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3 **Modelling the Effect of Lane-changing Mechanism in a**
4 **Weaving Section**

5

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28

1 **Abstract**

2 Weaving sections are subjected to complex lane-changing movements. In contrary to the
3 other motorway sections where a driver selects a target lane and finds a suitable gap to change
4 lanes, in weaving sections, the drivers' choices can be significantly affected by the actions of
5 the neighbouring drivers. For instance, if the leader vehicle is changing lanes in the same
6 direction, the subject driver may be inclined to move as a platoon and accept smaller lead
7 gaps to complete the lane change manoeuvre. Similarly, the acceptable gaps may be different
8 if there is a weaving manoeuvre as opposed to a *solo* lane change with minimal interactions
9 with the neighbouring drivers. Most of the existing lane-changing models however focus on
10 *solo* lane changes and ignore the differences in behaviour due to the differences in lane-
11 changing mechanisms.

12 The current study, therefore, extends the state-of-the-art lane-changing models to explicitly
13 account for the differences in behaviour under different lane-changing mechanisms using
14 trajectory data collected from a weaving section of a Motorway in UK. The model parameters
15 are calibrated using Maximum Likelihood Estimation technique and reveal significant
16 differences in the parameters of the gap acceptance model under different lane-changing
17 mechanisms. In particular, the results suggest that the relative speed to the current- and target-
18 lane leaders have varying impacts on the gap acceptance behaviour. The developed models
19 can have a significant impact in improving the fidelity of the micro-simulation outputs of the
20 weaving sections.

21 *Keywords; lane-changing, weaving section, latent plan framework, group behaviour, leader*
22 *effect*

23

1 **1 Introduction**

2 Weaving traffic involves two or more streams of traffic travelling in the same direction
3 crossing each other along a relatively short section between an on- and off-ramp. The
4 intensive lane-changing movements, of the merging (and diverging) traffic crossing to join
5 the main-line carriageway (and to the exit lane, respectively), leads to special operational
6 problems to traffic managers (HCM, 2010).

7 A significant body of literature on the studies of weaving has been concerned with
8 characterizing the average performance indicators (e.g. on capacity and average speed) of the
9 facility. Leisch and Leisch (1984) analysed the impact of weaving movements on the average
10 speed of the weaving and non-weaving traffic. Stewart et al. (1996) studied the impact of the
11 number of lanes on weaving capacity. Cassidy et al. (1989) found that the weaving speeds are
12 not as sensitive to geometric factors as previously believed. Roess and Ulerio (2000)
13 suggested a revision in speed algorithm in weaving section to avoid under-predicted weaving
14 capacity. Lertworawanich and Elefteriadou (2003, 2007) developed a series of capacity
15 estimation models for weaving areas. The capacity of weaving section is associated with
16 several factors i.e. number of lane change, weaving traffic flows, and the minimum available
17 length for completing the weaving movement (Shoraka and Puan (2010), and Liu et al.
18 (2012)). As a result of these earlier studies and an extensive empirical investigation (TRB,
19 2008), the guidelines on estimating the speeds of weaving and non-weaving traffic at a
20 weaving facility has been completely updated in the most recent 2010 Highway Capacity
21 Manual (HCM, 2010).

22 Most of the studies mentioned above are however concerned with the aggregated operational
23 performance at weaving sections and the evaluations are largely based on average weaving
24 flows and average traffic speeds. The existing models do not capture the detailed interactive
25 behaviour of the individual vehicles at weaving sections; a notable feature of which is the
26 intensive lane-changings.

27 Weaving traffic involves lane-changings of the merging vehicles to the right (for the UK
28 driving condition) and of the diverging traffic to the left. The two sets of lane-changings cross
29 paths all within a short distance defined as a weaving section, and without the assistance from
30 traffic control devices. In the UK, the typical length of a weaving section is between 2,000 –
31 3,000m (DMRB, 2006), while in the US the length is much shorter at between 900 – 1,800m
32 (HCM, 2000). The intensity of lane-changing makes weaving traffic one of the major sources

1 of congestion and incident on motorways (Jin, 2010; Liu and Hyman, 2012; Toledo and Katz,
2 2009).

3 Golob et al. (2004) reported that 36.8% of accidents in weaving section occur in the middle
4 lanes of weaving sections where 23.2% of accidents is classified as sideswipes accident due to
5 a high proportion of lane-changing traffic. This warrants the need for in-depth analysis of
6 lane-changing in weaving sections. Previous studies indicate lane-changing in weaving
7 sections are affected by density, length of the path, driving rule, and speed difference (Knoop
8 et al., 2012). Skabardonis and Kim, (2010) identified the kerbside and auxiliary lane as the
9 critical zone due to a significant lane change occurs in this area, particularly in the upstream
10 traffic of weaving section as shown in Shoraka and Puan (2010), and Wang et al. (1993). In
11 this case, the traffic prefers to change toward the target lane as soon as they enter the weaving
12 section area. Analysing the NGSIM vehicle trajectory data set, Bham (2006) identified that
13 intensive lane-changing occurs in the first 91 m (300 ft) of the weaving section where 73% of
14 the lane-changing traffic change lane in this particular area.

15 Wang et al. (1993) proposed a microscopic approach in order to analyse the impact of
16 individual movement on weaving section capacity. This study defined the capacity as the
17 function of flows and lane-changing rates. Al-Kaisy et al. (1999) and Al-Jameel (2011)
18 developed microsimulation models of urban weaving sections with distinct weaving rules.
19 Based on an detailed empirical examination of traffic interactions at two weaving sites in
20 Tokyo and Melbourne, Sarvi et al. (2011) developed a microsimulation model of drivers'
21 acceleration-deceleration behaviour during freeway weaving manoeuvres under congested
22 traffic conditions. A common feature in these existing microscopic studies of weaving traffic
23 is that the choices of the drivers (to change lane/not) are not considered to be directly affected
24 by the actions of other drivers in the same traffic stream. However, a recent detailed analysis
25 of vehicle trajectory data collected from a weaving area reveals that more than 20% of the
26 lane-changing at weaving section exhibits a so-called 'group behaviour', when a lead vehicle
27 is changing lane in the same direction, the subject vehicle would be more inclined to move as
28 a platoon and accept smaller lead gaps.

29 The current study investigates the effects of the group behaviour in further detail and proposes
30 a lane-changing modelling framework that explicitly accounts for the different lane-changing
31 mechanisms (i.e. isolated/solo, platoon and weaving movement). A random utility

1 maximization approach is used in this regard and the model parameters are calibrated using a
2 Maximum Likelihood Estimation (MLE) technique.

3 The rest of paper is organised as follows: Section 2 explores briefly the previous works on
4 lane-changing modelling based on random utility approach, Section 3 explains the proposed
5 model specification, Section 4 provides the site description with summary of traffic
6 characteristic, Section 5 presents the estimation results and discussion, Section 6 describes the
7 statistical test and modelling comparison and Section 7 summarises the conclusion and
8 suggests directions of future research.

9 **2 Lane-changing Models**

10 There is a large body of existing literature on modelling lane-changing behaviour. These can
11 be generally classified into three modelling approaches: models that are based on lane-
12 changing rules, game theory based approach on the interactive behaviour, and random utility
13 models of lane-changing choices.

