FIELD EVALUATION OF PASSING SIGHT DISTANCE PARAMETERS

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ABSTRACT

Drivers require a sufficient distance on a two-lane highway to ensure that they can safely maneuver past an impeding vehicle. The passing behaviour of drivers is an important element of safe passing maneuvers. In this paper, field studies were conducted in different countries to determine the passing behaviour of drivers. The study involved participants of both genders in different age groups. A passing profile was established using experimental data collected by Dual Camera Car DVRs and a GPS data logger device that records the instantaneous speeds and positions of different passing vehicles. Using the collected data, linear regression models were established for the initial time, passing time, and acceleration of the passing vehicles. The independent variables of the models were driver gender, age, driving experience, and average weekly driving hours. A passing sight distance (PSD) model was then developed using the mechanics of passing maneuvers on two-lane highways. The results of the proposed model were compared with those of the design guides and existing models. The comparison revealed that the existing PSD models are either too liberal or too conservative. The proposed PSD model, which reflects current driver behavior, should be of interest to highway designers.

Keywords: Passing sight distance; driver behavior, modeling.

1. INTRODUCTION

Adequate passing sight distance (PSD) should be provided to ensure improved safety of passing drivers on two-lane highways. PSD criteria are provided in the design of two-lane highways to allow a faster driver to pass a slower driver when there is a passing gap in the opposing traffic. The PSD criteria used in geometric design were established using many different models. These models include the AASHTO model (2004), the MUTCD model (FHWA, 2003), and models developed by Glennon (1988), Hassan et al. (1996), Jenkins and Rilett (2005), and El Khoury and Hobeika (2007). There is a large amount of variability in the results of these models (FHWA, 2003). The PSD criteria established are based on different assumptions about the specific distances to be included in PSD as well as other assumptions regarding the speed, acceleration, deceleration, and clearance distance used for passing. The elements of a passing maneuver are shown in Fig.1.

To illustrate, AASHTO (2004) developed the following model for the calculation of PSD based on field studies conducted prior to 1958:

\[ \text{PSD} = d_1 + d_2 + d_3 + d_4 \]

\[ d_1 = 0.278 t_1 (v - m + \frac{a t_1}{2}) \]

\[ d_2 = 0.278 v t_2 \]

where \(d_1\) = distance travelled by the passing vehicle during the perception-reaction times and during acceleration towards the encroachment point along the left lane (the time elapsed = \(t_1, s\)); \(d_2\) = distance travelled by the passing vehicle as it occupies the left lane (the time elapsed = \(t_2, s\)); \(d_3\) = clearance distance between the passing vehicle and
opposing vehicle at the end of the pass; \( d_4 = \) distance travelled from the opposing vehicle within two-thirds of the time a passing vehicle will occupy the left lane = \( 2/3\left(t_4 = 2/3\left(t_2\right), s\right) \); \( v \) = average speed of the passing vehicle (km/h); \( a \) = average acceleration (km/h/s); and \( m \) = speed difference between passing and impeding vehicles (km/h).

The purpose of this study was to develop a PSD model that reflects current driver behaviour in passing manoeuvres. In this regard, regression models for the initial time, passing time, and acceleration were developed using field observations. The remainder of this paper will describe the data collection and analysis, PSD parameter estimation, and details regarding the developed PSD model. A comparison between existing PSD models and the proposed model and a discussion of the variability of key parameters are then presented, followed by concluding remarks.

![Figure 1: Geometry of the Passing Maneuver](image)

2. DATA COLLECTION AND ANALYSIS

Field data were collected at four passing zones on a two-lane highway at three different sites: Abu Dhabi and Sharjah in UAE, and Muscat in Oman. The length of the passing zones ranged from 300 m to 1200 m. The lane width for each direction ranged from 3.5 m to 4 m. All data were collected during off-peak times on roads with good pavement conditions and good weather. The traffic flow rates ranged from 100 to 250 veh/hr. The sites with low flow rates were selected because the sites with higher flow rates resulted in limited passing manoeuvres, according to research conducted by Harwood et al. (2010). The speed limit of the study highways was 80 km/hr. Travel time and speed for each vehicle was recorded in 1 s time intervals using HD in-vehicle video cameras and GPS data loggers with accuracy levels below 1 km/hr. The total number of passing manoeuvres observed at all passing zones was 105. The sample was randomly selected from each group of passing drivers and included 17 male and 8 female drivers between the ages of 20 and 63 years. The mean age was 34 years with a standard deviation of 13 years. Table 1 shows the results of the field data collected for all passing manoeuvres.

