect the vehicle stopping distance and the PCE value.
5) The current capacity estimation method for urban roads with controlled intersections does not consider the traffic flow speed, the required headway, and vehicles' count

III. DATA VALIDATION ANALYSIS
A. MANUAL COUNT AND OBSERVATION

The authors made a field observation at a couple of road links of road A5036 starting from the 15th of July 2018 and conducted manual counts at the peak period of 4-6 pm for road A5036 at road link of A5038-A5207 on the 19th of July 2018. The findings of the field observation are:

1) The container port always utilize HGVa with 5-7 axles to transport intermodal shipping containers, even if the container is 20ft long or less
2) Tanker trucks are all with 5-6 axles, and this is regardless of the length of the tank
3) The difference between a five-axle truck and a six-axle truck is only when the six-axles truck raise one or two axles
4) Unloaded HGVa with no trailer is short, and they could overlap with vehicles with a length of ≤6.6m.
5) Loaded 5-6 axles CC HGVs are 35% of all 5-6 axles HGVs
6) Loaded five axles, CC HGVs are 41% of all loaded 5-6 CC HGVs
7) Unloaded 2-4 axles articulated HGVs without trailers are 11.4% of all 5-6 axles HGVs, and are 24.52% of articulated HGVs
8) Loaded non-CC curtain/box HGVs with 5-6 axles are 40.3% of all loaded

B. HEADWAY MEASUREMENT

Greenshields [59], Cunagin [28], and Seguin [27] had different approaches in obtaining headway data. However, all of the three utilized a type of photography system to determine the headway time. Greenshields [59] obtained his data by taking photos at a single site for every 5 seconds from the top of a nearby building, and Cunagin [28] utilized Super-8 movie films by using a time-lapse projector, and Seguin [27] obtained his data by installing a traffic evaluator system at the intersections of 11 sites.

The proposed method in section IV considers the required stopping distance for safety. However, most drivers do not

follow the safety gap. Therefore, rather than obtaining the headway data from field measurements, the authors of this paper have determined the headway distance by utilizing the vehicle's length and calculating the emergency stopping distance with consideration to the perception time and braking competency level for drivers. Therefore, the authors have not measured vehicles' headway and speed on the survey site.

C. HGV LOADING AND BODY TYPES

The authors have obtained the CC-HGV container loading from the Liverpool port's annual average data. However, the authors have designed the proposed method in section IV to allow variable loading factors. The authors have shown the impact of different loading scenarios on the traffic flow in another paper [60].

According to the DfT [61], HGVr with a weight of over 3.5tonnes has over 19 body types: Box Van, Tipper, Curtain Sided, Dropside Lorry, Flat Lorry, Refuse Disposal, Skip Loader, Insulated Van, Tanker, Panel Van, Street Cleansing, Car Transporter, Concrete Mixer, Livestock Carrier, Motor Home/Caravan, Tractor, Skeletal Vehicle, Goods, Tower Wagon, Other. They have different body lengths and weights.

According to the DfT [62], [63], the maximum allowed length and weight of an HGVr with four or more number of axles are 12m, and 32tonnes, respectively, and some of the HGVr falls into the length category of the ATC data [1] of light goods vehicles (LGV), and some will fall into the length category of HGVa.

The model considers an average weight, engine power, and dimensions for each of the four vehicles categorized in the ATC data. The user of this method can change the loading factor, vehicle's dimensions, engine power, temperature, wind speed, and any other variable concerning the vehicle specifications and the weather conditions.

D. DATA VALIDATION

To determine the effect of overlap between the Automatic Traffic Counter's (ATC) data categorization with the Annual Average Day Flow (AADF) data, we have:

1) Analyzed the vehicles' registration data set for Great Britain (GB) and North West (NW) area [61], and the AADF data set for road A5038 of link A566-A5036 [2] by utilizing regression and correlation analysis.
2) Compensating for vehicle type overlap by correcting the ATC data [1] by using the vehicle registration data [61].

The authors have utilized regression and correlation analysis to determine whether there are a close match and linear or monotonic relationship between the registration data and the AADF data for road A5038 (Road A5038 is an A road with the average percentage of HGVs). We utilized linear, quadratic, cubic, and power regression methods, and utilized the Pearson, Spearman, and Kendall's Tau methods for correlation analysis.

TABLE 4. Sum square error results based on existing GB & NW data as ŷ.

Vehicle Type Proportion	Data Type	Sum Square Error (SSE) for 5038 data as y and NW and GB data as ŷ
PC	5038-GB	0.007640
	5038-NW	0.022349
HGV	5038-GB	0.001379
	5038-NW	0.000547
LGV	5038-GB	0.014355
	5038-NW	0.021551
Motorcycle	5038-GB	0.014828
	5038-NW	0.011012
BUS/Coach	5038-GB	0.000386
	5038-NW	0.000633

TABLE 5. Results of average working daily count prediction of AADF data for road A5036 of link A5038-A5207.

Vehicle Type	Actual	Linear	Quadratic	Cubic	Power
Total Vehicle	19648	19079	20631	18967	19641
Motorcycle	104	61	80	87	55
Car/Taxi	14670	13633	14348	14334	13679
Bus/Coach	111	90	104	100	94
LGV	3078	3259	4257	3281	3384
HGVr	478	567	577	601	549
HGVa	1209	1469	1265	564	1880
All HGV	1687	2036	1842	1165	2429

TABLE 6. Correlation analysis by Pearson, Spearman, and Kendall's Tau_b methods.

Vehicle Type Proportion	Data Type	Pearson	Spearman's Rho	Kendall's tau_b
PC	GB set	0.607*	0.676**	0.517**
	NW set	-0.397	-0.685**	-0.450*
HGV	GB set	0.479	0.232	0.117
	NW set	0.730**	0.635**	0.467*
LGV	GB set	0.846**	0.858**	0.731**
	NW set	-0.168	-0.267	-0.149
Motorcycle	GB set	0.418	0.585*	0.436*
	NW set	-0.826**	-0.839**	-0.756**
BUS	GB set	0.529*	0.509*	0.367*
	NW set	0.428	0.468	0.333

Where ** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

The results of regression and correlation analysis have shown a closer match and a higher positive correlation between the vehicle's registration set for GB and the AADF data set for road A5038 for PCs, LGVs, and Buses than with the NW data set. In comparison, the NW data set showed a closer match and correlation with HGVs in the AADF data set, as in Table 4, Table 5, and Table 6. Both vehicle registration data sets showed a very close match with the AADF data set.

Therefore, the results validate the utilization of the overlap information that the author has collected from vehicle registration, and by compensating for the overlap effect, we can correct the ATC data and implement the change in the model, as in Table 7. The authors have implemented the correction factors in a system dynamics model to compensate for the vehicle categorization in the hourly traffic volume of ATC data.

TABLE 7. ATC data correction by compensating for the overlap effect.

Year 2015	≥5.2m	5.21-6.6m	6.61-11.6m	>11.6m
Average Working Day	12706	4921	1093	1824
Overlap correction factors	1.08	0.84	0.42	1.03
Corrected ATC Data	13722	4134	459	1879

IV. METHODOLOGY

This paper aims to determine the impact of HGVs on traffic flow. Expressing the effect of HGVs on traffic flow should be in PCE value. It is vital to have an accurate estimation of PCE and to determine the impact of HGVs on the road in comparison to PCs, to assess the congestion level and the effect of congestion on travel time delay. Accurate and realistic values of PCE are crucial in estimating the road capacity.

Taking into account the drawbacks of the current PCE and capacity estimation methods, the authors aim to estimate the PCE and capacity accurately with consideration to driver's professionalism, perception time (PT), and the minimum required stopping distance (SD) for safety. Also, the capacity estimation formula in (3) does not consider average speed flow even though the speed flow is directly proportional to road's capacity and inversely proportional to traffic density, as in $\{q = k*v\}$, where q is the traffic flow volume in the vehicle per hour (vehicle/h), and k is the traffic flow density in the vehicle per km (vehicle/km), and v is the traffic speed flow in kilometer per hour (km/h).

Therefore, the new out of the box approach that mainly depends on the average speed flow and PCE to determine the available capacity of the road. In an out of the box approach, we define the average traffic speed flow in km/h as the displacement of vehicles within one hour, e.g., if a vehicle is moving with an average speed of 60km/h for one hour, then the vehicle has moved by a distance of 60km.

Therefore, the availability of the road will depend on the average speed and not on the free flow speed (FFS), because the FFS applies when zero vehicles are on the road. The average speed of traffic is a valid measure of the available capacity.

For example, if a road's FFS is 64.4km/h and the actual average speed of traffic is 30km/h, then the vehicles are only moving 30km. Thereby, 30km is the only available distance, and according to that distance, we can calculate the available space for vehicles.

By calculating the vehicle's headway according to the vehicle's type, length, weight, braking efficiency, aerodynamics, deceleration and acceleration performance, and the PT and professionalism of the driver, we can align the vehicles according to their headways along with the 30 for every single lane and calculate the availability or deficit of headway distance, to enable us to insert or remove vehicles from traffic with consideration to the required SD for safety.

