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主 論 文 の 要 旨

論文題目 A STUDY ON MERGING BEHAVIOR AT URBAN EXPRESSWAY MERGING SECTIONS

（都市内高速道路流入部におけるドライバーの合流行動に関する研究）

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論 文 内 容 の 要 旨

The merging section is a key point on the expressway networks. It is regarded as a potential bottleneck and a source of traffic crashes due to the competition of two traffic flows for the same space. Therefore, its operations in terms of efficiency and safety are becoming increasingly important concerns. A lot of geometric layouts or control strategies have been applied to improve its operations. However, in order to reduce the implementation cost of the proposals of new geometric layouts or control strategies, it is necessary to find out a tool to evaluate any proposal before its actual implementation.

In the last few decades, the microscopic traffic simulation models (MTSMs) have been widely used as effective tools to evaluate the operational policy or new geometric design in terms of efficiency and/or safety of traffic facilities including the merging sections. However, to get reasonable evaluation results, it is very important to take into account of various influencing factors (*e. g.* traffic conditions, geometry, and individual reactions of merging vehicles to the mainline vehicles) on driver behavior for providing a more realistic representation of traffic operation. Unfortunately, at merging sections, the existing simulation models cannot precisely represent driver behavior under those influencing factors.

Driver behavior study at merging sections is a classical topic and it has been studied since the late 1930s. Even though, it still remains as a challenging topic. In the past, numerous studies were carried out to investigate driver behavior at merging sections. However, various influencing factors such as those mentioned above have not been thoroughly considered.

In another aspect, the existing guidelines are based on the design speed of on-ramp and expressway to estimate a minimum length of acceleration lane by assuming the traffic condition is free flow. However, operational conditions may be different from the assumed one. In reality, traffic congestion can occur due to unexpected increasing traffic demand, traffic accident and so on. Therefore, the proposed design of existing guidelines may lead to some biases that cannot satisfy driver expectation for all the cases of operational traffic conditions. On the other hand, it is necessary to design the length of acceleration lane from a safety point of view.

Therefore, this study tries to cover the gaps and limitations mentioned above by analyzing the behavior of merging vehicles and developing their behavior models taking into account of mainline traffic conditions, geometry of merging sections and reaction of the merging vehicles to the mainline vehicles. The study is based on microscopic vehicle trajectories extracted from video data. The video data were collected on two urban expressway merging sections in Nagoya City, Japan with wide ranges in geometries and traffic conditions. Moreover, the video data is utilized to explore the discrepancies between the observed data and assumed values of existing guidelines and assess the performance of merging sections from safety and efficiency points of view.

In **Chapter 1**, background information about basic issues of layout design and traffic operation is discussed. In addition, comprehensive discussions on potential applications of MTSMs for the evaluation of new geometric design and operational policies at merging sections and drawbacks of existing MTSMs are given. On the other hand, the necessity to get insights about driver behavior at urban expressway merging sections is deeply stated. Additionally, problem statement, objectives as well as research outlines are described.

Chapter 2 gives in-depth reviews of design methodology of existing guidelines and driver behavior studies at merging sections to further understand current problems. It is concluded that the existing methodology is based on a simplified assumption without considering the operational conditions. This might lead to some biases of driver expectation and therefore, it might cause safety problems or deteriorations of merging section capacity. As for state-of-the-art of driver behavior studies at merging sections, it is found that the geometry of merging section and traffic conditions have not been thoroughly studied yet. It is because there is lack of microscopic vehicle trajectory data with a wide range of geometric and traffic conditions. Moreover, several popular and frequently used MTSMs are reviewed to deeply get insights the drawbacks of existing MTSMs. The strength of each MTSM is briefly discussed. And the main behavior models incorporated in the existing MTSMs *e.g.* car-following and lane-changing are carefully examined. The results show that there are no models dedicated for merging areas. Therefore, the MTSMs cannot precisely reproduce driver behavior under effects of geometric and traffic conditions of merging sections.

On the other hand, **Chapter 2** gives an overview of the performance assessment of at merging sections including efficiency and safety assessments. As for efficiency, the density is usually adopted as indicator to assess the efficiency performance of merging sections (HCM, 2010). Other indicators include flow rate, delay, average travel speed, free flow speed and space. However, none of those indicators take into account effects of individual merging vehicles on the mainline vehicles. Therefore, it is needed to find out an indicator that can consider the effects of merging vehicles at a microscopic level. On the other hand, to assess the safety performance, there are two main ways. Those are historical crash data-based method and traffic conflict technique. The traffic conflict technique has some advantages over the traditional crash-based method for safety assessment e.g. frequency of occurrence and its short time requirement of observation. The conflicts can be extracted from video data or they can be employed from MTSMs. However, to achieve the realistic results, it is necessary to incorporate realistic behavior inside MTSMs to capture the variation of road user in real world conditions. Moreover, some crucial models need to be added as well.