The analysis of the field data involved the following assumptions regarding passing manoeuvres: (1) the passing vehicle moves at a constant speed during the perception and reaction times before applying the gas pedal and accelerating, (2) the passing vehicle continues to accelerate at a constant rate (acc) until it reaches the maximum speed at the highest speed point, and (3) once the passing vehicle decelerates within a constant rate (dec), it returns to the right lane. In their respective PSD models, Glennon (1988) and Hassan et al. (1996) assumed that the driver’s perception reaction time (PRT) prior to beginning a pass is equal to 1 s. In addition, the minimum time headway between the passing and impeding vehicles at the end of a completed passing manoeuvre (hi) and the minimum time headway between the passing and opposing vehicles at the end of a completed passing manoeuvre (h) are both 1 s.

The passing vehicle speed (\( V_p \)), impeding vehicle speed (\( V_i \)), and opposing vehicle speed (\( V_o \)) were recorded in 1 s time intervals using the GPS data logger (installed inside each vehicle). The starting time (\( t_1 \)) is defined as the time from the moment when a passing vehicle decides to complete the pass and moves the vehicle to cross the centreline towards the left lane (s). The starting gap time \( G_s \) is defined as the time from the moment when a passing vehicle begins to cross the centreline towards the left lane until it reaches the critical point (s). The passing time (\( t_2 \)) is defined as the time from the moment when a passing vehicle begins to cross the centreline towards the left lane and travels in the left lane to the moment it crosses the centreline and returns to the right lane (s). TTC is defined as the time between the opposing and passing vehicles when the passing vehicle completes the pass and drives back to the right lane (s), TRA-960-2
The passing maneuver parameters of field study for the passing vehicles that started crossing the centreline towards the left lane and reaching the critical point, then travelling in the left lane and crossing the centreline and reaching the opposing vehicle, respectively. This information was used to determine the starting gap time, end gap time and time to collision. The passing vehicle speed ($V_p$), impeding vehicle speed ($V_l$) and opposing vehicle speed ($V_o$) were recorded in 1 s time intervals using the GPS data logger (installed inside each vehicle) with an error rate below 1 km/hr. The distance from when the passing vehicle initiated the pass, distance moved from the moment of crossing the centreline towards the left lane, distance to reach the critical point, distance occupying the left lane to the moment the vehicle returned to the right lane, and the distance when the opposing vehicle moved during the passing maneuver were also measured using the GPS data logger (in meters).

In this paper, the data for $G_e$, $t_2$ and TTC were recorded using a Smartphone by pressing “Start” and “Lap” when analyzing the video camera for passing vehicles that started crossing the centreline towards the left lane and reaching the critical point, then travelling in the left lane and crossing the centreline and reaching the opposing vehicle, respectively. This information was used to determine the starting gap time, end gap time and time to collision. The distance travelled by the passing vehicle as it occupies the left lane ($d$), the distance when the opposing vehicle moved during the passing maneuver were also measured using the GPS data logger (in meters).

The observed field data for each variable (Table 1) were analyzed for the passing ($V_p$), impeding ($V_l$) and opposing ($V_o$) vehicle speed, the speed differential ($m$), passing vehicle length ($L_p$), impeding vehicle length ($L_i$), time headway between the passing vehicle and opposing vehicle at the end of the pass ($h$), average acceleration ($acc$), average deceleration ($dec$), the time of initial maneuver ($t_1$), time passing vehicle travels in the left lane ($t_2$), start gap time ($G_s$), the end gap time ($G_e$), total passing gap ($G_p$), time to collision (TTC), distance travelled by the passing vehicle during the perception-reaction times and during acceleration towards the encroachment point along the left lane ($d_1$), distance travelled by the passing vehicle as it occupies the left lane ($d_2$), clearance distance between the passing vehicle and opposing vehicle at the end of the pass ($d_3$), distance travelled from the opposing vehicle ($d_4$), and total passing sight distance ($d$). Table 1 presents the mean ($\mu$), standard deviation (SD), and coefficient of variation (COV) for all 105 passing maneuvers. The passing maneuver parameters are consistent with those obtained in previous research conducted by AASHTO (2004) and Jenkins and Rilett (2005).