14 Gipps (1986) was among the first to develop a lane-changing modelling framework based on
15 a ruled based approach, which captured the safety, necessity and desirability of the lane-
16 changing movement. In such rule-based models, the gap selection, acceleration and
17 deceleration behaviour have significant roles during the lane-changing process (Zhang et al.
18 1998), as well as the lane-changing objectives. Gipps (1986) classified lane-changing
19 objectives into mandatory lane-changing (MLC) where a vehicle has to avoid an obstacle in
20 front and discretionary lane-changing (DLC) where a vehicle changes lane in order to gain
21 speed advantage. Liu (2010) further described MLC as situations where a turning vehicle
22 having to get into the correct lane which allows that particular junction turnings, or a bus
23 needing to get into/out of a bus layby. While DLC, Liu (2010) included advanced lane-
24 changing in anticipation of junction turns further downstream. Most of the microscopic traffic
25 simulation software adopt the rule-based models (e.g. Hidas, (2005, 2002). Wei et al. (2000)
26 added pre-emptive lane-changing scenario and identified gap acceptance as a critical factor in
27 the lane-changing process. The lane-changing occurs if the driver accepts all three gaps: lead
28 gap at current lane, lead gap at target lane, and lag gap. Kesting et al. (2007) included a safety
29 aspect, which is represented as the critical acceleration threshold. Both the driver
30 aggressiveness (politeness factor) and lane-changing location have impact on lane-changing
31 rate, which locally increases around an inhomogeneity road (mandatory lane-changing).
32 Nevertheless, the ruled based approach has limitation by omitting the interaction between the

1 traffic during the lane-changing process. Specifying an identical gap acceptance threshold for
2 all drivers in this approach leads to unrealistic driving situation since in reality, each driver
3 has different preferences on the gap acceptance for each period of time.

4 Kita (1999) introduced a “game theory” based approach where lane-changing is modelled as
5 two person, non-zero-sum, non-cooperative game. The game is represented as the utility
6 function of the pay-off based on several available gaps (i.e. gap to lead vehicle, gap to
7 collision, etc.), the aim being taking the safest action. Wang et al. (2005) adopted the game
8 theory approach by simulating the cooperative lane-changing model and gap acceptance. The
9 cooperative behaviour of traffic, which allows the lag vehicle to create the gaps and facilitate
10 the merging movement, affects significantly the traffic performance of merging during the
11 congestion period. Liu et al. (2007) improved the game theory approach assuming that the
12 vehicle aims to maintain their driving conditions and minimise the speed variations. These
13 models however use limited explanatory variables (i.e. speed, available gaps and acceleration)
14 and thus have limited flexibility in capturing the full range of behaviours.

15 Yang and Koutsopoulos (1996) applied the random utility approach in the context of lane-
16 changing, which provides more flexibility in capturing the traffic interaction compared to rule
17 based approach and game theory based approaches. The lane-changing decision in this
18 approach is assumed to be affected by several factors i.e. driver impatient factor, relative
19 speed, and appearance of heavy vehicle. Adopting this approach, Ahmed et al. (1999)
20 performed an extensive work on modelling lane change decisions with discrete choice
21 modelling approach. In this study, lane-changing is modelled as a result of two-step process:
22 (1) lane selection and (2) gap acceptance. The model captures the decision of lane-changing
23 as a probability of target lane and gap acceptance function, which are estimated based on
24 MLE. Furthermore, Toledo (2003) suggested the joint model for lane choice and gap
25 acceptance where the MLC and DLC lane-changing conditions are integrated in a single
26 framework. In fact, the target lane choice is beyond the scope of the model and this modelling
27 framework, hence, is not applicable in a general lane-changing context.

28 Thus, Toledo et al. (2005) and Choudhury (2007) extended further this approach where the
29 choice set of lanes is assumed to include all available lanes as opposed to adjacent lanes. The
30 estimation result of this approach demonstrates that specifying the full set of available lanes in
31 the target lane choice set improves the goodness-of-fit as well as improving the simulation
32 results. Moreover, Choudhury (2007) investigated the effect of cooperation strategies in the

1 context of merging movement where the acceptable gaps for courtesy and forced merging
2 have been found to be significantly different than normal merging. However, those listed
3 models omit the differences between individual and group lane-changing which may affect
4 significantly the weaving section performance.

5 Gap acceptance is one of the significant components of the lane-changing model together
6 with the modelling framework, and the lane-changing tactical. Significant number of studies
7 has been performed with various structures and assumptions since early 60's. Herman and
8 Weiss (1961) presumed the gap acceptance follows the exponential distribution, while
9 Ashworth (1970) assumed a normal distribution. Bham (2008) studied both time gap and lag
10 acceptances under the congested and non-congested traffic which fit with gamma distribution.
11 He reported that the critical lag is slightly greater than the critical gap in both congested and
12 non-congested. Moreover, the merging drivers from the on-ramp traffic in both traffic
13 conditions are slightly more aggressive as they accept larger gap compared to the lane-
14 changing drivers toward the off-ramp. Incorporating the cooperation behaviour and accident
15 risk into the gap acceptance model, Chu et al. (2014) indicated that the merging tends to
16 accept the available gap at the adjacent lane at the first instance while the driver in low traffic
17 density (< 40 veh/km/lane) yields and merge in the following gap as he/she requires an
18 adjustment to merge toward a fast moving lane. In contrast, the driver will chase the vehicle at
19 the target lane for a space to merge if the target lane is denser compared to the on-ramp. The
20 probability of executing the lane-changing is increased in associated with the increased of the
21 time. The driver changes into the direct or yield-merging strategies if he/she fails for chasing
22 the gap in front the lead vehicle at the target lane. However, those gap acceptance models
23 have limitation in capturing the driver experience during the gap acceptance decision.

24 Daganzo (1981) proposed the probit model which is able to incorporate the correlation among
25 the time gap acceptance decisions of each individual. In this case, the mean value of the gap
26 acceptance model is known as the critical gap which is a random variable that is normally
27 distributed across the population. The assumption of normal distribution in the study results a
28 problem for those studies to avoid from negative value. Ahmed (1999), therefore, presumed
29 that the critical gap follows the log normal distribution to ensure the estimated critical gap as
30 a non-negative value. This approaches has been used widely in the recent development of gap
31 acceptance model i.e. Toledo et al (2005), Farah et al (2009), and Choudhury et al (2010).

1 The review of literature thus reveals a research gap in terms of capturing the effects of lane-
2 changing mechanism in the model structure. This can lead to unrealistic traffic characteristics,
3 especially in weaving sections where there is significant presence of group behaviours and the
4 effects of lane-changing mechanism are more dominant. The current study, aims to addresses
5 this research gap by extending the state-of-the-art random utility based models and explicitly
6 capture the lane-changing mechanism depending on the movement of the lead vehicle A case
7 study of traffic on a weaving section in UK motorway (M1 J42-43) is used to analyse the
8 extended lane-changing model with respect to different type of leader vehicle movements.

