Simulation Evaluation of Cooperative Intersection Traversing Method for Connected Vehicles

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INTRODUCTION
Connected Vehicles (CVs)

- Connected to network
- Communicate and share information with other vehicles (V2V) or roadside infrastructures (V2I)

Image Source: PHYS.org
Autonomous Driving with Connected Vehicles

- **Safe Driving Support**
  - Detect other vehicles near an intersection
  - Give way to an emergency vehicle
  - Detect pedestrians in blind spots

- **Connected Vehicles & Autonomous Driving Technology**
  ⇒ Cooperative, Safe and Efficient Traffic

Images Source: ITS Connect Promotion Consortium
Problem

However...

Connected vehicles and Non-Connected vehicles will be mixed and share the same roads

CVs can know other CVs’ information (position, speed, and etc.)
cannot know Non-CVs’ information

Need method to share and use information of Non-CVs
Purpose

- Target an intersection with mixed CVs and Non-CVs
- Propose a method for CVs to share information about the presence of Non-CVs near the intersection via V2V
- Consider safety and evaluate traffic flow efficiency
RELATED WORK
Related Work - 1

- Collective Perception
  - CVs with radar sensors and Non-CVs share the same road
  - CVs share the position information of surrounding vehicles detected by its sensor
  - CVs can perceive the position of many vehicles around 300 m (at 70% penetration rate, over 90% of all vehicles was perceived)

Image Source: Towards Automatic Driving – Collective Perception

Safety and Efficiency of Connected Vehicles Traversing an Intersection

- CVs get the position and speed of other CVs via V2V communication
- determine whether it is safe to enter an intersection without stopping to check for oncoming vehicles
- Travel time of vehicles was reduced compared with traffic right control and stop sign control

We consider mixed situation with CVs and Non-CVs

PROPOSED METHOD
Communication Procedure

Can enter the intersection?
If vehicle(s) is in the danger range **Unsafe (Not Traversable)**
Otherwise **Safe (Traversable)**
Communication Procedure

Broadcast constantly to CVs on the non-priority road
Traversable Example

No vehicle in the danger range
→ Transmit "Traversable Message"
"Traversable Message" from all relevant lanes → Enter the Intersection
There are vehicle(s) in the danger range → Transmit "Not Traversable Message"
Even one "Not Traversable Message"
→ Stop before the intersection

Stop!
Not Traversable Example - 2

Cannot sense vehicle(s) in the danger range → Not transmit message

Sensor coverage area
Ex.) 200 m
Not Traversable Example - 2

Cannot confirm safety
→ Stop before the intersection
Intersection Danger Range
- the range in which a vehicle on a non-priority road may collide with a vehicle on the priority road upon entering the intersection.

The length is calculated using speed limit of the priority road and Time-To-Collision (TTC).

\[ v_p \cdot t_{TTC} \]

- \( v_p \): Speed limit of the priority road [m/s]
- \( t_{TTC} \): TTC [s]
Assumed Connected Vehicles

- Autonomous Vehicles (AVs)
- Human-operated Vehicles (HVs)
  - Information is notified to drivers through onboard equipment and drivers make decisions and perform operations

The length of the intersection danger range (= TTC) differs between AVs and HVs!

- AVs need only small TTC if there are no collisions
- HVs need more time margin to prevent surprising drivers
Drivers on HVs surprised by vehicles entering the intersection from the non-priority road → Lead sudden brake, traffic jams and collisions
Safety with Intersection Danger Range - 4

- The minimum TTC for connected vehicles on the priority road to transmit traversable messages
  - Autonomous Vehicles
    - the maximum time required for a vehicle on a non-priority road to traverse an intersection: 3.5 s
  - Human-operated Vehicles
    - Above 3.5 s + Time margin to prevent drivers from being surprised: 1.5 s
    - $=5.0 \text{ s}$
The minimum TTC for connected vehicles on the priority road to transmit traversable messages

Autonomous Vehicles
- the maximum time required for a vehicle on a non-priority road to traverse an intersection: 3.5 s

Human-operated Vehicles
- Above 3.5 s +
  Time margin to prevent drivers from being surprised: 1.5 s
  $= 5.0$ s
Safety with Intersection Danger Range - 5

- Time margin to prevent drivers from being surprised

【Reference Study】
Analyzed the relationship between the TTC for a pedestrian and the driver’s surprise when a pedestrian suddenly started crossing the road

Less surprise \( \text{TTC} \geq 1.5 \text{ s} \)

※Although the target was a pedestrian, the situation is similar to that of vehicles entering from intersecting roads

EVALUATION
Prerequisites

Connected Vehicles in simulation experiment

- Can communicate with other CVs within a radius of 250 m ※1
- Communication frequency is 100 ms ※1
- Equipped with radar sensor that can detect a vehicle 200 m in front and behind ※2

