Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 21 (2017) 227–239

Transportation Research Procedia

www.elsevier.com/locate/procedia

2016 International Symposium of Transport Simulation (ISTS'16 Conference), June 23~25, 2016

Optimization of lane-changing distribution for a motorway weaving segment

David Sulejic [a]*, Rui Jiang [a], Nasser R. Sabar [a], Edward Chung [a]

[a] *Smart Transport Research Centre, Queensland University of Technology, Brisbane QLD 4000, Australia*

Abstract

The traffic in a weaving segment is subject to lane-changing turbulence in excess of that normally present on basic motorway segments. Empirical studies have observed a lane-changing concentration problem, as traffic flow increases, which can cause flow break down and congestion. This paper focuses on the lane-changing concentration problem in weaving segments. A Cooperative Intelligent Transport System (C-ITS) advisory has been shown to alleviate such a lane-changing concentration problem. The advisory aims to distribute the lane-changing along the weaving segment. Unlike previous methods in the literature, where weaving vehicles are assigned according to fixed distributions, this paper proposes an algorithm to optimize the lane-changing distribution. The proposed optimization algorithm was developed based on particle swarm optimization. The optimized lane-changing distribution for a one-sided motorway weaving segment using microscopic simulation has been evaluated. The initial results show that the proposed algorithm could be used as a successful optimization technique for the lane- changing concentration problem.

Keywords: Cooperative Intelligent Transport Systems (C-ITS); Weaving segment; Lane-changing distribution; Particle swarm optimization.

1. Introduction

Weaving segments, a common design for motorways, are formed when merge segments are closely followed by diverge segments (TRB, 2010). Weaving is generally defined as the crossing of two or more traffic streams travelling in the same direction along a significant length of motorway without the aid of traffic control devices (TRB, 2010).

* Corresponding author. Tel.: +614 13 708 441.
E-mail address: david.sulejic@hdr.qut.edu.au

10.1016/j.trpro.2017.03.092

Weaving segments require intense lane-changing maneuvers for drivers to access the lane appropriate for their desired exit. weaving segments therefore involve complex vehicle interactions, which presents safety and operational problems. The traffic in a weaving segment is subject to lane-changing turbulence in excess of that normally present on basic motorway segments (TRB, 2010). Empirical studies have shown that drivers tend to perform lane changes soon after they enter the segment as the traffic volume increases (Cassidy and May, 1991). The lane-changing concentration problem can cause bottlenecks, which leads to congestion.

Recent advancements in the field of cooperative intelligent transport systems (C -ITS) have enabled vehicles to send and receive real-time information (Weiss, 2011). Vehicle to vehicle (V2V) and vehicle to roadside infrastructure (V2I) communications have been extensively tested in real-world applications. In recent field trails, C- ITS applications have been shown to provide traffic safety, efficiency and environmental benefits (Green et al., 2014). One of the distinct benefits of C-ITS is that it offers individual traffic control, which differs from that offered by conventional ITS controls (such as variable message signs and variable speed limits). Therefore, C -ITS applications can be implemented to control and/or guide vehicles at a more refined level.

This paper focuses on the lane-changing concentration problem on motorway[1] weaving segments and how C-ITS can be implemented to reduce this problem. A C-ITS advisory is a potential application that can improve the flow by using V2I technology. The objective of a C-ITS advisory is to alleviate the problem by aiming to distribute the lane- changing in order to better utilize the existing infrastructure.

Mai, Jiang and Chung (2016) used a C-ITS-based lane-changing advisory in order to improve the lane-changing concentration problem on weaving segments by evenly fixing the lane-changing distributions over the length. However, no sophisticated optimization technique was involved to seek the optimal solution for the distribution.

The aim of this paper is to demonstrate how to optimize the distribution by using optimization techniques. It is proposed that an optimization algorithm, based on particle swarm optimization (PSO), be implemented to improve the lane-changing distribution. The proposed method was evaluated for a basic one-sided ramp motorway weaving segment with a short-length weaving configuration of 400m between merging and diverging segments. The evaluation method for the implementation of the optimization algorithm on the lane-changing distribution was traffic simulation.

The paper is structured as follows. Firstly, a literature review on the motorway weaving problem is presented. Secondly, the case study is presented. Thirdly, the proposed optimization algorithm is presented. Lastly, the experimental settings, results and findings are discussed, followed by the conclusion.

2. Literature review

This section briefly reviews the literature related to the lane-changing concentration problem in motorway weaving segments. The problem has been observed in several empirical studies.

Early research by Cassidy and May (1991) analyzed the traffic flow behavior in individual lanes of a weaving segment. Their research showed that a high concentration of lane-changing maneuvers occurred near the weaving entrance. The majority of lane changes were made before a reference point, 76m from the merge gore of a 445m section. Their analysis suggested that as the weaving flow increased, weaving vehicles become more anxious to change lanes over shorter travelled distances. They suggested that this increased feeling of pressure may encourage motorists to perform lane-change maneuvers as soon as possible. Therefore, this behavior may result in increased turbulence in the weaving area, decreasing weaving area capacity and becoming more vulnerable to congestion. Research by Kwon, Lau and Aswegan (2000) showed similar weaving behavior for a short one-sided weaving section of 129m.