Chapter 3 describes geometric and traffic characteristics of study sites as well as the data collection and processing. Two study sites on Nagoya Expressway route No. 3 were chosen. At both of the sites, the acceleration lanes are located in the middle of expressway carriageways and they were extended in October 2011. In addition, during the extensions, the acceleration lanes were slightly shortened due to construction work. Therefore, at each of the site, there exist three situations including "before", "during" and "after" the extensions. The video data were collected at the sites covering all situations of "before", "during" and "after" by using cameras positioned on the top of high building near to the sites. The video were recorded under different times of the day and days of the week in order to cover wide ranges of traffic conditions. From video data, microscopic vehicle trajectories were extracted by using an image processing technique. The microscopic vehicle trajectory data under various traffic conditions and wide ranges of acceleration lane length provide this study a good basis. On the other hand, **Chapter 3** also gives explanations of how to consider the effects of traffic conditions. In this study, the density of mainline traffic for each individual merging vehicle is adopted to take into account effects of traffic conditions.

In **Chapter 4**, an overview of the whole maneuvers of not only merging vehicles but also mainline vehicles are firstly presented. After that, the classification of gap choices of merging vehicles is given. The gap choices are divided into three types named "direct-", "chase-" and "yield-merging". Then the contents of this chapter deal with the analyses of driver behavior under consideration of geometric and traffic conditions. The effects of geometric as well as traffic conditions are quantitatively figured out. The results of this chapter will start a good step towards the following chapter. It is found that merging vehicles tend to reject the adjacent gap to yield mainline vehicles under low density conditions. Contrarily, when the density becomes higher, merging vehicles are prone to reject the adjacent gap to overtake the mainline vehicles. The analysis of relationship between relative space and relative speed indicates that merging vehicles choose a merging pattern depending on a certain *TTC* threshold. Moreover, it is found that both of the yield and chase choices result in further merging position compared to direct one. In general, it is concluded that the longer acceleration lane results in further merging positions. Furthermore, the traffic conditions do not significantly affect the means of merging positions but their variations. A similar tendency can be observed if acceleration lane length becomes longer. The analysis results indicate that the initial speeds are slightly influenced by traffic conditions but not acceleration lane length. As for merging speed, it is found that mainline traffic conditions significantly affect merging speeds.

Chapter 5 generalizes the analysis results from **Chapter 4**. Three models including gap choices, speed adjustment and merging maneuvers (merging position and speed) are proposed. After the choices of merging vehicles (direct-, chase- and yield-merging) can be determined by gap choice model, the speed adjustment and merging maneuvers are further developed for direct-, chase- and yield-merging, respectively. The concept of inverse Time to Collision (TTC^{-1}) is adopted as a variable for modeling gap choices and speed adjustment behavior. The inverse Time to Collision is estimated between the merging vehicle and the leading mainline vehicle as well as between the merging vehicle and the following mainline vehicle. Those are denoted TTC_L^{-1} and TTC_F^{-1}, respectively. Additionally, the geometry of merging sections and traffic conditions (density) are taken into account for all models.

The estimation and sensitivity analysis results indicate the decision of a merging vehicle decide to reject or accept the gap (choices) is significantly dependent upon TTC_L^{-1} and TTC_F^{-1}. Generally, the merging vehicles accept the gap in the cases of low potential collision with both the leading and following mainline vehicles. By contrast, they reject the gaps to avoid collision with the leading and following mainline vehicles. In addition, the speed adjustment models show that the longer acceleration lane results in a higher acceleration rate of merging vehicles. And the denser mainline traffic causes a lower that of merging vehicles. It is found that if TTC_L^{-1} is negative, merging vehicles increase their acceleration rate. On the contrary, if TTC_L^{-1} becomes positive and the collision can happen, merging vehicles tend to reduce acceleration rate to avoid the collision with leading mainline vehicles. In case of TTC_F^{-1}, the positive signs of coefficients indicate that when following mainline vehicles run faster than merging vehicles, they increase their acceleration rate to avoid collision with following mainline vehicles. Furthermore, a normal distribution was adopted to fit the models of merging position and speed. The results of model estimation and sensitivity analysis indicate that the models give consistent results with the analysis presented in **Chapter 4**.

Chapter 6 examines the discrepancies between assumed values of existing guidelines and observed ones including initial speed and merging speed. It is found that the assumed initial speeds are lower than the observed ones under all traffic conditions: low, medium or high densities. In addition, it is concluded that the assumed initial speed of Japanese guideline results in less discrepancies than that of AASHTO. On the other hand, the analysis of merging speed demonstrates that the assumed values by both AASHTO and Japanese guideline are lower than the average values of observed ones for the conditions of low and medium density. By contrast, in the case of high density, the assumed speeds of both of guidelines are higher than that of observed one, except the case of AASHTO for the acceleration lane length of 365m. In general, it is concluded that the length of acceleration lane should be designed appropriately taking into consideration of the length required for acceleration for the merging vehicles under the low and medium density conditions. However, under high density condition, the design of acceleration lane should consider the opportunity for merging vehicles to safely merge without adversely affecting the mainline flow.

