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A CELLULAR AUTOMATON FOR TRAFFIC JAM CAUSED BY RAILROAD CROSSING [a]

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A cellular automaton has been used to simulate traffic flow and it has been shown that a cellular automaton is useful to simulate traffic flow. Kashii Sando in Fukuoka City is known as a notoriously busy road with a busy railroad crossing. Therefore, we focus on the road and introduce a cellular automaton model to simulate the bottleneck situation due to the embarrassing railroad crossing. Following the traffic regulations in Japan, we have to stop in front of the railroad crossing even if no train is in the railroad crossing. Then we introduce parameters for the stop time of cars in front of the crossing when no train is in the crossing. Furthermore, parameters such as traffic volume are introduced and set based on the real traffic data. Three types of experiments are performed, each of which has the same total interception time by the crossing. We show that a traffic jam is considerably affected by the time that cars are stopped at the crossing and the railroad crossing signal is effective to reduce traffic jam for Kashii Sando.

Keywords: cellular automaton, traffic jam, railroad crossing.

1 Introduction

Kashii Sando (Figure 1), which crosses Japan National Route 3 and leads to Kashii-gu, the historic Shinto shrine located in Fukuoka City, has one lane in each direction. Though the road is about 1 kilometer long, the road is indispensable for neighbors to enter the Route 3. The intersection of Route 3 and Kashii Sando is designated as a serious traffic jam area by Fukuoka City in 2013.

The traffic jam on Kashii Sando is caused by multiple bottleneck situations. One of the causes is the torii, which is a guard frame of Kashii-gu that straddles the road and disturbs the flow of traffic. We also have the intersection next to the railroad crossing without a traffic signal, which worsens the traffic flow on Kashii Sando (Figure 2, Figure 3). Furthermore, the crossing gate on Kashii Sando comes down frequently by the train passing. In Japan, traffic regulations state that cars must always stop in front of a railroad crossing, even if a train is not there. However, if there is a railroad crossing signal which is an interlock system with

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Fig. 1. Photo of traffic jam on Kashii Sando

Fig. 2. Photo of the railroad crossing on Kashii Sando

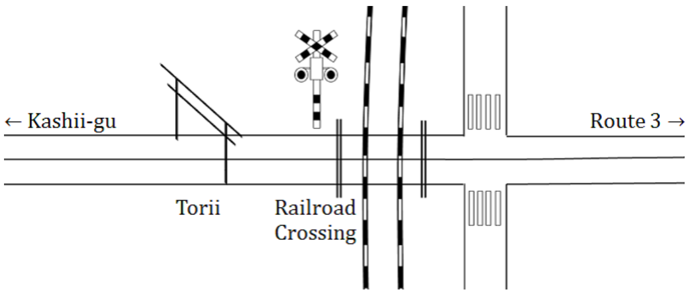

Fig. 3. Illustration of Kashii Sando

the railroad crossing, then we only need to follow the signal. That is, if the go-ahead signal is displayed, then we have no need to stop in front of the crossing. If the stop signal is displayed then a train is approaching and we have to stop in front of the crossing. Unfortunately, the railroad crossing on Kashii Sando is without that function. Therefore, from the above obstacles, we expect that the traffic jam on Kashii Sando is mainly caused by the railroad crossing.

On the other hand, cellular automaton introduced by John von Neumann [1], is known as a simple computing model consisting of cells each of which is in one of a finite number of states. In discrete time steps, each cell alters its state depending on the current states of the cell itself and a surrounding neighborhood of cells.

Comprehensive studies of cellular automaton have advanced including on their algorithmic aspects, computability and universality, and the simulation approach. On the simulation approach, cellular automata have been used for simulating traffic jam.

In this research, we focus on the railroad crossing and analyze the traffic jams on Kashii Sando by a cellular automaton. We introduce a parameter for car stop time in front of the crossing into our model in case a train is not there. Furthermore, parameters such as traffic volume are introduced and set based on the real traffic data.

2 Preliminaries

In order to demonstrate traffic flow using cellular automaton, we give some preliminaries of cellular automata and description of our model.

2.1 Cellular Automaton

A cellular automaton is a discrete computing model using the array of *cells* and a *local rule* (see [2], [3] for details). Each *state* of a cell is changed by the local rule at discrete time steps, starting with the *initial states*. The local rule is a function of the current states of the cell and its neighboring cells. A *radius* determines the range of the neighborhood.