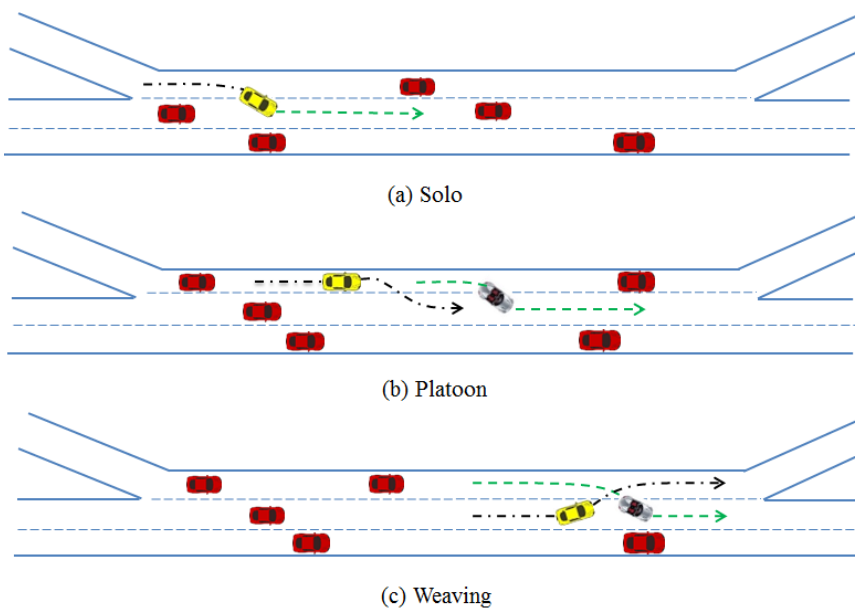
9 **3 Structure of the Lane-changing Model**

10 Weaving sections are subjected to complex lane-changing movements. In contrary to normal
11 motorway sections where a driver selects a target lane and finds a suitable gap to change
12 lanes, in weaving sections, the choices of the drivers can be substantially affected by the
13 actions of the neighbouring drivers. For instance, if the leader vehicle is changing lanes in the
14 same direction, the subject driver may be inclined to move as a platoon and accept smaller
15 lead gaps to complete the lane change manoeuvre. Similarly, the acceptable gaps may be
16 different if there is a weaving manoeuvre as opposed to a solo lane change which does not
17 involve any marked interaction with neighbouring drivers. The current research extends the
18 state-of-the-art lane-changing models by explicitly incorporating the type of lane change
19 (solo/individual, platoon and weaving) in the model framework.

20 HCM (2000) defines the platoon as a group of vehicles from the same traffic stream travelling
21 together, while weaving is the crossing of two or more traffic streams in same traffic direction
22 in a particular road length without any assistance of traffic control devices. Given those
23 definitions, this paper defines the lane-changing mechanisms as follows and shown in Fig 1 :

- 24 • Platoon (p) lane-changing is a situation when the subject and the preceding vehicle from
25 the same traffic stream change lanes together one after another (Fig 1a). The preceding
26 vehicle is termed as *front vehicle* in this paper.
- 27 • Weaving (w) lane change occurs if the subject vehicle and an adjacent vehicle from traffic
28 stream on the left/right, cross each other at the same period (Fig 1b). In other words, the
29 subject vehicle and the adjacentvehicle swap their lanes to follow their preferred path. The
30 adjacent vehicle initiating the weaving is termed as *lead vehicle* in this paper.
- 31 • Solo (s) lane change occurs when there is no group behaviour (i.e. no platoon or weaving
32 lane-changing manoeuvres).




1 The different lane-changing mechanisms yield differing sensitivities towards the positions and
 2 speeds of the front/lead vehicles in the current and target lanes and lead to variations in the
 3 acceptable gaps for the lane change. It may be noted that, in very congested conditions, there
 4 drivers in the mainline often slow down to assist the vehicles entering/exiting from/to the
 5 ramps, but this research deals with driving behaviour in moderately congested situations and
 6 hence the cooperative merging is beyond the scope of the research.



7

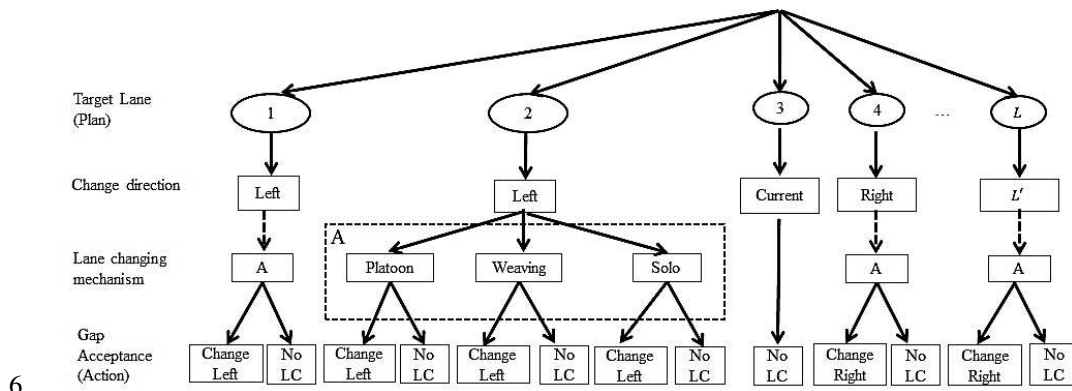
8 Fig 1 Schematic diagram of lane-changing mechanisms

9 Where;

- 10  : Subject vehicle
- 11  : Lead/front vehicle
- 12  : Non lane changing vehicle
- 13 - - - : Subject vehicle trajectory
- 14 - - - : Lead/front vehicle trajectory

15 Given the choice of the target lane and given the lane-changing mechanism, the subject driver
 16 accept/rejects the available gap. The acceptable gap can vary depending on the lane-changing
 17 mechanism. The acceptable gap is however unobserved in the data and only the final
 18 decisions of the driver (Change Left, Change Right or No Change) is observed. The observed
 19 plans/decisions are shown in rectangles and the unobserved ones are shown in ovals in the Fig
 20 2.

1 The proposed model structure is thus an extension of the Freeway Lane-changing Model
 2 proposed by Toledo et al. (2005) where the decision framework consists of choice of target
 3 lane and gap acceptance but there is no explicit consideration of the lane-changing
 4 mechanism. The details of the proposed target lane choice and gap acceptance model
 5 components are presented below.



6
 7 Fig 2 An example of the lane-changing framework for a driver in lane 3 of a 5 lane road
 8 An example of lane-changing structure for a subject driver in lane 3 is shown in Fig 2. The
 9 driver first selects a target lane, which is the most preferred lane considering the traffic
 10 conditions and his/her path plan. The choice of the target lane indicates the preferred direction
 11 of lane change. For example, for a subject driver in Lane 3 (as shown in Fig 2), lane 2 and 1
 12 are at the left hand side and lane 4 and 5 are on the right hand side. If the target lane is the
 13 same as the current lane, the lane-changing is not required (the observed action is 'No LC'). If
 14 the target lane is 1 or 2, then the driver looks for suitable gaps on the left. If the target lane is
 15 lane 4 or 5, the driver seeks suitable gaps on the right. A lane change is observed when the
 16 driver finds an acceptable gap in the desired direction and moves to that lane. Otherwise, he
 17 stays in the current lane. It may be noted that the choice of target lane is unobserved in the
 18 trajectory data since the driver may or may not be successful in moving to the target lane.

19 The driver looks for suitable gaps in the adjacent lane in the direction of the target lane and
 20 executes a lane change if he/she finds an acceptable gap. The acceptable gap can be different
 21 depending on the lane-changing mechanism (namely: solo, platoon or weaving). The
 22 observed actions of the front vehicle in the current and lead vehicle in the target lane (see Fig
 23 1) define the lane-changing mechanism. If the front vehicle is also changing lanes in the same
 24 direction, the subject driver has the option to execute (or not execute) a platoon lane change;

1 | whereas if the front_vehicle in the current lane is not changing lanes in the same direction but
2 | an adjacent vehicle in the target lane is making a change to the current lane, the subject driver
3 | has the option to execute (or not execute) a weaving lane change. The lane-changing
4 | mechanism is therefore observed in the data.