[1] “ motorway” and “ freeway” are used interchangeably.

They found that as the weaving flow began to increase, the diverging vehicles began to change to the auxiliary lane as soon as they entered the weaving zone. They observed that "most merging and diverging vehicles complete their lane changes before they reach approximately the middle point of the weaving zone" (Kwon, Lau and Aswegan, 2000, 136). Denny and Williams (2005) conducted a pilot study on a freeway weaving segment in Houston. They observed from field studies that weaving maneuvers were not uniformly distributed along the weaving segment at capacity. In fact, their observations showed that about 85% of the maneuvers took place in the first 120-150m of a 400m segment.

A study by ho Lee (2008) investigated the traffic behavior in freeway weaving bottlenecks. The research found that a high concentration of diverging maneuvers near the on-ramp triggered bottlenecks, resulting in vehicle slow-downs. The findings concluded that "it is not only the amount of lane changes that influence weaving bottleneck discharge flows, but also the concentrations of these maneuvers" (ho Lee, 2008, 59).

Al-Jameel (2013) has recently investigated driver behavior in weaving segments, as part of an empirical study. In that study, investigation of lane-changing locations within a 400m weaving segment found that 80% of merging vehicles and up to 90% of diverging vehicles performed lane changes in the first 100m of the section. Observations found that the location of the bottleneck would start at about 70m and oscillate between this location and the entrance point of the merge segment. This would propagate congestion upstream from the entrance area.

The C-ITS strategy proposed by Mai, Jiang and Chung (2016) used a lane-changing advisory to distribute lane-changes along an entire weaving segment. Their study showed that such an advisory could potentially reduce delay significantly.

Therefore, according to the literature, the lane-changing concentration problem can be observed to occur in weaving segments, particularly when the weaving flow increases. This behavior can lead to congestion, reducing the weaving capacity. The problem can be alleviated by distributing lane changes along the entire weaving segment. This can be achieved by using a C-ITS advisory to better distribute lane changes along the weaving segment.

3. Case Study

A case study has been used to demonstrate the application of the C-ITS lane-changing advisory and to implement the optimization algorithm. This section first covers the microscopic simulation setup including the network configuration and simulation settings. It then describes the process for the C-ITS advisory application. Lastly, the case study presents the performance indicator used for the evaluation of the weaving segment.

3.1. Network Configuration

Al-Jameel's (2013) empirical study examined the characteristics of driver behavior in weaving segments in field data extracted from video recordings of seven motorway weaving sites. This paper uses the existing network based on the M60 Motorway (Manchester City, UK) weaving segment configuration coded in AIMSUN by Mai, Jiang and Chung (2016).

The network, a short weaving segment with a length of 400m, has a width of four continuous lanes: three freeway-to-freeway lanes and a one-lane, left-side on-ramp followed closely by a one-lane, left -side off-ramp. The two ramps are connected by a continuous freeway auxiliary lane. The configuration can be defined as a one -sided weaving segment that requires no more than two lane changes to be completed successfully. The speeds are coded as 100km/h and 80km/h for the freeway and ramp sections, respectively. The geometry of the weaving segment is shown in Fig. 1a (considering left-hand side traffic direction).

The demand data for the weaving segment were taken from Al-Jameel' s study (2013). The case study model, which considered cars only in its traffic composition, had the following demand flow rates:

- Freeway-to-freeway (FF): 5300 veh/h
- Ramp-to-freeway (RF): 900 veh/h
- Freeway-to-ramp (FR): 900 veh/h
- Ramp-to-ramp (RR): 100 veh/h