Practical Example: A road link (RL) with a length of 2km, and there is an ATC installed at the RL's entrance. The ATC

measured the average speed for one hour (15min × 4), and the speed is 64.4km/h, and the ATC also counted the vehicles entering the RL the same hour. The average headway length for PC (private cars) is 61m. Therefore, the number of PCs that can occupy a single lane of the RL at any given time is the ratio of the RL's length to the PC headway, and it is equal to 2000/61 = 33 PCs.

Let us first assume that the traffic flow is uninterrupted (with no traffic light). A vehicle with a speed of 64.4km/h will exit the end of the RL in 1.86min. More vehicles will keep entering the RL during the hour at a speed of 64.4km/h. A PC with the latter speed can drive uninterrupted for an hour and travel 64.4km, which is equal to 32 times that RL's length (2km). We can get the same result when using the measure of time by dividing 60min by the time it takes to travel 2km (1.86min), and the result is 32. By multiplying the value of Q in the equation above, we will get 1056 vehicles per hour for a single lane.

From this perspective, it does not matter what the RL length is, the RL can be 500m, 2km, or tens of kilometers long, but what matters is the traffic speed flow during the hour that provides the availability of space for vehicle displacement. If the user of the model wants to utilize the speed for every 15min, then when applying the vehicle displacement approach to calculate the capacity, he/she should divide the capacity formula by four.

If the ATC has reported a heterogeneous traffic flow volume of 1000 vehicle/h and 50 of the vehicles are HGVs with a PCE equals to 3, then the 50 HGVs are equivalent to 150 PCs, and the PCE traffic flow volume is 1050 PC/h. By converting the heterogeneous traffic flow volume to a PCE traffic flow, we can estimate the actual impact of HGVs on the traffic. The authors will calculate the headway for every vehicle type by estimating the SD by integrating the PT and the driver's professionalism.

Integrating the driver's professionalism to the headway, PCE, capacity, and rescheduling is vital for planning and development purposes. According to section II.F, professional drivers apply brakes to the maximum force (20kg), while non-professional drivers apply only 50% of the maximum pressure on the brake pedal (10kg). Therefore, in this paper, we will consider professional drivers as 100% competent in braking, while non-professional drivers are 50% competent in braking. The braking competency level (BCL).

The authors will add 0.83s to the PT for 50% braking competency level (BCL[4]) drivers and 0.1s for 100% BCL drivers when assuming that professional drivers will only need another 0.05s to increase the pressure on the pedal to 20kg and that the non-professional drivers will only apply pressure up to 10kg (50% of the required pressure). Also,

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[4]The professional and non-professional drivers are expressed in this paper as 100% braking competent and 50% braking competent, and the braking competency level (BCL) expression that we will use throughout the paper will represent the professional and non-professional drivers by a BCL of 100% and 50%, respectively. The BCL will affect the braking pressure and the PT which would cause significant impact on the headway calculation.

the authors will utilize the BCL in the barking force calculation, and a professional driver with a BCL equals to 1 will apply twice the pressure that non-professional drivers apply, and it would significantly impact the deceleration level.

*Definition 1: **Braking Competency Level (BCL)** is a measure of the amount of pressure applied by the driver to the brake pedal and the time taken to achieve that. The BCL value is the ratio of the pedal pressure applied by the driver during braking to the required maximum pedal pressure. The higher the BCL, the higher the braking competency level of the driver. The BCL contributes to the vehicle's deceleration rate and the PT of the driver.*

The new methodology measures the PCE value at all hours of the day and calculates the headway not according to availability and traffic flow volumes but according to the required safety gap that provides sufficient time and space for the driver to bring the vehicle to a standstill and prevent an accident. The calculated headway will ensure a safe traffic operation and a rescheduling plan.

Typically, when the average speed flow increase the required SD will increase and when the traffic flow increase, the average speed will decrease and the gap between the following and leading vehicles decrease and the required acceleration performance to meet average speed will also decrease. The newly proposed PCE estimation method depends on the deceleration and acceleration performances of vehicles. The PCE formula includes the vehicular length, acceleration performance, and SD. The proposed PCE has a direct relationship with deceleration distance, acceleration distance, speed, and length of various non-PC vehicles.

A. DECELERATION COMPONENT

The deceleration capability of vehicles decreases with an increase in size and weight [61]. HGVs will need a longer distance to brake to stand still, and the stopping time for HGVs should be higher than the PCs stopping time. The braking force is the force caused by the applied pressure by the braking pad/shoe on the surface area of the braking disc or drum creating braking friction force, and it is by far higher than the rest of the braking forces.

Using stopping distance will ensure that any capacity assessment will be within the standard spacing requirement for a driver to react, stop, and maneuver safely. Thereby, the PCE estimation would be the ratio of the vehicle length and safe stopping distance to the length and safe stopping distance for PCs, and the deceleration component is the ratio of the vehicle to the headway of a PC as in (4), (5), (6), and (7).

The authors have decided to apply an additional space behind articulated HGVs (HGV$_a$) in particular. The extra space is equivalent to the SD of a PC (5) to provide enough space behind long vehicles to establish a clear vision for the HGVa driver to see the following vehicle, and for the following vehicle to see the pedestrians and the traffic ahead, provides flexibility in maneuvering, avoidance of objects that could fall from the back of the leading vehicle. The latter decision is due to the high probability of a PC following

an HGVa, which is the highest after the probability of a PC following an LGV. It is due to the high proportion of the flow of PCs of ≥ 0.85 and for the HGVa having the most extended vehicle in the traffic flow.

$$H_j = SD_j + L_j \qquad (4)$$

$$H_4 = SD_4 + L_4 + SD_1 \qquad (5)$$

$$PCE_i = \frac{H_i}{H_1} \qquad (6)$$

$$PCE_i = \frac{L_i + SD_i}{L_1 + SD_1} \qquad (7)$$

where,

H	is the headway distance in meter (m)
PCE	is the PCE value before including the HGV acceleration performance effect in meter per meter (m/m)
L	is the vehicle's length in meter (m)
SD	is the required stopping distance for safety in meter (m)
Subscript (j)	is the index of vehicle types: '1' for PC, '2' for LGV, and '3' for HGVr (j = 1 TO 3)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

To estimate the PCE value, we need to calculate the stopping distance (SD), and it requires the calculation of the braking forces of the vehicle. To estimate the braking forces, we need to utilize the dimensions, weight, air pressure, air temperature, and aerodynamics drag factors for the four types of vehicles. To estimate the PCE values for various types of non-PC vehicles, we need to calculate their SD, and the SD is a combination of the Braking Distance (BD) and the Perception Time Distance (PTD), as in (8).

$$SD_i = BD_i + PTD_i \qquad (8)$$

where,

SD$_i$	is the stopping distance in meter (m)
BD$_i$	is the braking distance in meter (m)
PTD$_i$	is the distance equivalent to the perception time in meter (m)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

In order to calculate the braking distance (BD), we need to utilize the vehicle's kinetic energy (KE) formula and determine the relationship between the B, vehicle's speed (S), and the braking deceleration rate (d$_{Bi}$), as in (9) and (10).

$$KE_i = Braking\ Force * Braking\ Distance \qquad (9)$$

$$KE_i = GM_i * d_{Bi} * BD_i = \frac{GM_i * S^2}{2} \qquad (10)$$

By eliminating the GM$_i$ on both sides of (10), we will get the BD$_i$ as in (11).

$$BD_i = \frac{S^2}{2 * d_{Bi}} \qquad (11)$$

where,

BD_i	is the braking distance in meter (m)
KE_i	is the kinetic energy in joule (J)
GM_i	is the vehicle's gross mass in kilogram (kg)
d_{Bi}	is the deceleration rate due to braking in meter per square second (m/s^2)
S	is the vehicle's flow speed in meter per second (m/s)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

The vehicle's speed is equal to the displacement of the vehicle (d) during a period (t). The authors have assumed that when the driver applies pressure on the pedal up to the maximum ability of the driver of at least 10kg (according to his/her BCL) will sustain this pressure level until the vehicle's speed drops to a standstill. Therefore, we will not consider the deceleration caused by the braking pressure of less than 10kg in the calculation of braking distance (BD).