Especially, one-dimensional cellular automaton has previously been used to simulate traffic jams [3],[4],[5]. The most basic model of traffic simulations is Wolfram's Rule 184 [3], in which the finite set of states is $\{0, 1\}$ and the radius is 1. A cell occupied by a vehicle is expressed by 1, otherwise by 0. If no vehicle is in front of the cell, that is, if the front cell is 0, then the vehicle moves forward one cell in one step without considering acceleration. Otherwise, the vehicle stays in the cell.

The local rule is described as follows:

$$s_i(t+1) = \begin{cases} s_{i-1}(t) & \text{if } s_i(t) = 0 \\ s_{i+1}(t) & \text{if } s_i(t) = 1, \end{cases}$$

where $s_i(t)$ is the state of the i-th cell at time t. In this paper, we construct a cellular automaton model based on Rule 184.

2.2 Description of the Kashii Sando Model

When we focus on only the railroad crossing, ignoring both the torii and the intersection, we can focus on one lane of Kashii Sando, starting from Kashii-gu, across the railroad crossing, and until the intersection with Route 3.

As shown in Figure 4, we assume that the road consists of 103 cells in one-dimension including the one railroad crossing cell located on the 52nd cell. We assume that one cell is 8 meters and one time step is 1 second. In front of the railroad crossing cell, called the stop cell, vehicles must stop for some fixed time (*stop time*). If the stop time is 0, then we consider the case that we can go across the railroad crossing without stopping. In this case, we assume that a railroad crossing signal is installed and we are allowed to proceed without stopping when the go-ahead signal is displayed.

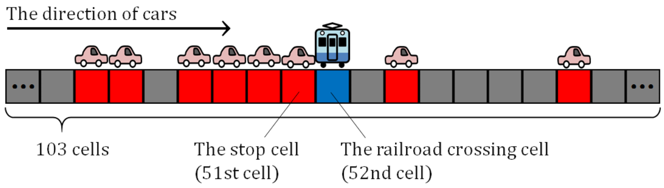

Fig. 4. Kashii Sando and railroad crossing represented by 103 cells

In this model, the *interval of interception* refers to the time interval between trains passing the railroad crossing, and the *interception time* refers to the time that a train blocks the railroad crossing.

The initial state of each cell is determined by the *initial vehicle probability*. Each cell is assigned either 1 (occupied by a vehicle) or 0 (vacant space) depending on this probability. A new vehicle enters the lane of Kashii Sando every *vehicle inflow time* steps, unless there is currently a vehicle in the 1st cell. The *average travel time* is the average number of steps for a vehicle to leave Kashii-gu and arrive at Route 3. The *travel number* is the number of vehicles that leave Kashii-gu and arrive at Route 3 in a specific time.

We apply the definition of a traffic jam given by the Japan Road Traffic Information Center (JARTIC) [6]. On an ordinary road, we say that a street has a *traffic jam* when the average speed of the cars is less than 10 kilometers per hour, and a street has *traffic congestion* when the average speed of the cars is less than 20 kilometers per hour. In this model, if the average travel time is more than 290.6 steps, then a street has a traffic jam, and if the average travel time is between 145.3 and 290.6 steps, then a street has traffic congestion.

3 Experiments and Analysis

First, we show an example of a simulation in Figure 5, in which the i-th row shows the road at the i-th time step. Each red cell corresponds to a vehicle, each black cell corresponds to a vacant space, and each blue cell corresponds to a train. Each vehicle moves forward (from left to right) across the railroad crossing. We set the number of time steps executed as 1759, which is converted into about 30 minutes, and we repeat each experiment 100 times.

We say that the average number of steps for a vehicle to leave Kashii-gu and arrive at Route 3, as *average travel time*. The *travel number* is the number of vehicles that leave Kashii-gu and arrive at Route 3 in a specific time.

We compare the average travel time, the travel number, and each standard deviation when vehicle inflow time V, initial vehicle probability I, and stop time S are varied. Based on real traffic data [7], we set $V = 4l$ $(1 \leq l \leq 3)$, $I = 0.2m$ $(1 \leq m \leq 4)$, and $S = 2n$ $(0 \leq n \leq 5)$.