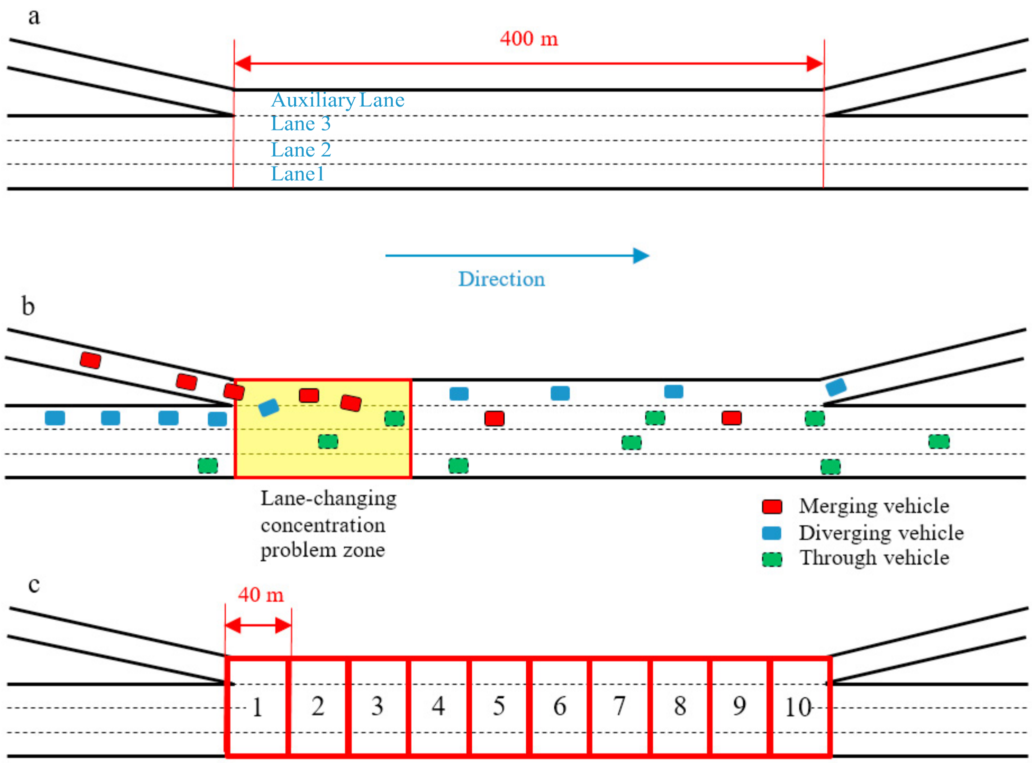

Fig. 1. Weaving segment: (a) geometry; (b) lane-changing concentration problem zone; (c) divided into ten sections.

3.2. Simulation settings

The model was built using a commercially available microscopic traffic simulation software, AIMSUN, which provides an Application Programming Interface (API) with its microsimulation software. The API, which enables AIMSUN to interface with external applications , was used for this study; the development language used was Python; the version of AIMSUN used was 8.1.2.

The simulation settings have been defined by Mai, Jiang and Chung (2016). Their model, which uses the observed data from Al-Jameel' s (2013) empirical study, calibrates and validates the high lane-changing concentration problem in the microsimulation. Therefore, their model can be reasonably tested for the purposes of this paper. Fig. 1b demonstrates the zone where the lane-changing concentration problem generally exists.

3.3. C-ITS advisory application

As noted, the C-ITS lane-changing advisory application, adapted from Mai, Jiang and Chung (2016), has been implemented using the microsimulation API for AIMSUN. The assumptions of the C-ITS strategy include:

- The communication signal strength was 100% guaranteed
- All vehicles are assumed to be equipped with 5.9 GHz Dedicated Short Range Communication (DSRC) connectivity (commonly used for C-ITS projects (Green et al. 2014))
- Each vehicle complies with the guidance provided by the C-ITS advisory
- Each vehicle is tracked by a roadside unit (RSU) to identify their lane
- Each vehicle's origin and destination is known; hence, a weaving vehicle can be identified.

The advisory application consists of five steps, which are discussed in sequential order. The process for the advisory application is shown in Fig. 2.

Step 1: collect the origin-destination (OD) information of each vehicle through V2I communications. Assuming a RSU located upstream of the weaving segment, vehicles equipped with C -ITS would send their OD path information to the RSU.

Step 2: classify the vehicles into weaving and non-weaving groups based on their OD information. For the non-weaving group, no further actions are required and proceed as usual.

Step 3: classify the weaving vehicles into the merging and diverging subgroups, based on their OD in formation, in order to allocate separate lane-changing distributions. Merging and diverging vehicles are referred to as ramp -to- freeway and freeway-to-ramp vehicles, respectively.

Step 4: assign a section to each weaving vehicle, from which point they may start to perform a lane-change. A section is defined as a zone across the weaving segment with a length dependent on the designated proportions. For example, if the 400m weaving segment is divided into ten sections, each section would have a length of 40m (refer to Fig. 1c). The weaving segment was divided into ten sections.

This set-up differs from Mai, Jiang and Chung (2016), as for the purpose of this study, the strategy was implemented to simulate C-ITS control at a more detailed level. Therefore, considering the simulation step of 0.4 seconds, ten sections with lengths of 40m would be suitable for a vehicle travelling at a speed of 100km/h. For example, at 100km/h a vehicle t ravels a distance of approximately 28m/s or 11m per simulation step. Therefore, the section length ensures vehicles are captured within the section during a simulation time step. Also, it ensures that the distance travelled does not exceed the section length over a simulation time step.

As part of Step 4, the lane-changing distributions are used for RF and FR vehicle groups separately. Therefore, a weaving vehicle is assigned section j , where $j \in n$ sections, according to the lane-changing distribution of its weaving group, RF and FR respectively.

Step 5: send each vehicle a lane-changing advisory to indicate where they may commence lane-changing. The strategy is assumed to provide advisory control; hence, lane-changing is not forced. Rather, the C-ITS application advises drivers when to commence lane-changing based on their location. For example, vehicles assigned to section one may commence lane-changing when they enter the weaving segment with a suitable gap, whereas a vehicle assigned to section five is advised not to change lanes until the fifth section in the weaving segment. The advisory restricts the lane-changing of the vehicles until they reach their assigned section, at which point the AIMSUN lane-changing model governs the lane-changing characteristics of individual vehicles (Barcelo, 2013).