However, the authors have included the time taken to press the pedal to the maximum ability of the driver in the PT, as in Table 3, and assumed that the vehicle's speed stays constant during the PT, and only starts to decelerate after the period of PT has ended. Therefore, we will assume we calculate the PTD by multiplying the PT by speed (S), as in (12).

$$PTD_i = S * PT_i \quad (12)$$

where,

PT_i	is the perception time in second (s)
PTD_i	is the distance equivalent to the perception time in meter (m)
S	is the average flow speed in meter per second (m/s)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

The calculation of the deceleration force due to rolling friction requires the rolling friction factor (R_i) and the gross mass of the vehicle (GM_i) (13).

$$FR_i = R_i * g * GM_i \quad (13)$$

where,

GM_i	is the gross mass of vehicle type (i)
FR_i	is the deceleration force due to rolling friction in newton (N)
g	is the acceleration due to gravity in meter per square second (m/s^2)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

The calculation of the deceleration or acceleration force due to wind requires air density, the front surface area of the vehicle, wind speed, average flow speed, aerodynamic drag coefficient of the vehicle [62], and acceleration due to

gravity (g). When the wind is running in the opposite direction of the traffic flow, it will cause a deceleration effect, and the WS, as in (14), will have a positive sign. If the wind is running in the direction of the traffic flow, the WS will have a negative sign.

$$FW_i = \left(\frac{1}{2}\right) * CD_i * \rho * F_{Ai} * (\pm WS + S)^2 * g \quad (14)$$

where,

FW_i	is the deceleration force due to aerodynamic drag resistance caused by wind speed in newton (N)
ρ	is the air density in kilogram per cubic meter (kg/m^3)
F_{Ai}	is the front surface area of the vehicle in square meter (m^2)
g	is the acceleration due to gravity constant, and it is equal to 9.8066 m/s^2
WS	is the wind speed in meter per second (m/s) either in the opposite (+) or supporting (−) direction of the vehicle flow
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

We can also calculate the braking force due to applying braking pressure to the braking pad's surface area, as in (15), calculating the braking pressure, as in (16), and by including the BCL to reflect the actual pressure applied to the brakes we can calculate the braking force, as in (17):

$$DPA_i = BPL * BPW \quad (15)$$

$$BP_i = Pressure = \frac{Force}{Area} = \frac{FB_i}{DPA_i} \quad (16)$$

$$FB_i = BP * DPA_i * BCL \quad (17)$$

where,

DPA_i	is the braking disk pad area for vehicle type (i) in m^2
BPL	is the braking pad's length in meter (m)
BPW	is the braking pad's width in meter (m)
FB_i	is the deceleration force due to applying brakes in newton (N)
BP_i	is the braking pressure in Pa
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

The calculation of deceleration or acceleration force due to road grade requires the value of grade angle as in (18). The determination of whether the force is going to cause a deceleration or acceleration effect depends on whether the value of grade is positive or negative, as in (19), where θ is the road surface slope angle (upgrade or downgrade) in degrees (°).

$$Grade = \sin(\theta) \quad (18)$$

$$FG_i = \pm Grade * g * GM_i \quad (19)$$

where,

FG_i	is the deceleration or acceleration force due to road upgrade or downgrades in newton (N)
g	is the acceleration due to gravity constant, and it is equal to 9.8066 m/s^2
GM_i	is the vehicle's gross mass in kilogram (kg)
Grade	is the road slope (+/−)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

Now, we are going to calculate the total braking forces and include the weather factor (WF) that considers the effect of rain, snow, and frost road conditions on the deceleration rate [63], as in (20):

$$FD_i = WF * (FR_i \pm FW_i + FB_i \pm FG_i) \tag{20}$$

$$d_{Di} = \frac{FD_i}{GM_i} \tag{21}$$

By inserting (11) and (12) in (8), and by substituting (21) with d_{Di} in (11), we will get the SD formula, as in (22):

$$SD_i = S * PT_i + \frac{S^2 * GM_i}{2 * FD_i} \tag{22}$$

where,

FD_i	is the deceleration force in newton (N)
FW_i	is the deceleration force due to aerodynamic drag resistance caused by wind speed in newton (N)
FB_i	is the deceleration force due to applying brakes in newton (N)
FG_i	is the deceleration or acceleration force due to road upgrade or downgrades in newton (N)
FRi	is the deceleration force due to rolling friction in newton (N)
PT_i	is the perception time in second (s)
SD_i	is the stopping distance in meter (m)
S	is the flow speed in meter (m)
GM_i	is the vehicle's gross mass in kilogram (kg)
WF	is the weather factor that represents the effect of rain, snow, and frost on the deceleration rate that affects all aerodynamics forces (WF = 0.1, 0.25, and 0.5 when there is ice, snow, or rain respectively) [63]
d_{Di}	is the total deceleration rate in meter per square second (m/s^2)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

B. ACCELERATION COMPONENT

The authors will determine the acceleration performance effect by considering the acceleration delay effect. The estimation of the acceleration delay takes into account the acceleration rate required by the non-PC vehicle to meet the average traffic flow speed of the road in comparison to the acceleration rate of a PC vehicle. HGVs have lower acceleration performance than PCs, especially at intersections.

By converting the acceleration delay of non-PC vehicles, we will be able to estimate the effect of non-PC vehicles on the traffic flow by determining the extra space required for the non-PC vehicles to accelerate to the average traffic flow speed. It is necessary to establish the relationship between engine power, GM_i, and the acceleration rate. By utilizing (10) and (23), we will get (24). The acceleration rate is equivalent to the change of speed per the change of time and considering that the vehicle starts with speed and time equal to zero, as in (25).

$$P_i = \frac{KE_i}{dt} \tag{23}$$

$$\frac{P_i}{GM_i} = \frac{S^2}{2 * dt} \tag{24}$$

$$a_i = \frac{S}{dt} \tag{25}$$

where,

KE_i	is the vehicle's kinetic energy in joule (J)
GM_i	is the vehicle's gross mass in kilogram (kg)
S	is the average flow speed in meter per second (m/s)
d	is the displacement of the vehicle in meter (m)
a_i	is the acceleration rate in meter per square second (m/s^2)
P_i	is the engine power in watt (w)
dt	is the period of change between two speeds in second (s)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

Now, from (24) and (25) we get (26):

$$\frac{P_i}{GM_i} = \frac{S * a_i}{2} \tag{26}$$

By utilizing (26), we can calculate the acceleration rate with no losses. The calculation of the vehicle's acceleration rate should consist of the traction factor (k), and the range of k is 0.3636-0.6 [63], as in (27).

$$a_{nli} = \frac{2 * P_i}{GM_i * S * k_i} \tag{27}$$

where,

GM_i	is the vehicle's gross mass in kilogram (kg)
S	is the average flow speed in meter per second (m/s)
P_i	is engine power in watt (w)
a_{nli}	is acceleration rate without losses in meter per square second (m/s^2)

k_i	is the traction force ratio is the ratio between the load on driven or braked wheels and the total gross weight in kg/kg
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

Now, the determination of acceleration rate losses is by deducting or adding the deceleration or acceleration forces due to the vehicle's aerodynamics forces and excluding the braking force. We utilized in calculating the acceleration rate with losses is done using (13-15),and (19), as in (28), (29), (30), and (31).

$$de_{Ri} = \frac{FR_i}{GM_i} \qquad (28)$$

$$a_{Wi} = \frac{FW_i}{GM_i} \qquad (29)$$

$$a_{Gi} = \frac{FG_i}{GM_i} \qquad (30)$$

$$a_{li} = a_{nli} - de_{Ri} \mp a_{Wi} \mp a_{Gi} \qquad (31)$$

where,

GM_i	is the vehicle's gross mass in kilogram (kg)
a_{li}	is acceleration rate with losses in meter per square second (m/s^2)
FD_i	is deceleration force in newton (N)
FR_i	is deceleration force due to rolling resistance in newton (N)
FW_i	is the deceleration or acceleration force due to aerodynamic drag resistance in newton (N)
FB_i	is the deceleration force due to applying brakes in newton (N)
FG_i	is the deceleration or acceleration force due to road upgrade or downgrades in newton (N)
a_{nli}	is acceleration rate without losses in meter per square second (m/s^2)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

*Definition 2: **Acceleration Space (AS)** is the space required by a vehicle to accelerate up to the average traffic flow speed.*

The calculation of the AS is by utilizing (11) and substituting the deceleration rate with (27), as in (32).

$$AS_i = \frac{S^2}{2 * a_{li}} \qquad (32)$$

where,

a_{li}	is acceleration rate with losses in meter per square second (m/s^2)
S	is the average flow speed in meter per second (m/s)

AS_i	is the acceleration distance required to reach the average flow speed of the road in meter (m)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

*Definition 3: **Space Available (SA)** is the space available in the road in one lane during an hour of driving, assuming that the flow volume and the average flow speed are the same on all lanes.*

The calculation of SA is necessary to determine the proportion of space occupied by non-PC vehicles on the road due to their lower acceleration performance, as in (42). We calculate the SA by considering the average flow speed, the number of lanes (NL), lane width factor (f_W) and the range of f_W are 0.8-1 [9], and effective green ratio (EGR) (EGR is the ratio of green and yellow light periods to the total traffic light cycle) and the range of EGR is 0.3-0.7 [9].