5 **3.1 Target lane choice**

6 The previous discussion demonstrates that the driver prefers the lane with the highest utility.
7 Presuming that all the drivers have the same set of available lanes over the road stretch, the
8 utility function of the driver (n) for choosing lane (l) at specific time (t) can be written as
9 follows:

$$10 \quad U_n^l(t) = \beta^l \cdot X_n^l(t) + \alpha^l \cdot \vartheta_n + \varepsilon_n^l(t) \quad l \in \{1, 2, 3, \dots, L\} \quad (1)$$

11 Where;

12 $U_n^l(t)$: Utility of target lane l of driver n at time t

13 $X_n^l(t)$: Vector of explanatory variables associated with driver n for lane l at time t

14 β^l : Vector of estimated parameters associated with target lane l

15 ϑ_n : Individual specific random error term to account for unobserved driver
16 characteristics, assumed to follow normal distribution $\vartheta_n \sim N(0,1)$

17 α^l : Estimated parameters of individual specific random term ϑ_n for lane l

18 $\varepsilon_n^l(t)$: Random error term associated with target lane l for n^{th} driver at time t

19 L : Total number of available lanes in the section

20 The candidate variables affecting the choice of the target lane may include general traffic
21 conditions (e.g. traffic density, average speed, orientation, etc. of each lane), surrounding
22 vehicle attributes (e.g. relative speeds, types of surrounding vehicles, etc.), path-plan impact
23 (e.g. whether or not the driver needs to take an exit or make a mandatory lane change in order
24 to follow the path and if yes, what is the remaining distance to the exit) and driver
25 characteristics (e.g. age, experience, stress level, aggressiveness, etc.). The driver
26 characteristics are however generally unobserved in the video recordings and represented by
27 statistical distributions (Choudhury, 2007; Toledo et al., 2005).

28

1 The choice modelling presumes the random error term ε_n^l is independently and identically
 2 distributed (IID). Therefore, the probabilities of lane choice l conditional on individual
 3 specific random term ϑ_n can be written as:

$$4 \quad P(l_n(t)|\vartheta_n) = \frac{\exp(UV_n^l(t)|\vartheta_n)}{\sum \exp(UV_n^l(t)|\vartheta_n)} \quad l\{1, 2, 3, \dots, L\} \quad (2)$$

5 Where ;

6 $P(l_n(t)|\vartheta_n)$: Probability of driver n choosing the specific target lane l at time t

7 3.2 Gap Acceptance

8 Gap acceptance is the second level of lane-changing decision making process. The driver
 9 evaluates both lead and lag gaps against his/her acceptable gaps threshold; known as critical
 10 gaps. The lead and lag gaps are accepted if both available lead gap and lag gaps are greater
 11 than the corresponding critical gaps.

12 The critical gap of a driver is not constant or static. Rather it varies among drivers and for the
 13 same driver across observations depending on the surrounding conditions. In the state-of-the-
 14 art models (e.g. Ahmed et al., 1996; Choudhury, 2007; Toledo and Katz, 2009; Toledo et al.,
 15 2005; etc.), critical gaps are assumed to follow the log-normal distributions (since the gaps
 16 have non-negative values) where explanatory variables represent the mean of the distribution.
 17 These models however do not address the effects of lane-changing mechanism on the critical
 18 gap values. The following formulation, that incorporates the effects of lane-changing
 19 mechanisms in the choice process, is therefore proposed:

$$20 \quad G_n^{cr,j,l',m}(t) = \exp\left(X_n^{j,l',m}(t) \cdot \beta^{j,l',m} + \alpha^{j,m} \vartheta_n + \varepsilon_n^{j,l',m}(t)\right)$$

$$21 \quad j \in \{lead, lag\}, \in \{s, p, w\}, l' \in \{left, right\} \quad (3)$$

22 Where;

23 $G_n^{cr,j,l',m}(t)$: Critical gap j at the direction of target lane l' of driver n at time t associated with
 24 lane-changing mechanism m (l' can be left or right)

25 $X_n^{j,l',m}(t)$: Vector of explanatory variables associated with driver n at time t associated
 26 with critical gap , target lane l' and lane-changing mechanism m

27 $\beta^{j,m}$: Vector of estimated parameters for critical gap j and lane-changing mechanism
 28 m

1 $\alpha^{j,m}$: Estimated parameters of individual specific random effect ϑ_n for critical gap j
2 and lane-changing mechanism m
3 $\varepsilon_n^{j,l',m}(t)$: Random error term associated with critical gap j and lane-changing
4 mechanism m for driver n at time t , ($\varepsilon_n^{j,l',m} \sim N(0, \sigma^{j,m^2})$)
5 m : Lane-changing mechanism, solo (s), platoon (p) or weaving (w)

6 Lane change at time t occurs if the driver accepts both the corresponding lead and the lag
7 gaps. The probability of accepting available gaps at the direction of lane l at time t
8 conditional on individual specific random term ϑ_n can therefore be expressed as follows:

$$\begin{aligned}
& P(lc_n(t)|l_n(t), m_n(t), \vartheta_n) \\
& = P(\text{accept lead gap}|l_n(t), m_n(t), \vartheta_n) * P(\text{accept lag gap}|l_n(t), m_n(t), \vartheta_n) \\
& = P(G_n^{\text{lead},l}(t) \geq G_n^{\text{cr,lead},l',m}(t)|l_n(t), m_n(t), \vartheta_n) * \\
& P(G_n^{\text{lag},l}(t) \geq G_n^{\text{cr,lag},l,m}(t)|l(t), m_n(t), \vartheta_n) \tag{4}
\end{aligned}$$

11 Where;

12 $G_n^{\text{lead},l,m}, G_n^{\text{lag},l,m}$: Available lead and lag gaps at target lane l .

13 Assuming a lognormal distribution of the gap acceptance probability can be written as
14 follows:

$$\begin{aligned}
& P(G_n^{j,l}(t) \geq G_n^{\text{cr},j,l,m}(t)|l_n(t), m_n(t), \vartheta_n) \\
& = P[\ln(G_n^{j,l}(t) \geq G_n^{\text{cr},j,l,m}(t)|l_n(t), m_n(t), \vartheta_n)] \\
& = \Phi \left[\frac{\ln(G_n^{j,l}(t)) - (X_n^{j,l,m}(t), \beta^{j,l,m} + \alpha^{j,m} \vartheta_n)}{\sigma^{j,m}} \right] \tag{5}
\end{aligned}$$

17 Where;

18 $\Phi[\cdot]$: Cumulative standard normal distribution

19 The gap acceptance is a result of interaction between the subject drivers and the traffic in the
20 adjacent lane in the direction of the target lane. The interaction can be represented by
21 variables like relative speed between the subject vehicle and lead and/or lag vehicle at the

1 target lane, relative speed between the subject vehicle and the front vehicle in the current lane,
 2 types of vehicle, distance to exit etc.