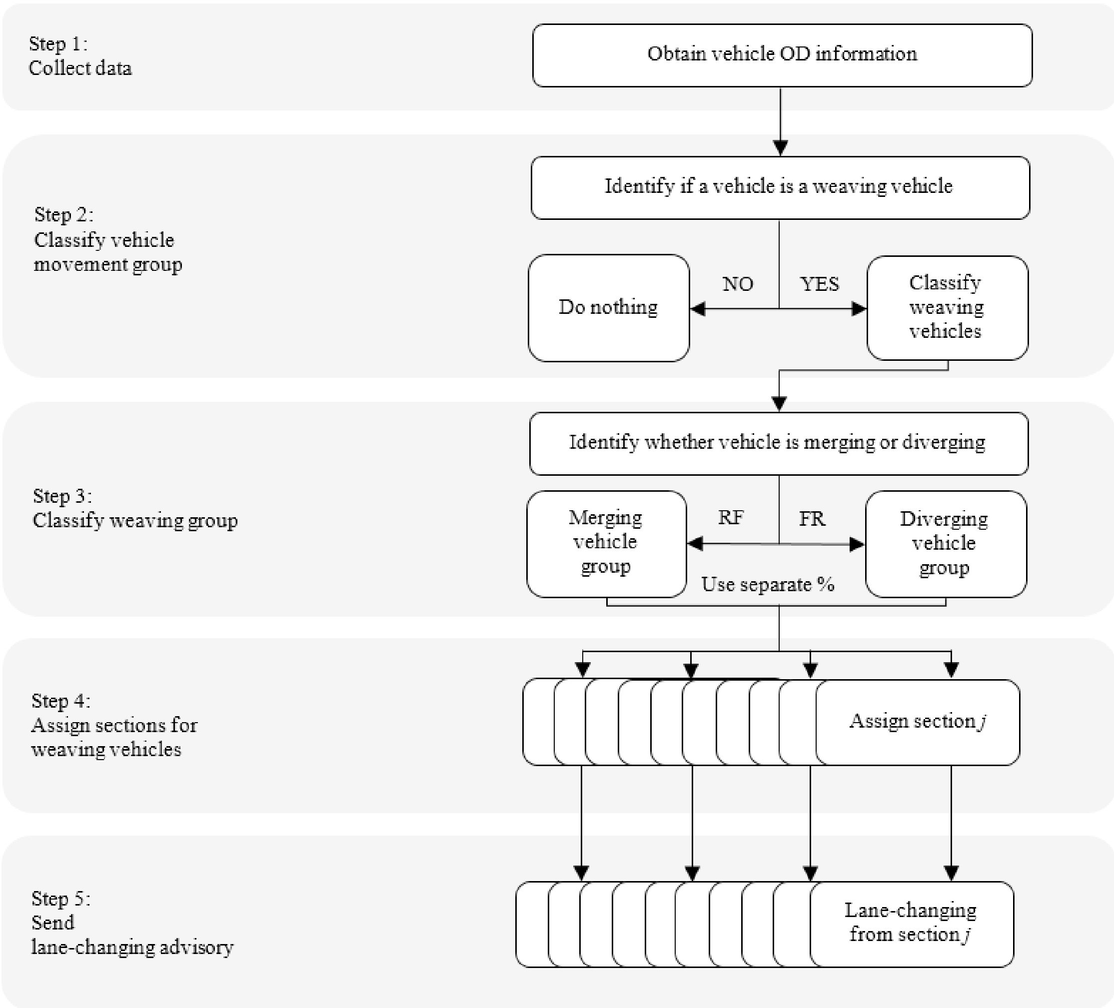

Fig. 2. Process chart for the lane-changing advisory application

The individual weaving vehicles will receive lane-changing guidance in the form of an audio and visual alert, as is commonly implemented in real-world C-ITS applications, such as those reviewed by Kanazawa et al. (2010) in Japan. See Fig. 3 for an example of an in-vehicle visual display unit for C-ITS applications. For the lane-changing advisory application, two different messages will be displayed:

- ‘Distance to lane change’ (countdown of distance until the assigned section)
- ‘Seek gap and perform lane change’ (the message alerts the driver to commence a lane change with a suitable gap)

Fig. 3. In-vehiclevisual display unit (Transport for NSW, 2015).

The purpose of the advisory is to distribute the lane-changing along the weaving segment to better utilize the infrastructure. This is achieved by optimizing the lane-changing distributions for RF and FR vehicles in Step 4. The actual lane-changing behavior may differ in a real-world scenario.

3.4. Performance indicator

The lane-changing distributions, assigned in Step 4, is optimized according to some performance indicator. This indicator helps evaluate the performance of the weaving segment after the optimization of the lane-changing distribution. The proposed performance indicator for the weaving segment was the minimum average speed (km/h). The average speed of all vehicles, weaving and non-weaving vehicles, is used for the segment. The average speed in the weaving segment will be representative of the traffic flow. If the traffic flow breaks down due to the lane - changing concentration problem, the average speed in the weaving segment will be lower, relative to the free -flow conditions. The average speed is measured over one-minute time intervals during the simulation run. The minimum of the average speeds will represent the peak, where traffic flow break-down is likely greatest. It is proposed to measure the average speed along the entire weaving segment. It is expected that measuring only a proportion of the segment, near the merge entrance, would push the lane-changing concentration further downstream. Therefore, minimum average speed over the entire segment shows how smoothly drivers crossed the weaving segment and tests whether the lane-changing concentration problem has been eased.