The authors utilized the average speed of traffic in the calculation of the SA when assuming an equal distribution of vehicles on all lanes. The flow speed rate represents the displacement space of traffic for every hour. Therefore, when estimating the SA, we will utilize average speed as a measure of the space available per hour, as in (33).

$$SA = S_d * EGR * f_W * NL \qquad (33)$$

where,

SA	is space available before applying the non-PC distance delay in meter per hour (m/h)
S_d	is the average traffic flow displacement for a single lane in meter per hour (m/h)
EGR	is the effective green ratio in second per second (s/s)
f_W	is the lane width correction factor
NL	is number of lanes for the road in lane (lane)

*Definition 4: **Acceleration Space Occupied (ASO$_i$)** is the extra space required for non-PC vehicles to accelerate to meet the average traffic flow speed in comparison to that of a PC.*

The calculation of ASO requires estimating extra acceleration space required by the non-PC vehicle in comparison to that of a PC, as in (32) and (34).

$$ASO_i = AS_i - AS_1 \qquad (34)$$

Now, we multiply (34) by the vehicle flow volume (FV$_i$) to determine the total occupied space of that vehicle type in traffic flow, as in (35).

$$ASOiE = ASO_i * FV_i \qquad (35)$$

where,

AS_i	is the acceleration space for a vehicle type (i) in meter per vehicle type (i) (m/vehicle (i))

AS_1	is the acceleration space occupied by a passenger car in meter per passenger car (m/PC)
ASO_i	is the acceleration space occupied by a vehicle type (i) in meter per vehicle type (i) (m/vehicle (i))
ASO_i	E is the total effect of acceleration space occupied for all the vehicles type (i) in the traffic flow
FV_i	is the flow volume of a vehicle type (i) in a vehicle (i) per hour (vehicle (i)/h)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

*Definition 5: **HGV Acceleration Performance Delay (HGV_di)** is the proportion of the extra acceleration space needed for vehicle type (i) in proportion to the required PC acceleration space for the vehicle to reach the average flow speed of the road traffic. The THGV_d is the total HGV acceleration performance delay for all the non-PC vehicles available in traffic.*

The estimate the HGV_d, we calculate the ratio of acceleration space occupied effect to the SA. The HGV acceleration delay (HGV_{di}) shows the proportion of space occupied by a vehicle type (i) due to the required acceleration space (36):

$$HGV_{d_i} = \frac{ASOiE}{SA} \qquad (36)$$

where,

HGV_{di}	is the total HGV acceleration performance delay for vehicle type (i)
ASO_iE	is the total effect of acceleration space occupied for all the vehicles type (i) in the traffic flow
SA	is space available before deducting the non-PC distance delay in meter per hour (m/h)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

*Definition 6: **Deceleration and Acceleration Passenger Car Equivalent value (PCE_DASi)** is the PCE for vehicle type (i) based on the deceleration and acceleration performance. The PCE_DASi reflects the effect of the deceleration and acceleration performances of non-PC vehicles in equivalent to PCs, and it includes the impact of vehicle's length, driver's competency level, perception time, and gross weight of the vehicle.*

The combination of HGV_{di} (36) and PCE_i (7) will result in the $PCE_{DASi,}$ which includes both effects of deceleration and acceleration (37).

$$PCE_{DAS_i} = PCE_i + HGV_{d_i} \qquad (37)$$

where,

PCE_{DASi}	is the passenger car equivalent for vehicle type (i)
HGV_{di}	is the total HGV acceleration performance delay in meter per meter (m/m)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa

*Definition 7: **Deceleration and Acceleration Passenger Car Equivalent value (PCE_DASi)** is the PCE for vehicle type (i) based on the deceleration and acceleration performance. The PCE_DASi reflects the effect of the deceleration and acceleration performances of non-PC vehicles in equivalent to PCs, and it includes the impact of vehicle's length, driver's competency level, perception time, and gross weight of the vehicle.*

The advantage of the PCE_{DASi} method is the ability to determine the impact of non-PC vehicles on the road during both peak and off-peak hours regardless of whether the total traffic flow volume is at a capacity level or not. This advantage allows the dynamic estimation of the PCE while the traffic flow is increasing or decreasing to anticipate changes and dynamically predict the available capacity.

*Definition 8: **Total HGV Acceleration Performance Factor (THGV_f)** is the proportion of the available space on the road after deducting the total extra acceleration space required by non-PC vehicles (THGV_d), as in (38).*

Now, we calculate the $THGV_f$ that represents the proportion of available space after deducting the percentage of total extra occupied space by all non-PC vehicles, as in (39).

$$THGV_d = \sum_{i=2}^{i=4} HGV_{d_i} \qquad (38)$$

$$THGV_f = 1 - THGV_d \qquad (39)$$

where,

$THGV_d$	is the total HGV acceleration performance delay of all non-PC in meter per meter (m/m)
$THGV_f$	is the total HGV acceleration performance factor for all non-PC vehicles in meter per meter (m/m)

The HGV factor reflects the effect of the acceleration performance for vehicles that are larger than a PC on the space available in traffic flow. The estimation of acceleration delay in length enables us to estimate the effect of non-PC vehicles on the PCE and the capacity estimation.

The lower the value of the HGV factor, the higher the effect of HGV delay on congestion. The HGV factor is not similar to the heavy vehicle factor (f_{HV}) [8], because the purpose of the f_{HV} is to estimate the PCE capacity in proportion to the given PCE values and vehicle type's percentage in the traffic flow. The proposed methodology estimates the HGV effect concerning the vehicle's acceleration performance in comparison with the PC acceleration performance.

This research utilizes the $THGV_f$ in developing the new capacity estimation method (C_{DAS}) to reflect the actual effect of HGVs on traffic flow at heterogeneous vehicular and traffic volumes at different hours of the day. The proposed method

will determine the hours of the day that the traffic volume exceeds the estimated capacity and the available capacity in other hours of the day.

Definition 9: ***Deceleration and Acceleration Space Capacity (C_{DAS})*** *is the capacity of the road in PCE value on-the-basis of the deceleration and acceleration performance of composite vehicle flow. The C_{DAS} dynamically changes in response to average flow speed, PC headway length, the volume of the non-PC vehicles, number of lanes, and the total volume of traffic.*

We determine the C_{DAS} rate by considering the required safety gap between vehicles that would facilitate enough space for stopping the vehicle safely and for maneuvering, and including the delay caused by non-PC vehicles (mainly HGVs) due to the deceleration and acceleration performances of HGVs. We will multiply the $THGV_f$ by SA and divide it by the PC headway length (H_1) as in (40), and this would determine the exact effect of HGVs on the space available and traffic volume and average flow speed. The author has replaced the saturated headway (hs) with the minimum required headway for a PC, as in (40).

$$C_{DAS_b} = \frac{SA_b * THGV_{fb}}{H_{1b}} \quad (Z^{\geq}/h) \quad (40)$$

where,

C_{DASb}	is the deceleration and acceleration space capacity
SA_b	is the space available
$THGV_{fb}$	is the total HGV acceleration performance factor of all non-PCs
Subscript (b)	means before rescheduling

As mentioned in section IV, the speed is directly proportional to the traffic capacity. However, the speed is also directly proportional to the headway, and the capacity is inversely proportional to the headway. Therefore, as in (40), capacity will increase with the increase of speed until the traffic reaches the optimum speed where the capacity is at its highest level and start to reduce as the speed start to increase even further.

For example, we can measure the optimum speed at different BCL values when assuming that the traffic consists of only PC vehicles, by varying the speed from zero to 64.4km/h, as shown in Fig. 1.

By utilizing the PC headway, we are considering the entire driving experience with all speed changes, and not only at the intersection. We can estimate the traffic volume in PCE (TF_{PCE}) by calculating the sum of all vehicle types' volumes multiplied by their PCE_{DASi} value in (37), as in (41).

$$TF_{PCEb} = \sum_{i=1}^{i=4} \left(FV_i * PCE_{DASi} \right) \quad (Z \geq /h) \quad (41)$$
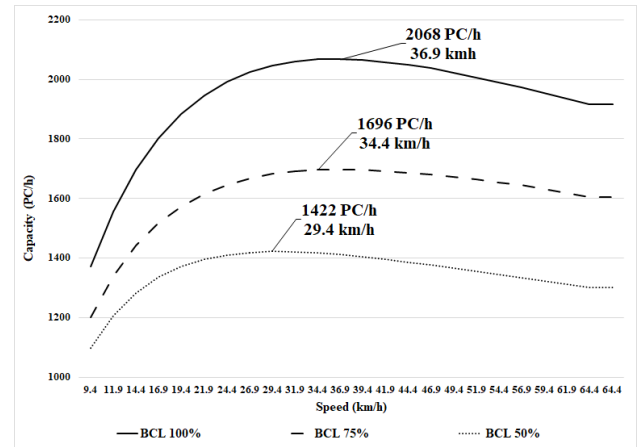
where,

FIGURE 1. The optimum speed and capacity for all PC vehicles traffic flow and with BCL of 50%, 75%, and 100%.