3 3.3 Likelihood

4 The likelihood function is applied to estimate the parameters of the lane-changing model. As
 5 mentioned in section 3.1, the lane-changing model consists of two components (1) target lane
 6 selection and (2) gap acceptance. The joint probability of observing a lane change at time t ,
 7 $P(LC_n^{l'}(t))$, therefore, is a joint probability of choosing target lane l and accepting the
 8 available gap at the direction of lane l and can be expressed as follows:

$$P(LC_n^{l'}(t)|\vartheta_n) = \sum_l \sum_m P(l_n(t)|\vartheta_n) * P(lc_n(t)|l_n(t), m_n(t), \vartheta_n)$$

9 (6)

10
 11 Both $P(l(t)|\cdot)$ and $P(lc_n(t)|\cdot)$ are given by equations 2 and 4 respectively. The trajectory data
 12 consists of a sequence of observations of the same driver over the study area. Assuming that
 13 the observations from different drivers are independent over time, the joint probability of the
 14 sequence observations can be specified as follows:

$$\begin{aligned} & [P(LC_n^{l'}(1)|\vartheta_n) * P(LC_n^{l'}(2)|\vartheta_n) * P(LC_n^{l'}(3)|\vartheta_n) * \dots * P(LC_n^{l'}(T_n)|\vartheta_n)] \\ & = \prod_{t=1}^{T_n} \sum_l \sum_m P(l_n(t)|\vartheta_n) * P(lc_n(t)|\vartheta_n) \end{aligned}$$

16 (7)

17 Where; T_n : Number of observed time period for each n^{th} driver (1, 2, 3, ..., T_n)

18 Integrating the equation 7, the unconditional likelihood function (L_n) of the observed lane-
 19 changing behaviour over the distributions can be written as follows:

$$LC_n = \int_{\vartheta} \prod_{n=1}^{T_n} \sum_l \sum_m P(l_n(t)|\vartheta_n) * P(lc_n(t)|\vartheta_n) f(\vartheta) d\vartheta$$

20 (8)

21 Note that $f(\vartheta)$ is a standard normal probability density function. Following the IID
 22 distribution of the error terms, the log-likelihood function for all N individual observation
 23 denotes:

1
$$L = \sum_{n=1}^N \ln LC_n \quad (9)$$

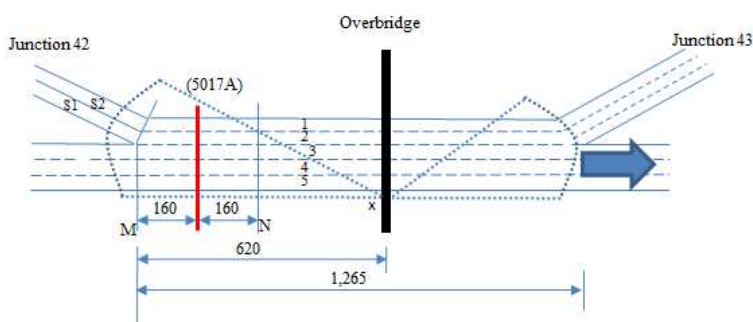
2 The maximum likelihood estimates of the model parameters are found by maximizing this
 3 function. The Broyden-Fletcher-Goldfarb-Shanno (BFGS) optimisation algorithm is used for
 4 the maximization.

5 **4 Data**

6 The observations were taken on the M1 between Junction (J) 42-43, northbound between
 7 Wakefield and Leeds. The observations were taken on Thursday, 16th May 2013 between
 8 16:30-18:30, when the motorway is relatively uncongested (as per the Management Incident
 9 Data Analysis (MIDAS) data logs). The motivation for focusing on this period (as opposed to
 10 the more congested morning peak traffic) is to capture the lane-changing behaviour under
 11 relatively free-flow traffic condition when the congestion is gradually building up and there
 12 are wider variations in lane-changing mechanisms.

13 **4.1 Site description**

14 The observation area J42-43 is a five lanes dual-carriageway (three lane for through traffic,
 15 and two auxiliary lanes) (Fig 3). The distance between J42-43 is 1,265m respectively, which
 16 is slightly shorter than the 2,000m recommended by DMRB (DMRB, 2006) for a weaving
 17 section.



18
 19 Fig 3 Observation area (distances are in metres)

20 Where;

- 21 : Over bridge where the video recording at J 42 was made at x point
- 22 1,2 : Auxiliary lane 1 and Auxiliary lane 2
- 3, 4, 5 : Main lanes traffic

- 1 S1, S2 : Entry slip or exit slip road lane 1 and lane 2
2 x : Location of video camera recording
3 : Traffic video coverage area
4 — : MIDAS Loop Detector Location and (loop detector ID)

5 The video recording was made from an overbridged located 620m downstream from J42 in
6 two directions. The first camera, faced the traffic from J42 and recorded all five lanes of
7 traffic. A second camera faced the J43 and recorded the traffic between the over bridge and
8 the exit ramp. The trajectory data has been extracted using a semi-automated vehicle
9 trajectory extractor application by Lee et al., 2008. Due to the limitations of the software, the
10 detailed trajectory data was available only for the first 320 m from J42 (between points M and
11 N in Fig 3). The rest of the data has been used only for creation of local origin-destination
12 analysis and number of lane changes. The details of the extraction procedure is discussed in
13 Kusuma et al. (2015). In addition, the speed and flow information from the MIDAS database
14 has been used to validate the trajectory data

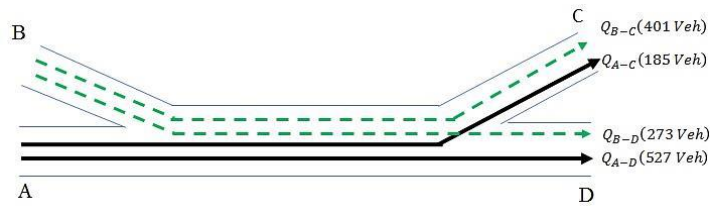
Comment [Z1]: Add reference

15 4.2 Traffic analysis

16 The current research focuses only on the highest 15min of traffic flow within the evening
17 peak, which occurs between 17:15-17:30. During these 15 minutes, the traffic video recorded
18 1,386 vehicles passing the observation area whilst the MIDAS detector in the area (detector
19 5017A) recorded 1,453 vehicles, resulting in 4.61% difference between the two
20 measurements. Several possible errors in the video extraction process could contribute to the
21 difference, including errors in the video resolution, video time step, and obscuration due to
22 the leading vehicles. The traffic composition (based on the trajectory data) is as follows:

- 23 • Small vehicles: 84.9%
- 24 • Vans: 10.6%, and
- 25 • Bus and heavy vehicles: 4.5%