When analyzing the passing maneuver parameters using AT RISK software (Palisade Corporation, 2013), the passing vehicle speed, $V_p = 23.5$ m/s, suggested by AASHTO (2004), is consistent with the speed of the observed field data (95th percentile). The coefficient of correlation between $m$ and speed, $pm_m$, is 0.691. The positive sign for this coefficient is logical because $m$ is expected to increase as the passing vehicle speed increases. A comparison of the elements of the PSD of the AASHTO model and the model proposed in this study is presented in Table 2.
3. PSD PARAMETER ESTIMATION

Linear regression models for initiating the passing time \( t_1 \) and passing time \( t_2 \) were developed using SAS software (2013) based on the field data collected for the development of the proposed model. Twenty five drivers participated in this study and a total of 105 observations were collected. A modified PSD model was also developed using the same field data. The development of regression models for the new parameters is presented in the following sections.

3.1. Initial Passing Time \( (t_1) \)

Regression analysis was performed for model \( t_1 \) for normal driving conditions. The independent variables were the drivers’ gender, age, driving experience, average weekly driving hours, and the speed difference. The repeated measures ANOVA revealed many significant variables which affect \( t_1 \) during different passing maneuvers. Several variable combinations were verified in order to develop models for \( t_1 \) in kinematic conditions. The linear model was developed as follows:

\[
[4] \quad t_1 = 3.8102 + 0.1002 \text{Gender} + 0.0209 \text{Age} - 0.0252 \text{Exp} - 0.0202 \text{Awh} - 0.0356 \text{m}
\]

where \( t_1 \) = initial passing time (s), \( \text{Age} \) = passing vehicle driver age (years), \( \text{Gender} \) = passing vehicle driver gender (0 for males and 1 for females), \( \text{Exp} \) = passing driver driving experience (years), \( \text{Awh} \) = passing vehicle driver weekly driving hours (hours), and \( m \) = speed difference (m/s). The results indicated that, at a 95% significance level, the speed difference \( m \) explained a suitable amount of the difference in the speed decrease \( (F = 0.7) \). The estimated slope of the linear regression line was considerably significant \( (t = -0.84, \text{p-value} = 0.41) \). The model Root MSE is 0.59; F-value is 4.06; and \( \text{Pr} > F \) is <.0001. These results indicate that an increase in the initial passing time during the passing maneuver is linearly related to \( m \) at the moment of starting initial acceleration.

To ensure acceptable performance of the proposed model, the model considered the initial time of the passing driver, which is the time required by the driver to initiate the passing maneuver. To obtain precise measurements of this time, field data were collected using different drivers who were selected from various countries. The initial time was then measured from the moment the driver began to react and initiate the passing maneuver. The mean of the initial time was 3.6 s and the standard deviation was 0.6 s. The 95% of the observations were less than 4.5 s. The value (3.6 s) could therefore be used.

3.2. Passing Time \( (t_2) \)

Regression analysis was performed for model \( t_2 \) for normal driving conditions. The independent variables were the drivers’ gender, age, driving experience, average weekly driving hours, and passing vehicle. The repeated measures ANOVA revealed many significant variables which affect \( t_2 \) during different passing maneuvers. Several variable combinations were verified in order to develop models for \( t_2 \) in kinematic conditions. The linear model was developed as follows:

\[
[4] \quad t_2 = 3.8102 + 0.1002 \text{Gender} + 0.0209 \text{Age} - 0.0252 \text{Exp} - 0.0202 \text{Awh} - 0.0356 \text{m}
\]

where \( t_2 \) = passing time (s), \( \text{Age} \) = passing vehicle age (years), \( \text{Gender} \) = passing vehicle gender (0 for males and 1 for females), \( \text{Exp} \) = passing driver driving experience (years), \( \text{Awh} \) = passing vehicle driver weekly driving hours (hours), and \( m \) = speed difference (m/s). The results indicated that, at a 95% significance level, the speed difference \( m \) explained a suitable amount of the difference in the speed decrease \( (F = 0.7) \). The estimated slope of the linear regression line was considerably significant \( (t = -0.84, \text{p-value} = 0.41) \). The model Root MSE is 0.59; F-value is 4.06; and \( \text{Pr} > F \) is <.0001. These results indicate that an increase in the initial passing time during the passing maneuver is linearly related to \( m \) at the moment of starting initial acceleration.