C_{DASb}	is the deceleration and acceleration space capacity
PCE_{DASi}	is the deceleration and acceleration space PCE value for vehicle type (i)
FV_i	is the volume of vehicle type (i) ($\mid Z\mid/h$)
TF_{PCEb}	is the traffic volume in PCE value ($\mid Z\mid/h$)
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa
Subscript (a or b)	(a) is for after rescheduling and (b) is for before rescheduling

After calculating the C_{DAS} and the PCE traffic flow before rescheduling, we can determine the available capacity in PCE (AC_{PCE}) by deducting the TF_{PCE} in (41) from the C_{DAS} in (40), as in (42):

$$AC_{PCEb} = C_{DAS_b} - TF_{PCEb} \quad (Z \geq /h) \quad (42)$$

C. RESCHEDULING ARTICULATED HGVs

To mitigate congestion or/and increase the capacity of road traffic, we need to reschedule HGVs. The author has conducted field observation and manual counting for the investigated road link and found that articulated HGVs are the only type of vehicles that carry dry and cryogenic intermodal containers. Therefore, we will only investigate the rescheduling of articulated HGVs.

In this research, there are two approaches to reschedule articulated HGVs. The first approach is to reschedule traffic flow to meet the current total daily sum of articulated HGVs, as in (43-47). The second approach is to reschedule traffic up to 85% of traffic flow capacity. For both approaches, we will require the rescheduling factor (RF) to control the total daily number of HGVa and TEUs.

Definition 10: ***Rescheduling Factor (RF)*** *is a factor that allows the user to control the total number of articulated HGV for every day by utilizing the required average articulated*

HGV traffic volume for every hour and deducting the articulated HGV volume before rescheduling the current total traffic volume.

The RF value in (46) represents the required ratio to accomplish the first approach, while the RF value to achieve the second approach is 0.85. By utilizing RF, we can determine the needed change in articulated HGV traffic volume to accomplish the two approaches, as in (43-47). If the aim is to achieve the first approach, then the target of an average number of articulated HGVs after rescheduling (FV_{4a}) should be equal to the average number of articulated HGVs before rescheduling (FV_{4b}) as in (44) and (47).

Therefore, we can determine the amount of shifted (removed from or inserted to the composite traffic flow) articulated HGVs, as in (45).

$$DFV_{4b} = \int_{k=1}^{k=24} FV_{4b} * dk \quad (Z \geq /h) \quad (43)$$

$$DFV_{4a} = DFV_{4b} \quad (Z \geq /h) \quad (44)$$

$$dFV_4 = FV_{4a} - FV_{4b} \quad (Z \geq /h) \quad (45)$$

$$RF = \frac{AFV_{4a} * PCE_{DAS4a} + TF_{PCEb} - FV_{4b} * PCE_{DAS4b}}{24 * C_{DASa}}$$
$$(46)$$

$$FV_{4a} = \frac{RF * C_{DASa} * (TF_{PCEb} - FV_{4b} * PCE_{DAS4b})}{PCE_{DAS4a}}$$
$$(Z \geq /h) \quad (47)$$

where,

DFV_{4b}	is the daily flow volume of HGVa vehicles before rescheduling
DFV_{4a}	is the required daily flow volume of HGVa vehicles for the first rescheduling approach
C_{DASa}	is the deceleration and acceleration space capacity after rescheduling
PCE_{DAS4b}	is the deceleration and acceleration space PCE value for vehicle type (4) before rescheduling
PCE_{DAS4a}	is the deceleration and acceleration space PCE value for vehicle type (4) after rescheduling
FV_{4a}	is the flow volume of HGVa vehicles after rescheduling
FV_{4b}	is the flow volume of HGVa vehicles before rescheduling
dFV_4	is the change in traffic volume for vehicle type (4) due to rescheduling
RF	is the rescheduling factor that allows control over the total daily articulated HGVs and TEUs (Definition 8)
Subscript (k)	is the index of time in hours, k = {1, 2, 3, 4, 5, . . . , 24}
Subscript (i)	is the index of vehicle types: '1' for PC, '2' for LGV, '3' for HGVr and '4' for HGVa
Subscript (a or b)	(a) is for after rescheduling and (b) is for before rescheduling

The rescheduling can include all articulated HGVs or only the CC HGV_a, and according to the manual counting results in section III, the CC articulated HGVs consist of only 35% of all articulated HGVs for the road under investigation. The authors only consider the CC HGVa in the calculation of the daily and annually transported TEUs by road freight.

The dynamic rescheduling takes into consideration the effect of increasing or decreasing the number of articulated HGVs for every hour of the day on the total traffic volume, capacity, and PCE_{DAS}. The rescheduling of articulated HGVs works by deducting the existing articulated HGVs in PCE value from the current total traffic volume and adding the new distribution of articulated vehicles in their PCE_{DAS} values to the traffic volume that excludes the existing articulated HGVs. The objective is to reduce the total traffic volume at peak hours, reduce the volume to capacity ratio, and improve the average flow speed.

If the aim is to achieve the second approach, then we can maintain the volume to capacity ratio (V/C) value at ≤0.85 to ensure seamless flow, optimum flow speed level, and avoid road congestion. According to TRB [8], the average speed flow of the traffic will drop sharply when the V/C exceeds 0.85, and we have substantiated this theory in this research. Therefore, when we reschedule to maximum capacity, the V/C should not exceed 0.85, otherwise rescheduling to a V/C equals one will lead to a sharp reduction in speed, and it will defeat the purpose of rescheduling.

For every removed or inserted articulated HGV, there will be changes in hourly articulated HGVs that will result in dynamic changes in the EGR, average flow speed, ASO_i, HGV_{di}, $THGV_d$, $THGV_f$, TF_{PCEa}, PCE_{DASi}, and C_{DAS} due to changes in the articulated HGV traffic volume. These changes will lead to dynamic loops that will force a recalculation for every single move.

The algorithms in (46) and (47) reflect the dynamic relationship between variables before and after rescheduling. Therefore, these dynamic relationships will create simultaneous equations such as (46) and (47) where variables are dependent on each other on both sides of the equations. We utilized a system dynamics software called Vensim to run this model. The results showed that the calculations of the variables FV_{4a}, PCE_{DASa}, TF_{PCEa}, ASO_{4a}, HGV_{d4a}, $THGV_{fa}$, average flow speed after rescheduling ($Speed_a$), EGR_a, and PCE_{DAS4a} are involved in 1420,1217, 1434, 244, 578, 855, 1829, 1275, and 965 dynamic loops, respectively.

If the traffic volume exceeds the C_{DAS} value, the port managers and logistic companies can estimate the excess flow is equivalent to TEUs and reschedule or change the routes of these articulated HGVs. By doing so, the companies can improve the level of service and allow the determination of the number of TEUs that the road can accommodate. The method would achieve rescheduling calculation with consideration to the average spacing between vehicles that must be

equal or higher than the stopping distance required to stop the vehicles without crashing the rear end of the leading vehicle. Also, in case of rescheduling.

D. ESTIMATING INDIVIDUAL VEHICLE'S SPEEDS

It is possible to estimate the speed of every vehicle type on the road by calculating the available average gap between following and leading vehicles on the road as in (48) and utilizing (32) and (48) to determine the maximum ability of drivers to accelerate towards the road speed limit as in (49). The drivers do not necessarily accelerate up to their maximum abilities. Therefore, there is a margin of error caused by drivers' behaviors.

Hence, by utilizing (49) for all four categorized types of vehicles and by considering the traffic flow rates of these vehicle types, we can estimate the average flow speed of traffic as in (50). Applying equation (50) has resulted in an accuracy of 96.74% and an average error of +1.82km/h.

$$AGAP = SA - \sum_{i=1}^{i=4} (FV_i * L_i) \qquad (48)$$

$$ES_i = \frac{SL * AGAP}{AS_i} \qquad (49)$$

$$AES = (\sum_{i=1}^{i=4} (FV_i * ES_i))/TF \qquad (50)$$

where,

AGAP	is the available average gap between following and leading vehicles in m
SL	is the road's speed limit in km/h
ES_i	is the estimated speed of vehicle type (i)

V. FINDINGS AND ANALYSIS

The results in Table 8 present the values of PCE_{DASi} and the required headway and gap for various vehicle types. The results show that the PCE_{DASi} only slightly changes with the change of BCL. However, the BCL value has a significant effect on the required headway and gap.

TABLE 8. Vehicle safety gap and average PCE_{DAS} values of the at a traffic flow speed of 64.4km/h according to (37).