26



1

2 Fig 45 Schematic of origin-destination in the weaving section

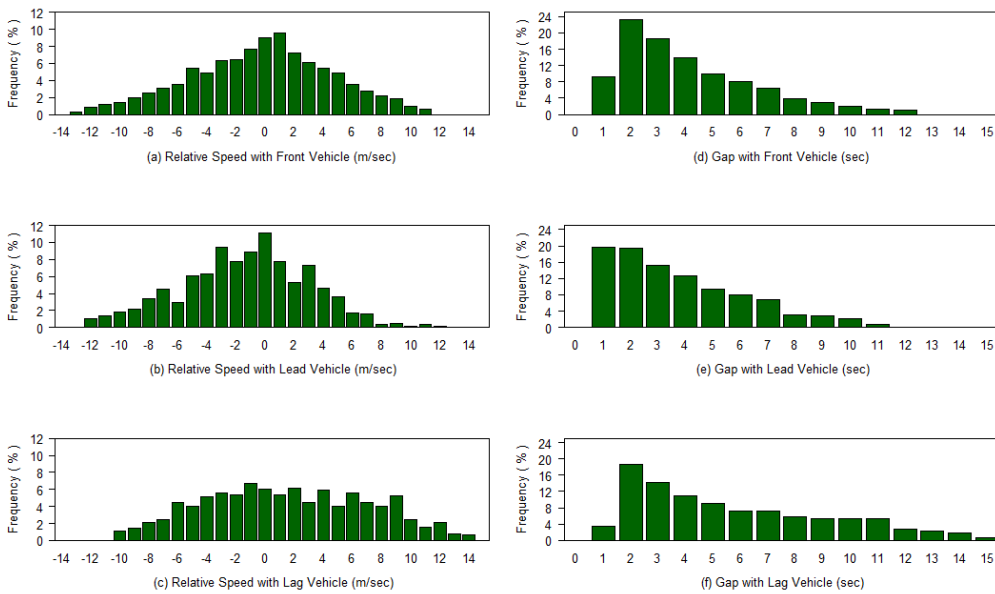
3 In terms of local origin and destination, as shown in Fig. 5, the observed weaving section has
 4 two origin nodes (A and B) and two destination nodes (C and D). The corresponding traffic
 5 volumes are shown in parenthesis.

6 The key observations are listed below:

- 7
- 8 • 731 (52.7 %) of the traffic observed in the video data make lane changes during the
 9 observation period.
 - 10 • 458 vehicles ($Q_{A-C} + Q_{B-D}$) require a mandatory lane-changing movement whether to
 11 exit from the motorway through lane 1 and 2 or merge to the main traffic on lane 3, 4,
 12 and 5. This type of lane-changing is approximately 62.7% of the total lane-changing
 13 traffic.
 - 14 • Around 95.0% of the total lane-changing traffic occurs in the upstream_section while a
 15 small proportion (5%) of lane-changing traffic change lanes after the overbridge.
 - 16 • Most of the vehicles make a single lane change (73.8% of total lane-changing traffic)
 17 while the rest make more than one changes.
 - 18 • The maximum number of lane changes made by vehicles is 3. This situation typically
 occurs for vehicles merging or diverging from the main traffic.

19 The potential spatial inaccuracies in the data has been a concern in this case and in spite of
 20 best efforts, the data is likely to have errors due to limitations of the video recording tool,
 21 pixel resolution, frame rate, camera vibration, camera synchronization and longitudinal and
 22 lateral angles. The locally weighted regression (xx) has been used to smooth the observed
 23 trajectories and to minimise the errors. The relative speed and positions of the vehicles are
 24 analyzed and presented in Fig. 6.

1 Speed in the observation area varies between 18.75 m/sec (66.38 km/h) and 37.87 m/sec
 2 (136.35 km/h), with mean value 25.96 m/sec (93.48 km/h). In this case, 19.5% of the traffic
 3 moves over the speed limit (which is 70 mph (112 km/h)).



4
 5 | Fig 5.6 Relative speed between the subject vehicle and (a) front vehicle at current lane, (b)
 6 | lead vehicle and (c) lag vehicle at the target lane, and gap acceptance at (d) front
 7 | vehicle, (e) lead vehicle and (f) lag vehicle.

8 The mean relative speed between the subject and the front vehicle at the current lane, lead
 9 vehicle in the target lane and lag vehicle at the target lane are -0.75, -1.91 and 1.35 m/sec
 10 respectively. The distributions of these speeds are presented in Fig. 6 (a, b, and c). It may be
 11 noted that the distributions of the lead and lag vehicles reflect only when the subject vehicle
 12 executes a lane change.

13 In terms of gap acceptance, the mean accepted lead and lag gaps at target lane are 3.27 sec
 14 and 5.23 sec respectively. The distribution of accepted gaps is presented in Fig 6 (d, e, and f)
 15 The distribution profiles are skewed to the left side and resemble lognormal distribution

16 4.3 Group behaviour

17 The trajectory data has been analysed to explore potential presence of platoon and, weaving
 18 effects. and the following split has been observed:

1 1. Solo (76.6%)

2 2. Platoon (10.7%)

3 3. Weaving (12.7%)

4 Therefore, 23.4% of the lane-changing traffic is observed to be involved in group behaviour
5 where the majority performs the weaving manoeuvre. Lane 3 and lane 2 traffic take the
6 largest share of weaving traffic compared to the other lanes. The data illustrates that 3.6 % of
7 the lane-changing traffic involve weaving lane-changing mechanisms when changing from
8 lane 3 to lane 2 (diverging from the main traffic). Similarly, most of platoon lane-changing
9 appears from lane 3 toward lane 2 (3.5% of the lane-changing traffic).

10 5 Estimation and result

11 Both target lane and gap acceptance of lane change model are estimated jointly using a
12 maximum likelihood approach which has been discussed in Section 3. Table 1 summarises the
13 estimation result of the proposed lane change modelling specification.

14 Table 1 Lane-Changing Model Estimation Result

| Modelling Variables | Parameter | t-value |
|---|-----------|---------|
| Target Lane Model | | |
| Lane 2 constant | 0.800 | 11.917 |
| Lane 3 constant | 1.0493 | 15.601 |
| Lane 4 constant | 0.0699 | 0.887 |
| Lane 5 constant | -1.292 | -8.986 |
| Average speed (m/sec) | 0.0174 | 4.701 |
| Occupancy (%) | -0.00185 | -0.160 |
| Relative speed to the front vehicle (m/sec) ^{*)} | 0.0487 | 8.801 |
| No of lane-changing required | -10.223 | -19.485 |
| Exponent component of distance to exit (m) | -0.135 | -1.475 |
| α left direction | -0.0644 | -0.454 |
| α right direction | 0.0667 | 0.500 |
| Critical Gap Solo | | |
| Gap constant | -0.864 | -5.012 |
| Relative speed with lead vehicle at target lane (m/sec) ^{*)} | -0.0204 | -3.521 |
| Relative speed with front vehicle at current lane (m/sec) ^{*)} | -0.00730 | -0.814 |
| α gap | 1.437 | 5.103 |
| σ gap | 0.150 | 3.85 |
| Critical Gap Platoon | | |
| Gap constant | -2.360 | -5.591 |
| Relative speed with lead vehicle at current lane (m/sec) ^{*)} | -0.263 | -13.029 |

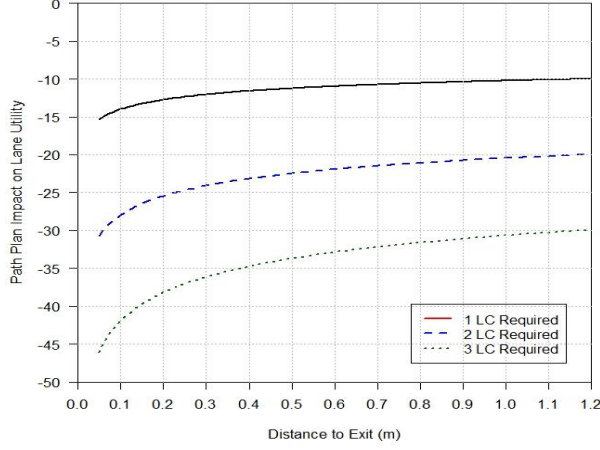
| | | |
|---|-----------|--------|
| α gap | 1.200 | 1.513 |
| σ gap | 1.692 | 4.000 |
| Critical Gap Weaving | | |
| Gap constant | -0.539 | -3.759 |
| Relative speed with lead vehicle at target lane (m/sec) ^{*)} | -0.127 | -3.703 |
| α Gap | 1.681 | 4.458 |
| σ Gap | 0.410 | 4.498 |
| Critical Lag for All Types of Leader Movement | | |
| Lag Constant | 0.421 | 4.096 |
| Relative speed with lag vehicle at target lane (m/sec) ^{**))} | 0.0146 | 2.841 |
| α Gap | 2.418 | 4.320 |
| σ Gap | 0.872 | 4.210 |
| Number of observation | 17,891 | |
| Number of driver | 1,386 | |
| Number of parameters | 28 | |
| Initial Log-Likelihood | -9935.222 | |
| Final Log-Likelihood | -6512.663 | |
| Adjusted Rho-Bar Square | 0.342 | |