According to our observation, the interception time at the railroad crossing caused by local train is about 60 seconds. From the train timetable, 10 trains usually pass the railroad crossing in a half hour. Based on this fact, we propose the following Experiment A. With the same total interception time, we present Experiment B and C. The following three experiments, sharing the same total interception time, are presented in the respective subsections:

Exp.A: We set the interval of interception as 160 steps, and the interception time as 60 steps. The total number of train passes is 10.

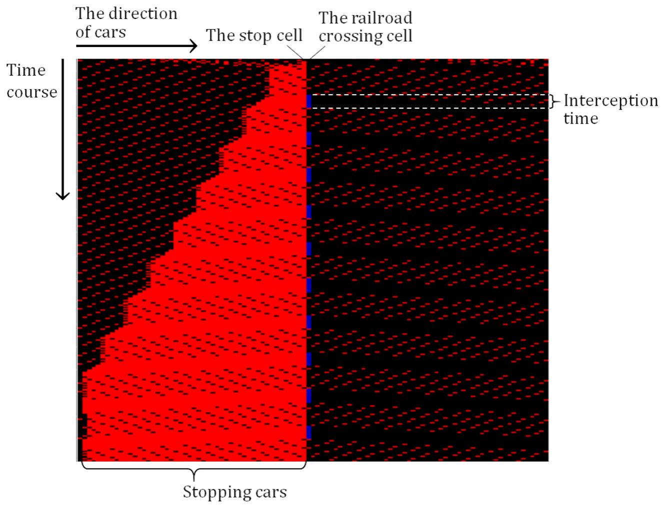

Fig. 5. Time-space diagram of Kashii Sando. $V = 12$ (steps), $I = 0.2$, $S = 10$ (steps)

Exp.B: We set the interval of interception as 320 steps, and the interception time as 120 steps. The total number of train passes is 5.

Exp.C: We set the interval of interception as random, and the interception time as 60 steps. The total number of train passes is 10.

In the following subsections, we describe each experiment and analysis.

3.1 Experiment A: Interval of Interception 160, Interception Time 60

In this experiment, ten trains pass the railroad crossing at the fixed intervals of 160 steps. Each interception time is set as 60 steps.

Table 1 (resp. Table 2) shows the average travel time (resp. standard deviation of average travel time) for each $V = 4l$ $(1 \leq l \leq 3)$, $I = 0.2m$ $(1 \leq m \leq 4)$, and $S = 2n$ $(0 \leq n \leq 5)$. By the definition of traffic jam and traffic congestion, the annotation indicates whether each case is in traffic jam, traffic congestion, or not by the definition of JARTIC.

From Table 1, we see that the average travel time decreases with the increase of the vehicle inflow time. Furthermore, the average travel time increases with the increase of the initial vehicle probability and the stop time. Obviously, with the increase of the average travel time, the street condition gets worse and it has traffic congestion then traffic jam.

As for standard deviation, a large part of the data in Table 2 indicates that the standard deviation increases with the increase of the initial vehicle probability, vehicle inflow time, and stop time.

Based on Table 1, Figure 6 (resp. Figure 7, and Figure 8) shows the average travel time for $I = 0.2m$ $(1 \leq m \leq 4)$ and $S = 2n$ $(0 \leq n \leq 5)$ with $V = 4$ (resp. $V = 8$ and $V = 12$). Figure 7 and Figure 8 imply that the stop time has little effect on the average travel time for $V = 8$ and $S = 0, 2$, and for $V = 12$ and $S = 0, 2, 4$ regardless of the initial vehicle probability.

As for the travel number in Experiment A, almost all the figures in Table 3 indicate that the travel number decreases with the increase of the vehicle inflow time. Furthermore, the

Table 1. Average travel time in Experiment A

V	I	S					
		0	2	4	6	8	10
4	0.2	192.9†	268.9†	393.1*	499.5*	621.4*	683.7*
4	0.4	193.9†	282.0†	419.7*	542.3*	680.5*	748.4*
4	0.6	205.8†	301.6*	449.1*	576.5*	741.7*	813.3*
4	0.8	229.3†	332.9*	485.9*	631.3*	802.3*	899.1*
8	0.2	121.1	125.3	239.0†	404.8*	533.2*	601.1*
8	0.4	123.5	127.7	304.6*	475.8*	626.4*	704.1*
8	0.6	128.4	137.9	383.3*	552.2*	708.0*	794.5*
8	0.8	154.3†	175.3†	454.1*	618.9*	795.5*	897.8*
12	0.2	116.1	119.7	127.5	169.3†	352.5*	433.6*
12	0.4	117.3	123.5	134.5	263.7†	482.1*	584.5*
12	0.6	131.5	133.5	173.8†	382.3*	627.9*	745.3*
12	0.8	157.0†	175.2†	251.5†	534.9*	766.8*	874.5*

* The street has a traffic jam.
† The street has traffic congestion.