BCL	PC		LGV		HGVr		HGVa	
	HT	PCE_{DAS}	HT	PCE_{DAS}	HT	PCE_{DAS}	HT	
50%	3.43	1.12	3.62	2.1	4.77	3.1	4.93	
100%	2.33	1.11	2.41	1.33	3.02	2.4	3.22	

The results show that the PCE for non-passenger car vehicles at 64.4km/h with BCL of 100% and 50% is 1.11 and 1.12, 1.33 and 2.1, and 2.4 and 3.1 for LGV, HGVr, and HGVa, respectively. The results also show that the required safety headway time with BCL of 100% and 50% is 2.33s and 3.43s, 2.41s and 3.62s, 3.02s, and 4.77s, and 3.22s and 4.93s for PC, LGV, HGVr, and HGVa, respectively at 64.4 km/h. Also, the PCE_{DAS} value of HGVa with a professional driver is less than PCE_{DAS} value for HGVa with a non-professional driver by 0.7, as in Table 8.
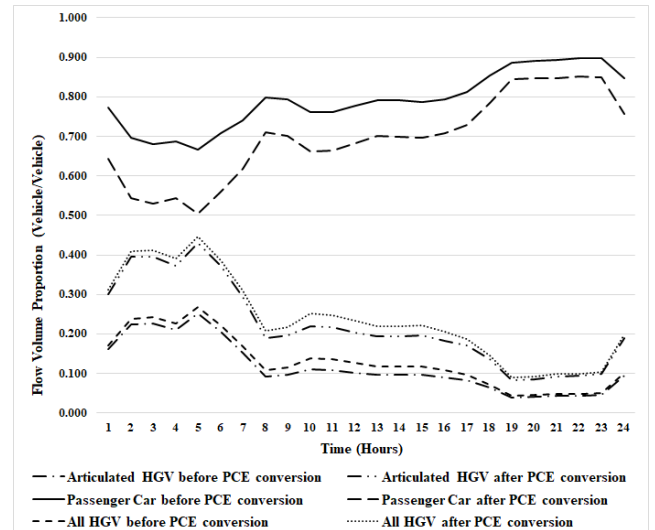

FIGURE 2. Vehicle types' proportions in traffic flow before and after converting the total traffic flow volume to the equivalent PCE_{DAS} value by using the ATC data. Where HGV is the sum of rigid and articulated HGVs. Superscript (*) means that the volume proportion is in the PCE_{DAS} equivalent.

The BCL is inversely proportional to the required headway and gap. If the BCL increases, then the braking distance and PT decrease, and consequently, the required gap between the leading and following vehicles will decrease. Therefore, the headway will reduce, and when the headway decreases, the impact of the vehicle length on the PCE_{DASi} value will increase.

Figure 2 shows the average percentage of all HGVs before the conversion of the non-PC vehicles to their PCE_{DASi} values is 13%, and the maximum can reach 20% while the average percentage of HGVs after the conversion is 30% and the maximum percentage can reach 43%. The percentage of non-HGVs before and after conversion drops from 87% to 69%, and the maximum percentage drops from 94% to 80%, respectively. However, the PC flow volume remains the main contributor to traffic flow. Figure 3 shows the ATC data set of traffic flow volumes for four types of vehicles and the total traffic flow volume before conversion to PCE value.

Also, Fig. 3 shows the morning and evening peak hours 7 am-9 am and 4 pm-7 pm. At the evening peak from 4 pm-7 pm, the volume to capacity ratio exceeds 85%, which forces the traffic speed flow to fall sharply, as in Fig. 4.

Figure 5 illustrates the performance of six existing PCE estimation methods that we discussed in the literature review. Due to the lack of data of speed for every type of vehicle, we assessed the Cunagin's and Keller's methods using two approaches; the first approach is to use the free flow speed (FFS) value for trucks and PCs, as in Fig. 5 for Keller1 and Cunagin1. The second approach is to utilize the PWR and the traction force constant, as in Fig. 5 for Keller2 and Cunagin2. The difference in results between the two approaches is approximately 0.5 PCE, and unless we have a variable speed data for trucks and passenger cars, the results will
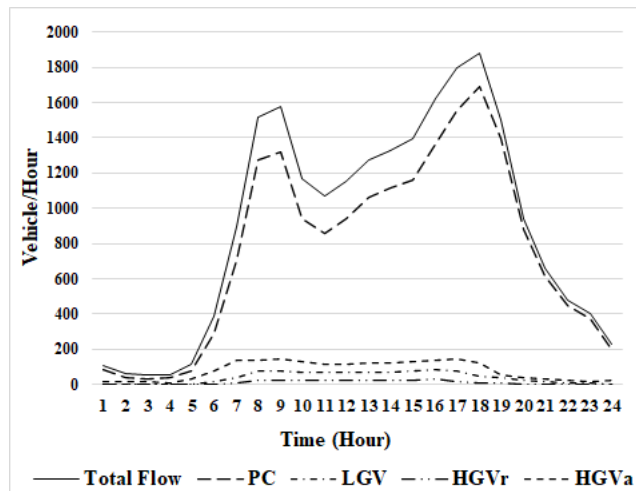
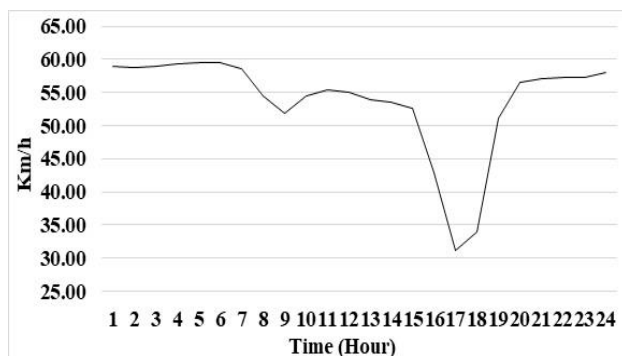**FIGURE 3.** Traffic flow volumes for the heterogeneous traffic flow.

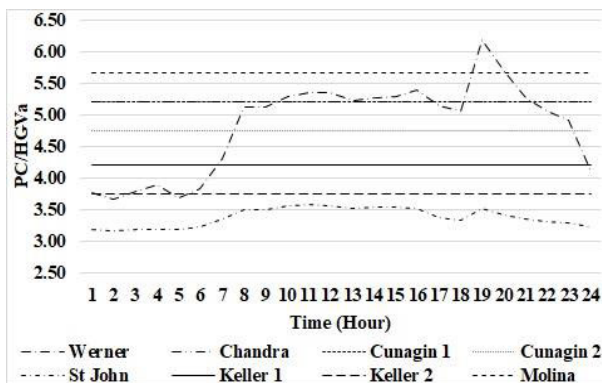**FIGURE 4.** Traffic flow speed on a working day.

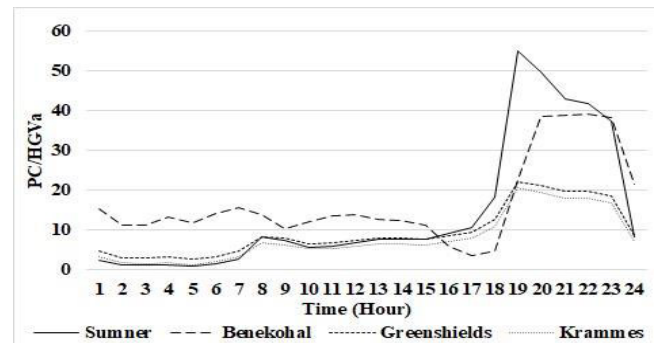**FIGURE 5.** PCE estimation methods that utilize traffic flow volumes, speed, and dimensions and the assessment utilizes the ATC data.

FIGURE 6. PCE estimation methods that utilize traffic flow volumes and speed and the assessment utilizes the ATC data.

stay constant, and we cannot determine the difference in the impact of trucks during different hours of the day.

Therefore, we will not be able to determine the trucks' impact on the capacity, demand increase, and removing or inserting trucks in the traffic flow. We assessed the Chandra method by utilizing FFS and vehicle' length, and the results of Chandra's PCE was equal to the results for Cunagin1, and we applied the Molina method by utilizing the FFS and the saturation headway of 2s and resulted in a relatively higher constant value of PCE.

The Werner's [25] and St John's [10] methods in Fig. 5 showed a direct relationship with the traffic-flow peak-hours pattern in Fig. 3. The St John method showed a more stable performance in comparison to the Werner method, and they are slightly proportional to the average traffic flow speed during the evening peak from 4-6 pm.

The methods of Chandra, Cunagin, Keller, and Molina are proportional to speed and dimensions, and they do not show any response to the changes in traffic flow volume and the percentage of HGVs in the traffic flow, and the PCE value will only variate with the changes in the average speed and average vehicle's dimensions, as shown in Fig. 5.

Figure 6 demonstrates the performance of four PCE estimation methods that utilize headway, speed, and traffic flow. Due to the absence of available headway data for different types of vehicles, the method that we utilized to calculate the headway is by using the vehicle traffic flow volume. Therefore, all four methods mainly used traffic flow volume values to determine the PCE. The results in Fig. 6 show a volatile performance with significantly high PCE values at the evening off-peak hours, and especially the Sumner method results that reached 552 at 7 pm. Therefore, we reduced the scale the Sumner method results by ten times. However, the four methods showed the same pattern of performance.