The performance indicator must also ensure that missed turns are penalized. Missed turns occur when a weaving vehicle is unable to perform their required lane change before the end of the segment. This tends to occur when they are assigned a section close to the end of the diverging point and no suitable gap is found to change lanes. This is not desirable for drivers. Therefore, the indicator incurs a penalty for missed turns, in the order of 1km/h for each missed turn. The lane-changing distributions will be optimized based on the evaluation of the performance indicator. This is derived from the results of the traffic simulation in AIMSUN.

The next section describes the proposed optimization algorithm used to improve the performance of the weaving segment.

4. Optimization algorithm

The proposed optimization algorithm used to seek the optimal lane-changing distribution was based on particle swarm optimization. The PSO algorithm, originally introduced by Eberhart and Kennedy (1995), is a population-based heuristic algorithm. It can be implemented efficiently to generate solutions for the lane -changing concentration problem. Genetic algorithms were attempted previously for this problem but their crossover and mutation functions proved difficult when dealing with the given constraints. PSO has been implemented for this problem since the fitness evaluations can be used to guide the search (Paquet and Engelbrecht, 2003). The problem can be defined as continuous; therefore, PSO is a suitable algorithm.

PSO has proved to be a useful algorithm to optimize unconstrained functions; however, if a number of constraints are added to the objective function, the problem becomes more complicated (Paque and Engelbrecht, 2003). Two notable constraints exist in the lane-changing distribution optimization problem. Firstly, there is a linear constraint for each particle (i.e. each potential solution), whereby the sum of all percentages for the lane -changing distribution must be equal to 100%. Secondly, there are upper and lower bound constraints for each dimension, whereby each percentage must be greater than 0 and less than 1. Therefore, the PSO algorithm must perform the search for potential solutions whilst satisfying the implicit constraints of the optimization problem.

The problem can be defined as a constrained numerical optimization problem that seeks to find $\bar{x}$, which minimizes $f(\bar{x})$, subject to $Ax = b$. Mezura-Montes and Coello (2011) state that “constraints may cause the search to keep away the focus on optimization to just seeking a feasible solution.” Therefore, the PSO algorithm needs a mechanis m to deal with the constraints of the problem while maintaining its focus on optimization. Paquet and Engelbrecht (2003) have proposed a new particle swarm optimizer that specifically handles linearly constrained optimization problems. The linear PSO, introduced to optimize problems with linear equality constraints using a constraint-preserving method, has been adapted for the purpose of optimizing the lane-changing distribution problem.

The linear PSO algorithm updates each particle’ s velocity and position using equations (1) and (2):

$$v_i^{t+1} = wv_i^t + c_1 r_1^t \left(y_i^i - x_i^t\right) + c_2 r_2^t \left(\hat{y}^t - x_i^t\right) \tag{1}$$

$$x_i^{t+1} = v_i^{t+1} + x_i^t \tag{2}$$

where v_i^t is the velocity of particle i at time step t , x_i^t is the position of particle i at time step t and ω is the inertia weight. The stochastic nature of the algorithm is determined by $r_1^t, r_2^t \sim U(0, 1)$, which are random values, sampled from a uniform distribution in the range [0,1]. These random numbers are scaled by acceleration coefficients c_1 and c_2, where $0 \leq c_1 , c_2 \leq 2$. The global best, $\hat{y}^t$, is the position with the best performance within the swarm; the personal best, y^t, is the best position the particle has visited since the first step, associated with particle i.

The linear PSO is guaranteed to always meet the set of linear constraints; however, a constraint handling mechanis m is required for the upper and lower bound constraints. The percentages distributed to each section of the weaving segment is bounded by upper and lower limits, where $0 \leq x_j \leq 1$ for each x_j, j= 1, $\cdots$, n for n dimensions in $\bar{x}$. To control the exploration of the particles, the velocities have been clamped to stay within the upper and lower limits. The residual percentages, resulting from velocities exceeding the maximum allowed velocity in dimension j, are distributed randomly to dimensions whose velocity satisfy the constraints. Hence, the velocity equation will ensure the solutions remain within the feasible domain.

The pseudocode for the proposed algorithm is presented in Fig. 4.

```
Algorithm PSO
Input PSO parameters
Create and initialize swarm
Begin
  For each particle do
    Initialize position
    Compute fitness values
    p_best = fitness value
    Initialize velocity
  End
  Choose the particle with best fitness value in the population. Call it g_best
  Do
    For each particle
      Apply the velocity
      Update fitness value
      If the fitness value is better than p_best then
        p_best = fitness value
      End If
    End For
  Update g_best
  While Stopping condition not satisfied
End
```

Fig. 4. Pseudocode of particleswarm optimization algorithm.

5. Experimental settings and results

This section presents the experimental settings relating to the optimization algorithm. The experimental results show two aspects from the experiment. Firstly, the performance of the optimization algorithm in minimizing the fitness function is evaluated. Then, using the optimized lane-changing distribution, the performance of the motorway weaving segment in the case study is evaluated. Lastly, the findings of the experiment are presented.