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### Table 2: Comparison of the Elements of PSD Model

<table>
<thead>
<tr>
<th>Variables</th>
<th>AASHTO</th>
<th>Proposed Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passing speed, ( V_p ) (m/s)</td>
<td>23.5</td>
<td>20.1</td>
</tr>
<tr>
<td>Speed difference, ( m ) (m/s)</td>
<td>4.2</td>
<td>3.7</td>
</tr>
<tr>
<td>Average acceleration, ( a ) (m/s^2)</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Initial time, ( t_1 ) (s)</td>
<td>4.3</td>
<td>3.6</td>
</tr>
<tr>
<td>Time occupation of left lane, ( t_2 ) (s)</td>
<td>10.7</td>
<td>9.6</td>
</tr>
<tr>
<td>Distance traveled during Initial maneuver, ( d_1 ) (m)</td>
<td>89.0</td>
<td>62.5</td>
</tr>
<tr>
<td>Distance traveled during occupation of left lane, ( d_2 ) (m)</td>
<td>251.0</td>
<td>200.8</td>
</tr>
<tr>
<td>Clearance distance, ( d_3 ) (m)</td>
<td>75.0</td>
<td>36.6</td>
</tr>
<tr>
<td>Opposing vehicle distance traveled, ( d_4 ) (m)</td>
<td>168.0</td>
<td>97.1</td>
</tr>
<tr>
<td>Total distance (m), ( d_1 + d_2 + d_3 + d_4 )</td>
<td>583.0</td>
<td>396.9</td>
</tr>
</tbody>
</table>
combinations were verified in order to develop models for $t_2$ in kinematic conditions. The linear model was developed as follows:

$$[5] \quad t_2 = 8.968 + 3.515 \text{Gender} + 0.223 \text{Age} - 0.303 \text{Exp} - 0.166 \text{Awh} - 0.111 Vp$$

where $t_2$ = passing vehicle time when occupying the left lane (s), and $Vp$ = passing vehicle speed (m/s). The results indicated that, at a 95% significance level, the passing vehicle speed ($Vp$) explained a suitable amount of the difference in the speed decrease ($F = 1.60$). The estimated slope of the regression line was considerably significant ($t = -1.26$, p-value $= 0.21$). The model Root MSE is 1.89; F-value is 15.33; and Pr > F is <.0001. These results indicate that an increase in the passing time during the passing maneuver is linearly related to $Vp$ at the moment of starting initial acceleration. The passing time was then measured from the moment the driver crossed the centreline towards the left lane until the moment the driver crossed the centreline to return to the right lane. The mean of the passing time was 9.6 s and the standard deviation was 2.5 s. The 95% of the observations were less than 14.6 s. The value (9.6 s) could therefore be used.

### 3.3 Acceleration Rate (acc)

Regression analysis was performed for model acc for normal driving conditions. The independent variables were the drivers’ gender, age, driving experience and average weekly driving hours. The repeated measures ANOVA revealed many significant variables which affect acc during different passing maneuvers. Several variable combinations were verified in order to develop models for acc in kinematic conditions. The linear model was developed as follows:

$$[6] \quad acc = 0.7032 - 0.0874 \text{Gender} - 0.0015 \text{Age} + 0.0009 \text{Exp} + 0.0003 \text{Awh}$$

where $acc$ = passing vehicle acceleration rate ($\text{m/s}^2$). The results indicated that, at a 95% significance level, the model Root MSE is 0.30; F-value is 0.46; and Pr $> F$ is <.0001. These results indicate that increases in the passing vehicle acceleration rate during the passing maneuver are linearly related to the drivers’ gender, age, driving experience and average weekly driving hours at the moment of initial acceleration.