※1 in accordance with MIC "ITS communication requirements", ETSI "Cooperative Awareness Message", and SAE "Basic Safety Message"

※2 Matching the performance of in-vehicle millimeter wave radar sensor in practical use
Simulation Environment - 1

- Simulator
  PTV Vissim 9
  - A microscopic multi-modal traffic flow simulator developed by Planung Transport Verkehr AG, Germany
  - Supports the Component Object Model (COM) interface
  - Programmed the operation of CVs with script files
Simulation Environment - 2

- Layout of the intersection used for evaluation simulation
Evaluation Indexes

- **Travel Time Delay**
  1. Time taken for a vehicle to traverse measurement section (actual travel time)
  2. Time taken to traverse the same section without stopping when entering the intersection (ideal travel time)

  Evaluate the difference between the actual time and the ideal time ($1 - 2$)

- **Maximum Queue Length**
  - the maximum length of the traffic queue at the intersection
# Simulation Settings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed limit</td>
<td>Priority Road: 50 km/h</td>
</tr>
<tr>
<td></td>
<td>Non-Priority Road: 40 km/h</td>
</tr>
<tr>
<td>Ratio of vehicles (Priority : Non-Priority)</td>
<td>3 : 1</td>
</tr>
<tr>
<td>Lane width</td>
<td>3.5 m</td>
</tr>
<tr>
<td>Measurement time × number</td>
<td>30 minutes × 10</td>
</tr>
<tr>
<td>Minimum TTC to transmit traversable message</td>
<td>Autonomous: 3.5 s</td>
</tr>
<tr>
<td></td>
<td>Human-operated: 5.0 s</td>
</tr>
<tr>
<td></td>
<td>(3.5 s + 1.5 s time margin)</td>
</tr>
</tbody>
</table>
Comparison with Conventional Methods

- Two Conventional Models

Stop model: The conventional intersection with stop signs

Traffic light model: The conventional intersection with traffic lights
Simulation Parameter

- Traffic volume
  - The number of vehicles per lane per hour

- Penetration rate of Connected Vehicles
Simulation Running – Color Classification

Non-Connected Vehicle
Simulation Running – Color Classification

Connected Vehicle transmitting traversable message
Simulation Running – Color Classification

Connected Vehicle transmitting not-traversable message
Simulation Running – Color Classification

Connected Vehicle not receiving or transmitting message
Simulation Running – Color Classification

Connected Vehicle judging that can enter the intersection
Simulation Running – Color Classification

Connected Vehicle judging that cannot enter the intersection
Simulation Running - Movie
RESULTS
Comparison of Travel Time Delay

- Traffic volume: 500 vehicles/h
- Penetration rate: 70%

Our method was the smallest
Comparison of Maximum Queue Length

- Traffic volume: 500 vehicles/h
- Penetration rate: 70%

Our method was the smallest (Straight or left turn lane)
Change in Travel Time Delay with Traffic Volume

- Penetration rate: 70%

Traffic light model was the smallest around 500 vehicles/h. Our method was the smallest around 550 vehicles/h.
Decrease in Travel Time Delay with Penetration Rate

- Traffic volume: 500 vehicles/h
- expressed as relative values (with 0 % penetration rate being 1.00)

Decreased monotonically as penetration rate increased
  - When 50 % penetration rate: 30 % down
  - When 90 % penetration rate: 50 % down

30 % penetration rate or more lower than the traffic light model
DISCUSSION
DISCUSSION

- Intersection traffic efficiency was improved by our method
  - Traffic volume ~500 vehicles/h
    - effective at intersections with average traffic volume
  - Penetration rate of CVs 30 %~
    - effective even during the early stages of connected vehicles introduction
  - Our method uses only V2V communication
    - no need to install and maintain roadside devices such as traffic lights

- Efficiency was not improved at intersections with heavy traffic
  - Need another advanced method at Intersections in urban areas

- Safety can be ensured by setting the TTC dynamically in accordance with characteristics of drivers and vehicles
CONCLUSION
CONCLUSION

- **Background**
  - Connected Vehicles and autonomous driving technology
  - Looking ahead to the time when CVs and Non-CVs will share the same road

- **Purpose**
  - We developed a method that enables CVs traverse the intersection efficiently based on information from other CVs in the mixed CVs and Non-CVs situation

- **Evaluation**
  - Using a traffic flow simulator
  - Compared with conventional intersection mediation method

- **Result**
  - Our method improve efficiency of average traffic volume intersections and can ensure safety
Thank You for Your Kind Attention!

For any question or comment, please contact koki.higashiyama@nislab.doshisha.ac.jp