5.1. Optimization algorithmsettings

The optimization algorithm settings are defined by its PSO parameters. The algorithm has been modified from the original PSO algorithm in order to handle the constraints of the problem; however, the input parameters remain the same as those of the original PSO.

Each particle in the swarm represents a lane-changing distribution for RF and FR vehicles, assigned in Step 4 (Fig. 2). Each dimension of the particle represents a percentage of the lane-changing distribution, assigned to each section. The lane-changing distribution for RF and FR vehicles are optimized separately. In all experiments the

inertia weight ω was set to 0.7, while the values of c_1 and c_2 were set to 1.5. The initial swarms were initialized such that $\sum \bar{x}_i$= 1 holds for each particle in the swarm. The swarm size was set to 10 particles. The number of iterations was set to 50 with a stall iteration limit of 10. The PSO will stall if there is no improvement to the global best.

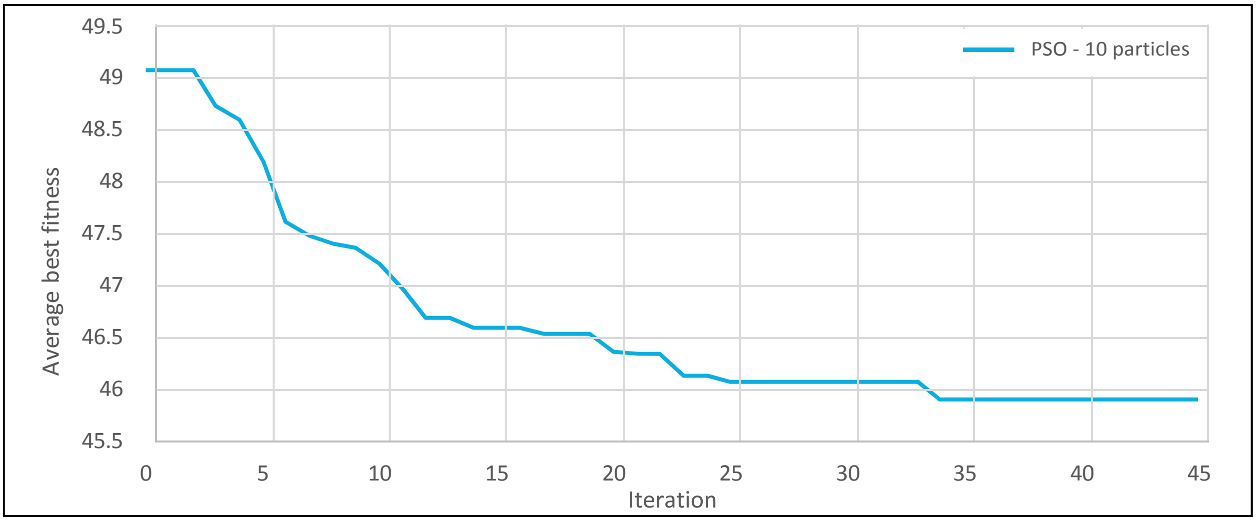

Fig. 5. Results of the average best fitness.

5.2. Results

The proposed optimization algorithm was tested to optimize the performance indicator described in Section 3.4. The performance indicator was calculated using the output of the traffic simulation, which was used for the fitness evaluation of the algorithm. The algorithm was tested for one replication of the microscopic simulation. The averages over 10 simulations of the algorithm were used to assess its performance. The average best values, shown to converge on the minimum after 35 iterations, is displayed in Fig. 5.

The average, maximum, minimum and standard deviation of the best fitness values, at the final generation over 10 simulations, are shown in Table 1. Although the global minimum cannot be guaranteed, these results indicate that the optimization algorithm seems to converge near a minimum fitness value.

Table 1. Results of 10 simulations.

PSO	10 particles
Average	45.905
Maximum	47.945
Minimum	44.415
Standard Deviation	1.146

The results of the optimized lane-changing distributions were compared with the base case (the ʻdo nothingʼ case), whereby the C-ITS advisory has not been implemented. The optimized case represents the C-ITS advisory control with an optimal lane-changing distribution, as assigned in Step 4. Therefore, the proposed optimization algorithm was used to seek the optimal solution of the distribution percentage for weaving vehicles.

Let RF% and FR% indicate the lane-changing distributions for ramp-to-freeway and freeway-to-ramp, respectively. The minimum average speed was averaged over 20 replications for each case. The minimum average speed over the entire segment for the base case was 51km/h. The best minimum average speed found by the algorithm was 62.4km/h. The lane-changing distributions that give the best evaluation for the performance indicator are as follows:

- RF% = [14%, 0%, 14%, 11%, 5%, 6%, 21%, 29%, 0%, 0%]
- FR% = [30%, 7%, 3%, 9%, 22%, 27%, 3%, 0%, 0%, 0%]

Table 2. Average delay comparison.

Movement	FF	FR	RF	RR	Average
Travel timein free flowconditions (s/veh)	55.2	49.7	45.5	40.1	
Traffic volume(veh)	5300	900	900	100	
Delay in base case (s/veh)	22.68	29.11	11.96	5.84	17.4
Delay in optimized case (s/veh)	14.67	16.04	12.56	5.98	12.31
Percentage improvement	35%	45%	-5%	-2%	29%

Table 2 shows the average delay comparison between the optimized and base cases. It can be seen that, on average, the optimized case has reduced delay. The ramp movements (RF and RR) experience greater delay in the optimized case. However, the freeway movements (FR and FF) experience significantly better improvement to the average delay.