The PCE values of the four methods, as in Fig. 6, are not proportional to the HGVs' traffic volume and flow rate proportion. Even though the HGV traffic flow percentage is at its lowest rates during evening off-peak hours from 7-11 pm, as shown in Fig. 2 while the HGV's PCE values are at their highest according to the Sumner, Benekohal, Greenshields, and Krammes methods as shown in Fig. 6. The four methods only apply at a congestion period where the traffic flow volume equals or exceeds capacity level.

All the ten methods did not show any correlation with average traffic speed flow, weight, and even the Werner and St John methods, which demonstrated a high correlation with traffic flow volumes did not correlate with the average speed, weight, and acceleration performance. Also, most of the PCE methods consider measuring the PCE value at off-peak hours, and all of them considered for full capacity traffic flow volumes where the volume to capacity ratio is equal to one. In order to be able to plan for demand increase and
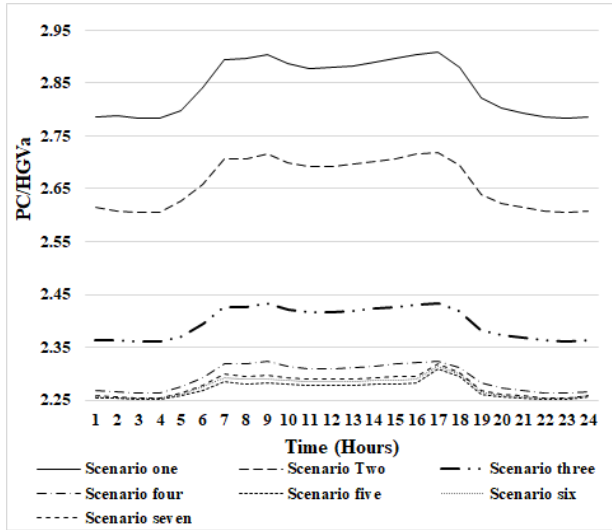
FIGURE 7. PCE_{DAS4} results for seven different scenarios by varying a combination of three variables of BCL, speed, and weight.

FIGURE 8. Capacity estimation utilizing the f_{HV} and capacity estimation utilizing the C_{DAS} method. Where C is the deceleration and acceleration space capacity estimation method (C_{DAS}).

FIGURE 9. Estimated traffic flow volume based on the PCE value by utilizing the PCE_{DAS} method when considering six different scenarios.

rescheduling shipments and shift them to off-peak hours, we need a PCE estimation method that determines the impact of HGVs even with low traffic flow volumes.

The results in Fig. 7 show the PCE_{DAS} for articulated HGVs by applying seven scenarios with a combination of variables of BCL, speed, the number of lanes, lane width, and gross mass:

1) Two-lane road, 64.4km/h speed, 50% BCL, lane width of 3.65m, and maximum authorized GM
2) Two-lane road, 64.4km/h speed, 100% BCL, lane width of 3.65m, and maximum authorized GM
3) Two-lane road, 64.4km/h speed, 50% BCL, lane width of 3.65m, and average GM
4) Two-lane road, 64.4km/h speed, 100% BCL, lane width of 3.65m, lane width of 3.65m, and average GM
5) Three-lane road with a lane width of 3.65m at variable speed and 75% BCL
6) Three-lane road with a lane width of 3.3m at variable speed and 75% BCL
7) Three-lane road with a lane width of 3m at variable speed and 75% BCL

The results of these scenarios in Fig. 7 show that the difference between scenarios 1 and 4, and between scenario 3 and 2 when changing the GM from maximum authorized to average GM will reduce the PCE_{DAS} by 0.44 and 0.37, respectively. The results also show that when BCL increases from 50% to 100%, PCE_{DAS} will reduce by 0.12 and 0.55 for scenarios 1 and 3 where the GM is at the maximum authorized level and scenarios 4 and 2 where the GM is average, respectively.

Figure 7 shows that in scenarios five to seven with average speed and average BCL, the PCE_{DAS} increases with the reduction of the lane's width. However, the changes in PCE_{DAS} for scenarios five to seven are shallow (0.01). The PCE_{DAS} is directly proportional to traffic flow volume, weight, and speed flow, as shown in Fig. 7.
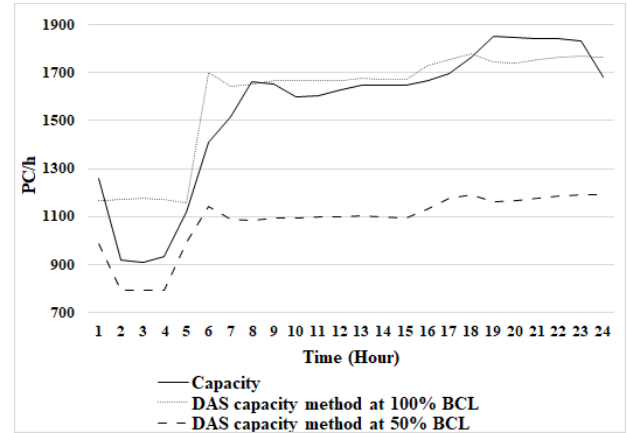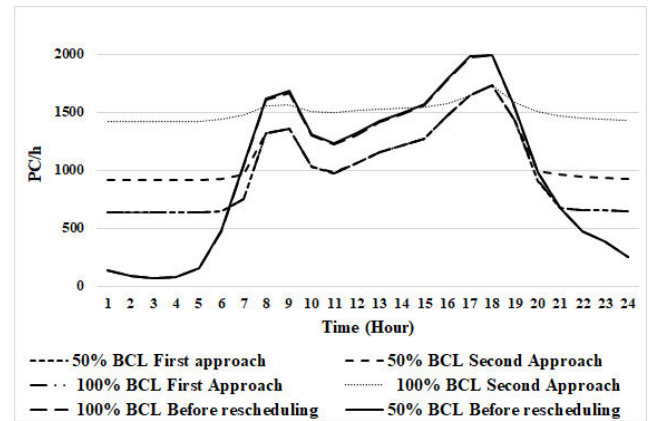
If the average speed flow increases, the SD and headway will increase, and because the HGVs have lower acceleration performance than PCs, the PCE_{DAS} will increase. In the same sense, if the HGV's GM increased, the power to weight ratio decreases, and the acceleration rate will decrease. Therefore, the HGV will require a longer time and space to accelerate up to the average speed flow of the traffic, and the HGV's PCE_{DAS} will decrease.

Figure 8 shows the performance of the C_{DAS} method in comparison to the vastly used formula that mainly depends on the f_{HV} value and ignores the changes in average speed flow. The utilized PCE values for calculating the f_{HV} are 1.2, 2, and 3 [56] for an LGV, HGVr, and HGVa vehicles, respectively. The results in Fig. 8 show that the current capacity method has overlooked the competency level of drivers and the PT, and the capacity only considers professional drivers. As the average alertness and competency of drivers decreases, the BCL will decrease, and thereby, PT will increase, leading to a reduction in the road's capacity, as shown in Fig. 8.

Figures 9 and 10 show the impact of rescheduling approaches one and two on the traffic flow volume in PCE_{DAS} value (TF_{PCE}) and the volume to capacity ratio (V/C),
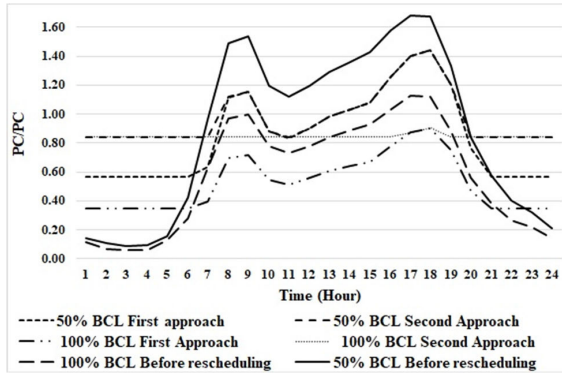
FIGURE 10. The volume to capacity ratio when considering six different scenarios.

TABLE 9. Rescheduling of articulated HGVs container carriers up to capacity level.

No.	Road design scenarios with a BCL of 75% for Outward road freight from port to NW and UK	Annual TEUs in kTEU	
		Extra lane HGVa access only	All vehicle access
1	Building a third lane and all lanes with a width of 3m	878	650
2	Building a third lane and all lanes with a width of 3.3m	1156	826
3	Building a third lane and all lanes with a width of 3.65m	1706	1224
4	Two-lane road for the year 2017 after rescheduling	-	810
5	Year 2017 demand before rescheduling	-	279

respectively. As mentioned in section IV.C, the rescheduling to maximum capacity does not mean rescheduling to a V/C of one, because exceeding a V/C of 0.85 will lead to a sharp decrease in the traffic average speed flow and cause congestion. Thereby, it will defeat the purpose of rescheduling, which is mainly to improve traffic flow operation, reduce travel delay, and prevent or reduce congestions and accidents, and not only for meeting the port demand.