### 4. PASSING SIGHT DISTANCE MODEL DEVELOPMENT

The components of the proposed passing sight distance model are illustrated in Fig. 1. The distances $d_1$ and $d_2$ of the proposed PSD model are similar to those of the AASHTO model (Eq. 1) and are given by

$$[7] \quad d_1 = t_1 \left(v_p - m + \frac{a t_1}{2}\right)$$

$$[8] \quad d_2 = v_p t_2$$

However, the distances, $d_3$ and $d_4$ are represented by

$$[9] \quad d_3 = h(v_p + v_o)$$

$$[10] \quad d_4 = t_o v_o$$

where $PSD$ = passing sight distance (m); $v_p$ and $v_o$ = passing and opposing vehicle speed during the passing maneuver (m/s), respectively; $t_1 =$ initiated time that the passing vehicle travelled during perception-reaction time and acceleration towards crossing the left lane (s); $t_2 =$ time that the passing vehicle occupied the left lane (s); $h =$ time headway at the end of passing (s); $a =$ average acceleration (m/s$^2$); $t_o = t_2 - G_o =$ the opposing vehicle time (s). Note that $t_o$ is calculated based on the AASHTO (2004) and TAC (2007), as described by Harwood et al. (1998) and Hassan et al. (1996). As previously explained, the passing and opposing vehicle speeds are considered to determine the passing maneuver on a two-lane highway. PSD is computed using the following equation:

$$[11] \quad PSD = t_1 \left(v_p - m + \frac{a t_1}{2}\right) + t_2 v_p + h(v_p + v_o) + t_o v_o$$

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where $PSD =$ passing sight distance (m) and $v_p =$ passing vehicle speed (m/s). The differential speed, $m$, was found to be a constant of 4.2 m/s (15 km/h) based on the AASHTO design guide. Conversely, based on the field studies, the $m$ variable was calculated by Glennon (1988) and Hassan et al. (1996) as follows

$$[12] \quad m = 24 - \frac{v_d}{10}$$

where $m =$ speed differential (km/h), and $v_d =$ design speed (km/h). In this study, $m = v_p - v_l$ based on the field data. The proposed PSD model uses the field data which correspond to a design speed of 80 km/h for the safety margin with respect to the minimum PSD calculation.

5. DISCUSSION AND COMPARISON

There is a reasonable explanation for choosing the parameters of the regression models. For the models of $t_1$, and $t_2$, a positive sign for the gender parameter indicates that female drivers take a longer time than male drivers under similar conditions. A positive sign for the age parameter indicates that time will increase with age, which is consistent with the results obtained in previous research conducted by Mehmood and Easa (2009). A negative sign for the driver experience and average weekly driver hour parameters indicates that drivers with high experience and average weekly hours take less time than drivers with less experience and less weekly hours under similar conditions, which is consistent with the results obtained in previous research conducted by Mehmood and Easa (2009).

Table 3 compares the mean values of the proposed PSD model with those of AASHTO (2004), MUTCD (2003), Glennon (1988), Hassan et al. (1996) and El Khoury and Hobeika (2007) for a design speed of 80 km/h. The comparison shows the improved mean of the proposed model, however, the AASHTO model is more conservative when compared to the other PSD models.

<table>
<thead>
<tr>
<th>Element</th>
<th>PSD (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AASHTO (2004)</td>
<td>538.0</td>
</tr>
<tr>
<td>MUTCD (2003)</td>
<td>245.0</td>
</tr>
<tr>
<td>Glennon (1988)</td>
<td>253.0</td>
</tr>
<tr>
<td>Hassan et al. (1996)</td>
<td>297.0</td>
</tr>
<tr>
<td>El Khoury (2007)</td>
<td>211.2</td>
</tr>
<tr>
<td>Proposed Model</td>
<td>396.9</td>
</tr>
</tbody>
</table>

6. VARIABILITY OF KEY VARIABLES

Passing maneuvers are complicated and the passing driver must make a number of decisions that are based on the prevailing passing conditions. The driver chooses the size gap within the opposing traffic, the distance to follow behind the impeding vehicle, and the distance they should leave in front of the impeding vehicle when returning to the right lane. The driver also chooses when they begin to accelerate, the rate at which they accelerate, when they begin to decelerate, and the rate at which they will decelerate. The primary motivation for passing maneuvers is the desire to maintain a particular travelling speed. A passing driver will overtake an impeding vehicle by travelling at a higher speed within the opposing traffic lane. If there are no oncoming vehicles in the opposing lane, the passing driver may choose to continue passing the impeding vehicle at a constant speed or accelerate to minimize the time spent in the left lane. If there are oncoming vehicles in the left lane, the driver must slow down and follow the impeding vehicle until they have the opportunity to pass. Before the completion of the passing maneuver, the passing driver may choose to decelerate to a desired travel speed.