The time-mean speeds over the auxiliary lane and lane 3 (adjacent freeway lane) are shown in Fig. 6 and Fig. 7, respectively. These two lanes are selected because they are the most turbulent in terms of lane-changing activity. The distance is shown from upstream, before entering the segment, to downstream of the weaving segment. As it can be seen from the figures, the speed drop in both the auxiliary lane and lane 3 is more severe in the base c ase where there is no C-ITS advisory control. The base case shows a significant drop in speed on the auxiliary lane close to the entrance of the weaving segment (0-50m). The lane 3 speed profile shows a similar slowing down entering the weaving segment and speeding up further downstream. This clearly indicates the bottleneck formation caused by the lane-changing concentration. This bottleneck formation, where vehicles slow down significantly, can cause congestion due to excessive braking near the weaving entrance area. The optimized case shows a smooth speed curve in comparison for both lanes. This indicates that the lane-changing concentration problem was alleviated effectively, with the speed profile remaining relatively flat throughout the weaving segment .

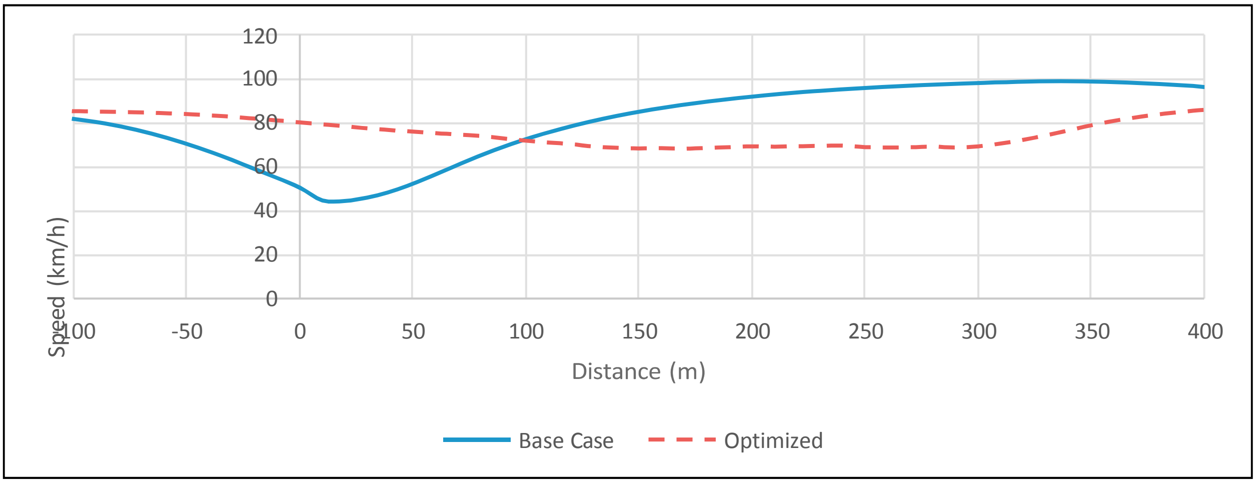

Fig. 6. Time mean speed overauxiliary lane.

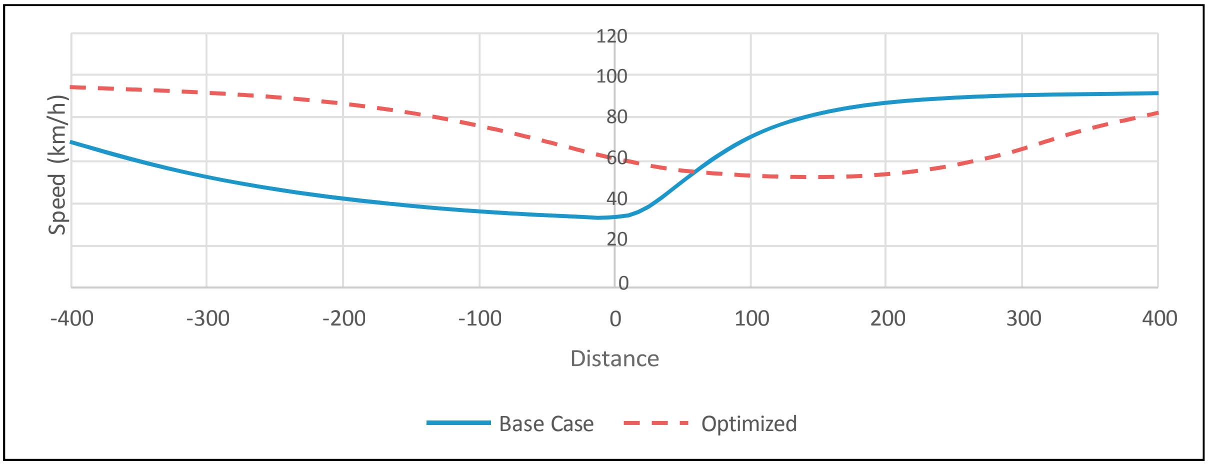

Fig. 7. Time mean speed over lane 3.