^{*)} lead or front veh. speed – subject veh. speed; ^{**))} lag veh. speed – subject veh. speed

5.1 Target lane model

The estimation result demonstrates several attributes, which affect the target lane choice of the driver such as relative speed, average speed, occupancy, and path-plan impact. The lane specific constant in Table 1 implies that all else being equal, lane 3 and lane 2 are preferred more than the other lanes. It may be noted that those two lanes provide higher flexibility in terms of merging or diverging from the main traffic beyond the study area. As expected the drivers prefer lanes with higher average speed and faster lead vehicles and lower lane occupancy.

The path-plan attributes explain the relation between the remaining distance to exit and dummy variable of number of lane-changing required toward the desired target lane. As shown in [Fig 6Fig-8](#), the utility of the target lanes requiring mandatory lane changes decrease as the driver approaches the mandatory lane-changing point. The utility is reduced slightly large if more than 1 lane change is required compared to a single lane change. Similar to the previous studies (i.e. Toledo et al., 2005), the path-plan impact of lane-changing demonstrates that the traffic tends to perform a pre-emptive lane-changing movement at the upstream of weaving section rather than delaying toward the downstream (close to the off-ramp).



1

2 | Fig 68. Impact of path-plan lane changes on the lane utility

3 The heterogeneity captures the driver aggressiveness with respect to the target lane location
 4 either left or right of the current lane location. A negative sign on the left lane-changing
 5 direction implies that the driver moving to the left have a higher level of aggressiveness
 6 compared to those moving to the right direction. Furthermore, this is intuitive as the left lane-
 7 changing driver has a priority when perform a lane-changing. It is worth noting that the UK
 8 driving rule mandates provision of priority to the upcoming traffic from the right lane. On the
 9 other hand, moving on the right/far-side lanes requires more cautious as the driver merges
 10 toward the higher speed lane. It is important to ensure for the driver to change in a safe
 11 manner and minimises the accident risk for both subject vehicle and neighbourhood traffic.

12 Giving the estimation result in Table 1, the target lane utility can be written as follows:

$$\begin{aligned}
 13 \quad U_n^l(t) = & \beta^l + 0.0174 * \bar{V}_n^l(t) - 0.00185 * occ_n^l(t) + 0.0487 * \Delta V_n^l(t) + \left((d_n^{exit}(t))^{-0.135} * \right. \\
 14 \quad & \left. (-10.223 * no.LC(t)) \right) - \alpha^l * \vartheta_n(t) + \varepsilon_n^l(t) \quad (10)
 \end{aligned}$$

15 Where;

16 β^l : Lane l specific constant

17 $\bar{V}_n^l(t)$: Average speed at lane l of driver n at time (t) (m/sec)

18 $occ_n^l(t)$: Lane l occupancy level of driver n at time (t) (percentage (%))

19 $\Delta V_n^l(t)$: Relative speed between n^{th} driver and the leading vehicle at lane l at time (t)

1 $d_n^{exit}(t)$: Remaining distance to the mandatory lane-changing point of the n^{th} driver at time
2 t , ∞ if no mandatory lane-changing is required.

3 $no.LC(t)$: Number of lane-changing required toward the target lane at time t

4 $\alpha^{l'}$: Estimated parameters of individual specific random effect ϑ_n for direction l'

5 $l' \in \{left, right\}$ depends on the orientation of target lane l with respect to the current lane.

6 The choice of the target lane indicates the direction of lane-change (e.g. stay in the current
7 lane, look for gaps in the right, look for gaps in the left) and the driver looks for acceptable
8 gaps in that direction.

9 **5.2 Critical gap acceptance model**

10 The gap acceptance is a second level of the lane change decision-making process. As
11 mentioned, three different mechanisms of lane changes have been considered here: solo,
12 platoon, and weaving.

13 The estimation results indicate that the critical gap of solo lane-changing movement is
14 affected by both relative speeds at the target lane and current lane. Meanwhile, the critical gap
15 of the platoon and weaving lane-changing mechanism are affected by the relative speed at the
16 current lane and relative speed at target lane respectively. This is intuitive as for the platoon
17 mechanisms; the front vehicle in the current lane has a more dominant role whereas for the
18 weaving mechanism, the lead vehicle in the target lane has a more dominant role. The relative
19 speeds have a negative sign in all critical gap lane-changing mechanisms. These findings
20 denote that the subject driver requires a larger gap in associated with the increased of relative
21 speed.

22 The coefficients of the individual specific random terms and the standard deviations are also
23 significantly different depending on the lane-changing mechanism. The estimation results
24 indicate that the platoon lane-changing has the highest level of aggressiveness compared to
25 the other types of lane-changing mechanism. Meanwhile, the weaving lane change is less
26 aggressive due to the complexity of the weaving movement where the lane-changing driver in
27 this mechanism has to cross with neighbourhood traffic stream without any assistance from
28 traffic control device. Indeed, This characteristic raises an safety issue as stated in Golob et
29 al. (2004) where significant proportion of accident in the weaving section is a swidewipe
30 collusion

1 The lead critical gap functions for the three lane-changing mechanisms are presented below:

$$2 \quad G_n^{cr,lead,l,s}(t) = \exp\left(-0.864 - 0.0204 * \Delta V_n^l(t) - 0.00730 * \Delta V_n^{cl}(t) + 1.437 * \vartheta_n^{lead,s}(t) + \right. \\ 3 \quad \left. \varepsilon_n^{lead,s}(t)\right), \varepsilon_n^{lead,s}(t) \sim N(0, 0.150^2) \quad (11)$$

$$4 \quad G_n^{cr,lead,l,p}(t) = \exp\left(-2.360 - 0.263 * \Delta V_n^{cl}(t) + 1.200 * \vartheta_n^{lead,p} + \varepsilon_n^{lead,p}(t)\right) \\ 5 \quad \varepsilon_n^{lead,p}(t) \sim N(0, 1.692^2) \quad (12)$$

$$6 \quad G_n^{cr,lead,l,w}(t) = \exp\left(-0.539 - 0.127\Delta V_n^l(t) + 1.681 * \vartheta_n^{lead,w} + \varepsilon_n^{lead,w}(t)\right), \\ 7 \quad \varepsilon_n^{lead,w}(t) \sim N(0, 0.410^2) \quad (13)$$