The two approaches' scenarios in Fig. 9 show the TF$_{PCE}$ traffic flow before and after rescheduling by considering two BCL values of 50% and 100%. The results of rescheduling show that the average hour increase in TF$_{PCE}$ for approach one and two for a BCL of 50% is 222% and 299%, respectively, and the average increase for a BCL of 100% is 225% and 455%, respectively.

The results also show that the 50% BCL TF$_{PCE}$ average hourly flow is only 0.8% more than the 100% BCL TF$_{PCE}$ one before rescheduling, and the first approach scenario of rescheduling provides an even lower difference between the 50% and 100% BCL TF$_{PCE}$. However, by rescheduling, according to the second approach, the scenario of a 100% BCL TF$_{PCE}$ flow is 134% times the 50% BCL scenario.

There is a limitation in peak hour shifting by rescheduling, because of the limited number of HGVa vehicles during peak hours. As shown in Fig. 2, unlike the PC vehicles, the HGVa vehicles' proportion reduces during peak hours due to the congestion delays, and during the evening peak hours, the PC flow proportion exceeds 0.85. Therefore, there is a limitation in the rescheduling ability to reduce the volume to capacity ratio (V/C), as shown in Fig. 10.

The results show that by increasing the average BCL from 50% to 100%, the number of hours that have a V/C of over 0.85 reduces from 13 hours to 8 hours without rescheduling. Also, by applying both rescheduling approaches, the number of hours that have V/C of over 0.85 will reduce from 13 hours to 11 hours for 50% BCL scenario before and after rescheduling, respectively, and from 8 hours to 2 hours for the 100% BCL scenario before and after rescheduling, respectively.

The results in Table 9 show the annual transported TEUs by road freight by considering the second approach of rescheduling to the maximum capacity under five different scenarios.

Scenario three provides the most comfortable road condition, and it can accommodate the year 2030's demand target without compromising road safety, as in Table 9. However, the authors have assumed in scenarios one to three that the third lane is only for CC HGVa use, and the other two lanes are for mixed traffic. Usually, when highway and local authorities build extra lanes or new roads, more people will use them.

Even if the extra lane in scenario three is for all vehicle access, the third lane plan will accommodate the year's 2030's demand target. However, the all access plan is not feasible for scenario two one and two. Scenario four provides a short term solution to meet the target for 100% of the year 2020's demand and meet up to 71% of the year 2030's demand without building extra lanes, new roads, or choosing alternative routes. However, if the port managed to meet split model targets for rail and inland waterway freight of 10% and 5% of the total number of processed TEUs for the year 2030, scenario four plan will meet up to 84% of the year 2030 target.

Scenarios one and two for CC HGVa access only show the effect of reducing the lane's width, and the results in Table 9 show that reducing the lane width by 0.35m and 0.65 will reduce the annual TEUs by 33% and 50%, respectively. The reduction of the lane's width will reduce the flexibility and maneuvering space, which in turn reduces the average speed flow and cause congestion. However, there is a trade-off in scenarios one and two, where the number of lanes increased. Therefore, the annual TEU for scenario one for CC HGVa access only plan is nearly equal to that of scenario four.

VI. CONCLUSION
In this paper, the authors have presented the development of two novel methods for estimating the impact of HGVs on the traffic flow operation by measuring the passenger car equivalent value for non-passenger car vehicles, and for estimating the road's capacity to facilitate planning, development, and rescheduling that would help to meet the Liverpool containership port terminal. The two methods are the deceleration and acceleration space passenger car equivalent estimation

method PCE$_{DAS}$ and the deceleration and acceleration space capacity estimation method C$_{DAS}$.

The authors have utilized the vehicle's size, gross mass, traffic flow volume, the braking system, the average speed flow, engine power, wind speed, road's grade, road friction, weather conditions, and the drivers' perception time and braking competency level to calculate the deceleration and acceleration performance of vehicles and determine their impact on the traffic flow capacity. The out of the box approach of vehicle displacement provides realistic roadway availability calculation for the capacity estimation method because the average speed flow is inversely proportional to the traffic flow volume.

The analysis results revealed that the vehicle's headway is directly and inversely proportional to the driver's perception time and the driver's braking competency level, respectively. Also, the capacity is directly and inversely proportional to the average speed of the road and the vehicle's headway, respectively, and the optimum speed where capacity is at its highest level varies is directly proportional to the average BCL of the traffic.

The results show that the passenger car equivalent for non-passenger car vehicles at 64.4km/h with BCL of 100% and 50% is 1.11 and 1.12, 1.33 and 2.1, and 2.4 and 3.1 for LGV, HGVr, and HGVa, respectively. The results also show that required safety headway time with BCL of 100% and 50% is 2.33s and 3.43s, 2.41s and 3.62s, 3.02s, and 4.77s, and 3.22s and 4.93s for PC, LGV, HGVr, and HGVa, respectively at 64.4km/h. Also, the PCE$_{DAS}$ value of HGVa with a professional driver is less than PCE$_{DAS}$ value for that with a non-professional driver by 0.7.

If drivers maintained these gaps, this would save lives and prevent accidents, and by setting the automatic distance control in vehicles to a safer gap allow enough time and space for drivers to decelerate to a standstill or to a speed that would prevent a rear-end vehicle accidents. The results of rescheduling show how that possibility of meeting the year 2020's target for Liverpool's container port by 100% and up to 84% of the year 2030's target in the short term and the long term both the ports meet the target by building an extra lane. The extra lane will either be HGVa access only when all lanes have a width of $\geq$3.3m or all vehicle access when all lanes have a width of 3.65m.

Although the case study is on Liverpool container port in the UK, the method and algorithms are compatible with all urban roads that have controlled intersections in the UK and all the countries that use the highway capacity manual (HCM) of the USA.

VII. METHOD'S APPLICATIONS
The development of the PCE and capacity methods is for assessing the impact of the container carrier HGVs on the traffic flow. The necessity of these methods is due to the ongoing demand increase for container carriers and the increase in traffic congestion. Therefore, in order to overcome these problems, the logistics and road planners need to determine the feasibility of building new roads, lanes, or reschedule shipments to accommodate the demand increase for road freight.

In order to reschedule or re-route CC-HGVs, the port and logistics transportation managers will require a PCE method that considers all the variables that are associated with road freight, congestion, safety, and rescheduling. Such as different loading weights and volumes, container sizes, number of trailers, engine power, driving safety, aerodynamics, lane width, traffic lights, and driver's health and response to events on the road when considering long journeys and night shifts. Also, the new PCE method must be effective in peak and off-peak hours of the day for rescheduling purposes.

The capacity estimation must consider average flow speed and safe headway to be able to determine the effect of CC-HGVs on the traffic flow speed before and after rescheduling or rerouting. The headway of a vehicle has to be assessed according to the driving safety and not according to the real average headway, because part of road planning is to improve the level of service of the road, reduce congestion, and reduce accidents.

There are several applications for the proposed method:

1) The container terminal managers and logistic transportation companies have access to trucks' dimensions and drivers' records, and the load's weight and volume. They can utilize the new method to determine the available road space for HGVs to apply a dynamic rescheduling calculation that can determine the efficient combination for the type of HGVs and loading factors that help to ship dry and cryogenic intermodal containers in the most effective logistic routing.

2) The container terminal managers and logistic companies, local and national travel authorities, and councils can have access to vehicle registration, drivers' license, and load factor, and routing. Hence, they can coordinate and integrate the new method's algorithms with the existing traffic operation and logistics systems and determine the optimum intermodal logistics network operation.

3) The local and national travel authorities and councils can utilize the new method in traffic operations and road construction and development planning.

4) The developers can utilize big data to improve the model outcome and obtain detailed and commercialized projections that help to plan for road development.

5) The method contributes to road level of service estimation as in [67] that can help to reduce road accidents' casualties and costs

6) The new method also contributes to automated braking and cruising systems by estimating the safe stopping distance.

VIII. PAPER AND RESEARCH LIMITATIONS
There are some topics of the research that are out of the scope of this paper, due to the expected extended paper length,

such as the traffic speed flow prediction, accident prevention, pedestrian fatality and severe injury prevention, and the level of service assessment. Also, we require further extensive research for topics, such as the full aerodynamics, driver behavior, social, economic, and environmental impact on the traffic flow.

The capacity estimation method is suitable for all urban roads and streets in the UK and the USA that have controlled intersections, and it does not cover roundabouts, tunnels, minor roads, rural roads, and uncontrolled intersections.

The model design is microscopic, and in further work, the authors can develop it to assess a wider area by connecting road links. The challenge is that the method is dependent on the ATC to obtain the traffic counts and speed of the traffic flow. However, the model can estimate the traffic flow speed by utilizing the traffic flow counts data [60] and the average gaps between vehicles, as in section IV.D.

The research does not cover driver's behavior of large vehicles such as long HGVs and high Q container carriers, tankers and cryogenic container tank carriers, that can face some issues in loss of balance when turning at intersections and roundabouts, or due to crosswind.

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