Field data for many passing maneuvers were examined in order to identify whether or not a test driver should begin to accelerate and then begin to decelerate. The acceleration began once a passing vehicle moved towards the left lane. The deceleration began before the passing vehicle moved back into the right lane, which is consistent with the results obtained in previous research conducted by Jenkins (2004). A DFT of passing vehicle speed ($v_p$) duration for passing...
maneuvers is provided in Fig. 2a. The passing vehicle speed duration distribution was normal with a mean of 20.1 m/s and a standard deviation of 2.4 m/s. All of the results were obtained using the Kolmogorov-Smirnov test (Z = 0.10). A DFT of the time of initial maneuver (t₁) duration for passing maneuvers is provided in Fig. 2b. The time of initial maneuver duration distribution was normal with a mean of 3.6 s and a standard deviation of 0.6 s. All of the results were obtained using the Kolmogorov-Smirnov test (Z = 0.15).

A DFT of the time passing vehicle travels in the left lane (t₂) duration for passing maneuvers is provided in Fig. 2c. The time passing vehicle travels in the left lane duration distribution was lognormal with a mean of 9.6 s and a standard deviation of 2.5 s. All of the results were obtained using the Kolmogorov-Smirnov test (Z = 0.09). A DFT of the average acceleration (acc) duration for passing maneuvers is provided in Fig. 2d. The average acceleration duration distribution was normal with a mean of 0.61 m/s² and a standard deviation of 0.30 m/s². All of the results were obtained using the Kolmogorov-Smirnov test (Z = 0.12). The distribution shows the variability of the passing vehicle speed, the time of initial maneuver, the time that the passing vehicle travels in the left lane, and the average acceleration of drivers during passing maneuvers.

Figure 2: Density functions of observed passing maneuver field data: (a) passing vehicle speed (m/s); (b) time of initial maneuver (s); (c) time the passing vehicle travels in the left lane (s); and (d) average acceleration (m/s²).

7. CONCLUSIONS

This study presents a new methodology for the study of passing maneuvers: in-vehicle video data recording and a GPS data logger. These methods provide improved video image quality and allow for the determination of complete trajectories with increased accuracy. This methodology allowed the researchers to obtain passing maneuver data with increased efficiency and accuracy. This study investigated the effect of driver behaviour on passing maneuvers and presented a regression model for passing time, both of which are necessary elements of passing maneuvers. The driver factors included gender, age, driving experience and average weekly driving hours. The analysis demonstrated that new variables can be introduced into the model. One of these new variables was ℎ for the clearance distance. The drivers who have more time to make a pass extend the distance travelled in the left lane, affecting PSD. The inclusion of this variable makes the model suitable for PSD criteria. This research study presents design procedures that account for variations in all contributing parameters within the PSD formulation.

A new PSD model for two-lane highways is presented in this paper. The results were validated for a design speed of 80 km/h. The proposed model is more conservative than the MUTCD, Glennon and El Khoury models, however, the AASHTO model overestimate the PSD design requirement design. This study has some limitations. This study is based on only 25 participants and a larger number of participants will certainly improve parameter estimation. In addition, the PSD model was developed using only one set of field data for a design speeds of 80 km/h, and more field
data should be collected to further confirm the model and update the PSD parameters. Future research should extend the analysis to include speed data on highways with design speeds ranging from 70 to 90 km/h. These data could then be added to the distribution for each design speed. In addition, a reliability analysis should be conducted to improve PSD design requirements.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. Dabbour and Dr. Felemban for their help in the data collection in Abu Dhabi, UAE and in Mecca, Saudi Arabia, respectively. The financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) is acknowledged.

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