Chapter 6 also assesses the performance of merging sections from safety and efficiency point of views. The inverse Time to Collision is adopted to assess the safety performance. By collecting the conflicts between the merging vehicles with both the leading and following mainline vehicles at starting merging moment, the performance of merging sections from the safety point of view is assessed. It is found that the longer acceleration lane length lead to reduce not only the conflict possibilities ($TTC > 0$) but also the dangerous conflicts ($TTC <$ 4s). On the other hand, the results show that chase- and yield-merging involve in more possible and dangerous conflicts than the direct-one. Since the longer acceleration lane provide enough space for the merging vehicle to compete with the mainline vehicles to close speed differences between them, it makes the merging vehicles to have more probabilities of directly merging. This also explain why the longer acceleration lane can reduce the possible and dangerous conflicts between the merging vehicles and the corresponding mainline vehicles. On the other hand, the speed reduction percentage of mainline vehicles was proposed to assess the efficiency performance. It is concluded that the impacts of merging vehicles on mainline speed reduction become significant under high density condition. Regarding the length of acceleration lane, it is found that the effect of acceleration lane length on speed reduction of mainline vehicles under low density conditions is not noticeable. On contrary, under high density condition, the acceleration lane length has significant impacts on speed reduction of mainline vehicles due to merging vehicles. However, it seems long acceleration lane length exhibits more negative impacts on speed reduction percentage of mainline vehicles. However, this conclusion needs to be further investigated.

Finally, **Chapter 7** gives research conclusions and provides some recommendations for future works. Generally, the contributions of this study can be summarized as follows. (i) The existing studies, operational policies, design methodology and MTSMs were carefully reviewed. And then, the some drawbacks and limitations were figured out. (ii) By using the microscopic trajectory data, which have a special characteristic and have never existed in the literature, the effects of geometry and traffic conditions are thoroughly considered. The relationships among driver behavior (*i.e.* gap choice, speed adjustment, merging position, merging speed, etc.) and those influencing factors were in-depth explored. (iii) The driver behavior models including gap choice, speed adjustment, merging position and merging speed were developed. The developed models covered the whole maneuvers of merging vehicles. In addition, the models took into account of the reactions of merging vehicles toward the mainline vehicles. And the effects of geometry as well as traffic conditions were thoroughly considered for model development. Therefore, when the developed models will be incorporated in a MTSM, it is expected to improve the representation of traffic operations of existing MTSM at the merging sections. (iv) The inverse Time to Collision was newly added into the models of gap choice and speed adjustment in order to capture the reactions of merging vehicles from a safety point of view.

Although the study showed some positive contributions, it has limitations. These limitations open some directions for future works. (i) The study is limited to the local characteristics of study sites where the acceleration lanes are located in the right hand-side with the available ranges of acceleration lane lengths from 170 to 365m. In future, collecting data of left hand-side entrances with more ranges of acceleration lane lengths to generalize the analysis results and model estimations is necessary. (ii) Since only the leading merging vehicles were considered in this study, the analysis results and proposed models may not appropriately applied for the following merging vehicles. The behavior of the following merging vehicles is much more complicated than that of the leading merging vehicles. Because the following merging vehicles have to react not only to the mainline vehicles but also to the leading merging vehicles. Therefore, data collection of the following merging vehicles are necessary to verify how different it is between the leading merging vehicles and the following merging vehicles. (iii) The gap choice model in this study only considered the situation in which a single vehicle merges into one gap. However, in the real world, two vehicles or more can merge into one gap and it causes more and more negative impacts on the mainline vehicles.

This situation might usually happen when the merging vehicles come to the acceleration lane within a platoon. (iv) In this study, the mainline vehicle maneuvers have not been considered. However, to archive a more realistic representation of traffic operations at merging sections, the mainline vehicle maneuvers need to be further analyzed and model as well. (v) This study did not consider the heavy vehicles and the study is, therefore, limited to only passenger cars. Future work should take heavy vehicles into consideration for the analysis and modeling. (vi) Finally, the safety and efficiency performance assessment of merging sections were based on the data were extracted from vehicle trajectory. Although the results showed a tendency, they are limited to the sample size, available ranges of acceleration lane lengths and traffic conditions at the study sites. Moreover, there are contradictions of extending the length of acceleration lane from safety and efficiency points of view. One suggests that it would reduce conflict probabilities while the other one seems to imply the deterioration of merging section efficiency. Therefore, it is thought that it may exist an optimal acceleration lane length which satisfies both safety and efficiency. In the future, after improving the limitations mentioned above and by incorporating all necessary models into an MTSM, it is possible to find out the optimal acceleration lane based on the data employed from the MTSM.