5.3. Experimental Findings

The main findings from the experimental results are summarized as follows:

- The proposed optimization algorithm has been tested as a successful optimization technique for the lane - changing concentration problem.
- The fitness value was occasionally found to converge prematurely and stall over multiple iterations. Therefore, the PSO parameters need to be adjusted to allow the algorithm to perform better.
- Missed turns were observed during the traffic simulation. Therefore, the missed turns penalty function needs be adjusted to account for this in the performance indicator.
- A sensitivity analysis needs to be performed to test the results of the optimization algorithm under different demand conditions.

The findings from these initial experimental results demonstrate the current work in progress of the optimization algorithm. They will inform and motivate the direction for future work.

6. Conclusion

In this paper an optimization algorithm was proposed and evaluated for the optimization of lane-changing distribution for a motorway weaving segment. It was observed from empirical research that a lane-changing concentration problem occurs in weaving segments close to capacity. The spatial distribution of lane changes was found to be concentrated near the entrance, at times as soon as vehicles enter the segment. This behavior generally leads to congestion and reduces the weaving capacity. A C-ITS advisory was shown to alleviate the problem by distributing lane changes along the entire segment according to fixed distributions. This paper introduced an optimization algorithm, based on PSO, to improve the lane-changing distribution for weaving vehicles. The findings show that the optimization algorithm is successful in improving the lane-changing distribution, considering the constraints of the problem. The evaluation of the case study revealed that the optimized lane-changing distribution significantly improved delay.

Findings indicate that further improvement to the optimization algorithm is necessary. Also, different performance indicators may be tested for future work, to measure the improvement of the weaving performance. It has been clear that the results rely on several assumptions. Therefore, future work would need to test these assumptions more comprehensively. Although field tests would provide more accurate outcomes, the evaluation from the traffic simulation shows improved efficiency for a weaving segment when optimizing the lane-changing distribution. This paper concludes that the proposed optimization technique can be used to optimize the lane - changing distribution in a motorway weaving segment.

Acknowledgements

The author would like to acknowledge the Department of Transport and Main Roads, Queensland, for providing the support to perform this research under the Study and Research Assisted Scheme.

References

Al-Jameel, H., 2013. "Characteristics of the Driver Behaviour in Weaving Sections: Empirical Study." *International Journal of Engineering Research and Technology* 2 (11): 1430-1446.

Barceló, J., 2010. *Fundamentals of traffic simulation.* New York: Springer.

Cassidy, M.J., May, A.D., 1991. "Proposed analytical technique for estimating capacity and level of service of major freeway weaving sections."
Transportation Research Record: Journal of the Transportation Research Board (1320): 99-109.

Mezura-Montes, E., Coello, C.A., 2002. "Constraint-handling in genetic algorithms through the use of dominance-based tournament selection."
Swarm and Evolutionary Computation 1 (2011): 173-194.

Denny, R.W., Williams, J.C., 2005. "Capacity and Quality of Service of Weaving Zones." *Final Report, National Cooperative Highway Research Program, Project 3-55.*

Eberhart, R., Kennedy, J., 1995. "A new optimizer using particle swarm theory." *Proceedings of the sixth international symposium on micro machine and human science* 1: 39-43.

Green, D., Bennett, P., Han, C., Faber, F., Ballingall, S., 2014. "Cooperativeintelligent transport systems (C-ITS)-an overviewof the ARRB/Austroads C-ITS work program 2010-2013." *Road & Transport Research: A Journal of Australian and New Zealand Researchand Practice* 23 (2): 15-28.

ho Lee, J., 2008. "Observations on Traffic Behavior in Freeway Weaving Bottlenecks: Empirical Study and Theoretical Modeling." PhD diss. ProQuest.

Kanazawa, F., Kanoshima, H., Sakai, K., Suzuki, K., 2010. "Field operational tests of Smartway in Japan." *IATSS research* 34(1): 31-34. Kwon, E., Lau, R., Aswegan, J., 2000. "Maximum possible weaving volume for effective operations of ramp-weave areas: Online estimation."
Transportation Research Record: Journal of the Transportation Research Board (1727): 132-141.

Mai, T., Jiang, R., Chung, E., 2016. "A Cooperative Intelligent Transport Systems (C-ITS)-based lane-changing advisory for weaving sections."
Journal of Advanced Transportation. Accessed April 6, 2016. doi: 10.1002/atr.1373.

Paquet, U., Engelbrecht, A.P., 2003. "A new particle swarm optimiser for linearly constrained optimization." *IEEE*, 227-233.

Transport for NSW., 2015. "Cooperative Intelligent Transport Systems". Image Accessed March 28, 2016.
http://roadsafety.transport.nsw.gov.au/research/roadsafetytechnology/cits/index.html

TRB (Transportation Research Board)., 2010. *HCM2010 Highway Capacity Manual.* Washington D.C.: Transportation Research Board.

Weiss, C., 2011. "V2X communication in Europe–From research projects towards standardization and field testing of vehicle communication technology." *Computer Networks*, 55 (14): 3103-3119.