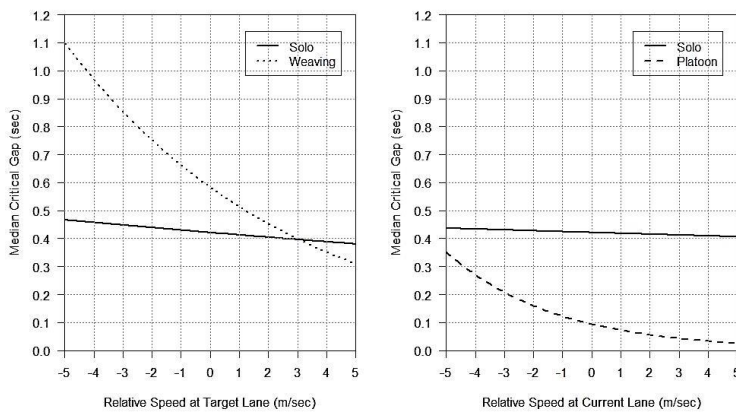
8 Where;

9 $G_n^{cr,lead,l,m}(t)$: Critical lead gap at the direction of target lane l of n^{th} driver at time t
 10 for lane-changing mechanism m , where m ; Solo (s), Platoon (p) or Weaving
 11 (w)

12 $\Delta V_n^l(t)$: Relative speed between the n^{th} driver and the lead vehicle in the direction
 13 of the target lane l at time t

14 $\Delta V_n^{cl}(t)$: Relative speed between the n^{th} driver and the front vehicle at current lane l
 15 at time t

16 The variation of lead critical gap median value with different types of leader effect critical gap
 17 in corresponds with relative speed is presented in [Fig 7](#)[Fig-9](#) respectively.



18
 19 | Fig 79. Variation of median lead critical gaps in different type of leader effect as a function of
 20 relative speed

1 The differences in the specification of the critical lag gap depending on the lane-changing
 2 mechanism revealed statistically insignificant differences (which is intuitive) and therefore a
 3 common lag gap acceptance model has been retained. The results indicate that the relative
 4 speed coefficient has a positive sign indicating that the critical lag gap of the lane-changing
 5 vehicle is larger if the lag vehicle in the target lane is moving faster. The estimated critical lag
 6 gap is summarised as follow;

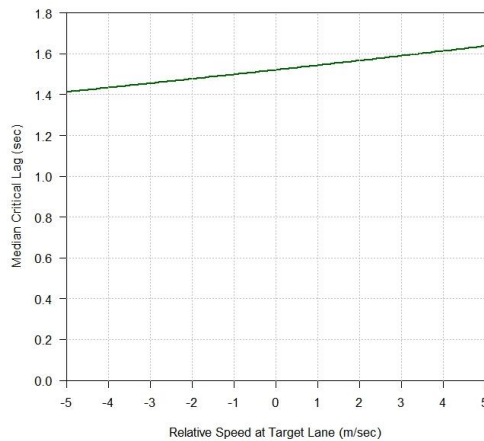
$$7 \quad G_n^{cr,lag,l}(t) = \exp\left(0.421 + 0.015 * \Delta Vtar_n^{lag,l}(t) + 2.418 * \vartheta_n^{lag} + \varepsilon_n^{lag}(t)\right) \quad (14)$$

8 Where;

9 $G_n^{cr,lag,l}(t)$: Lag critical gap at target lane l of driver n at time t

10 $\Delta V_n^l(t)$: Relative speed between the n^{th} driver and the lag vehicle in the direction of the
 11 target lane l at time t

$$\varepsilon_n^{lag}(t) \sim N(0, 0.872^2)$$



12

13 Fig 8-10. Variation of median lag critical gap as a function of relative speed

14 Similar to Bham (2008), the variations of critical gap and lag median values for all lane-
 15 changing mechanisms (solo, platoon and weaving) in Fig 7-9 and Fig 8-10 indicate that
 16 lane-changing traffic in the relative non-congested traffic considers a larger lag while they
 17 accept smaller gaps. In addition, the individual specific constant of critical lag model also
 18 confirms this finding as it has slightly larger value compared to all lane-changing
 19 mechanisms. That is to say that the driver is more alert when accepting the lag due to the

1 difficulty in interpreting the lag vehicle behaviour (i.e. observe through the mirror) rather than
 2 the downstream traffic movement.

3 **6 Model Comparison**

4 The proposed model is compared with a reduced form model that ignores the effect of lane-
 5 changing mechanisms in the model structure. The reduced form model assumes same critical
 6 gap functions irrespective of the lane-changing mechanism and is estimated with the same
 7 trajectory data. The summary statistics of the estimation results for the two models, presented
 8 in Table 2, show an improvement in the fit of the model, even when accounting for the larger
 9 number of parameters in the proposed model.

10
11
12
13
14

Table 2. Model Comparison

| Statistic | Restricted | Unrestricted |
|---|------------|--------------|
| Likelihood value ($L(\beta^*)$) | -6544.203 | -6512.663 |
| Number of parameters (k) | 20 | 28 |
| Adjusted rho-bar $\bar{\rho}^2 = 1 - \frac{L(\beta^*) - k}{L(0)}$ | 0.339 | 0.342 |
| Akaike information criterion ($AIC = L(\beta^*) - k$) | -6564.203 | -6540.663 |

15

16 The model with explicit lane-changing mechanisms has larger values in terms of both Akaike
 17 Information Criteria (AIC) and Adjusted Rho-Square (ρ^2). Furthermore, the improvement in
 18 the goodness of fit is also tested using Likelihood Ratio Tests:

19 Likelihood Ratio Test value = $2 * (L(\beta^{*,res}) - L(\beta^{*,unres}))$
 20 $= 63.08 > \chi_8^2(15.51)$ (15)

21 This confirms that the inclusion of the lane-changing mechanisms in the decision framework
 22 results in an improved goodness-of-fit even after discounting for the increase in the number of
 23 parameters.

1 **7 Conclusion**

2 This paper extends the latent-plan modelling framework on lane-changing behaviour to
3 explicitly incorporate the effect of lane-changing mechanism (platoon, weaving and solo) in
4 the modelling framework. The model parameters are estimated using vehicle trajectory data
5 collected from M1 motorway network between J42-43. Estimation results indicate a
6 significant differences in characteristics between the three types of lane-changing mechanisms
7 which is supported by statistically significant improvements in the goodness-of-fit results

8 In addition to the potential to improve the fidelity of microsimulation tools, particularly in the
9 context of improved simulation of weaving sections, the results have interesting practical
10 implications. For example, parameter values indicate that (a) platooned LC takes smaller gap
11 and is more aggressive; (b) platoon and weaving drivers are more sensitive to relative speed
12 changes and increase their critical gaps significantly with negative relative speed; and (c) LC
13 most likely to occur at the beginning of a weaving area. The implication of (a) can be
14 considered from a safety point of view: platooned LC is unsafe and should therefore be
15 discouraged. Interventions to do that could include advice on keeping a larger headway.
16 Advice/intervention (such as the variable speed limits) to equalise vehicle speeds would,
17 according to (b), reduce the critical gap and therefore improve LC efficiency. For (c),
18 intervention to separate LC for merging from LC for diverging would reduce the intensity of
19 LC at the beginning of weaving area and spread LC across the whole weaving area. This can
20 improve safety as well as the traffic performance of the weaving section.

21 The current models are yet to be validated in the microsimulation tools. Moreover, it will be
22 interesting to test the transferability of the estimation results in other weaving sections.
23 Another potential direction of extension can be to investigate the effect of the lane-changing
24 mechanism on acceleration behaviour.

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