Table 2. Standard deviation of average travel time in Experiment A

V	I	S					
		0	2	4	6	8	10
4	0.2	2.76	5.64	9.85	14.10	16.96	25.22
4	0.4	5.02	9.15	13.05	21.11	24.29	24.18
4	0.6	8.11	19.75	18.36	21.33	33.23	35.96
4	0.8	21.88	31.89	42.07	57.60	54.75	68.78
8	0.2	6.23	4.83	8.16	25.97	26.98	30.04
8	0.4	10.01	11.14	30.15	28.82	32.54	42.41
8	0.6	11.05	16.22	34.71	32.04	32.57	37.45
8	0.8	36.51	30.89	42.77	51.03	53.57	72.43
12	0.2	8.01	6.87	8.32	21.95	35.08	40.75
12	0.4	12.65	13.18	15.89	35.50	48.98	47.19
12	0.6	20.18	22.81	35.13	55.84	64.87	53.64
12	0.8	51.34	49.07	59.83	57.96	74.51	72.90

Table 3. Travel number in Experiment A

V	I	S = 0	2	4	6	8	10
4	0.2	349.3	263.3	176.3	132.2	100.1	87.6
4	0.4	349.3	257.1	167.7	123.2	91.1	78.9
4	0.6	344.6	247.8	158.6	113.5	81.3	69.2
4	0.8	329.0	234.2	147.6	103.3	71.8	58.7
8	0.2	207.2	205.2	174.0	132.2	100.4	87.7
8	0.4	207.3	205.3	167.1	123.6	90.9	78.1
8	0.6	207.5	205.5	157.8	113.3	81.6	68.4
8	0.8	206.7	205.1	147.7	103.2	71.6	58.7
12	0.2	138.2	137.1	136.2	130.3	100.2	88.4
12	0.4	138.4	137.4	136.4	123.0	90.9	78.8
12	0.6	138.6	137.6	136.5	113.9	82.1	68.5
12	0.8	138.4	137.4	136.6	103.3	71.7	58.4

travel number decreases with the increase of the initial vehicle probability and the stop time.

Figure 10 and Figure 11 imply that the stop time and the initial vehicle probability have little effect on the average travel time for $V = 8$ and $S = 0, 2$, and for $V = 12$ and $S = 0, 2, 4$ regardless of the initial vehicle probability, which is quite similar to the graphs of average travel time of Figure 7 and Figure 8.

As for standard deviation of travel number, each value in Table 4 is quite low in comparison to the one in Table 2. Therefore, the total number of vehicles which leave Kashii-gu and arrive at Route 3 in a specific time is stable, in contrast with that, the difference of travel time is quite extreme especially in the traffic jam.

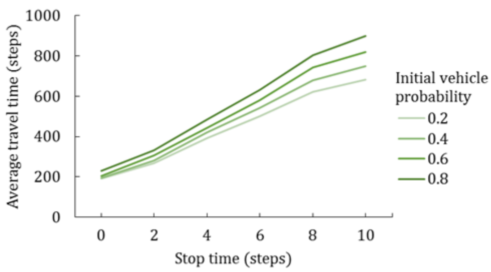

Fig. 6. Graph of average travel time from Table 1 for $V = 4$ (steps)

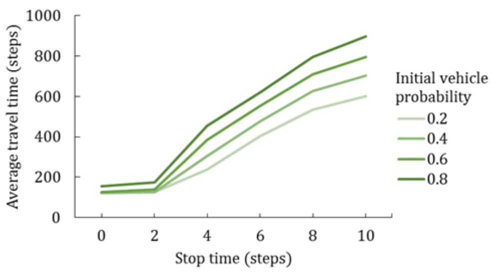

Fig. 7. Graph of average travel time from Table 1 for $V = 8$ (steps)

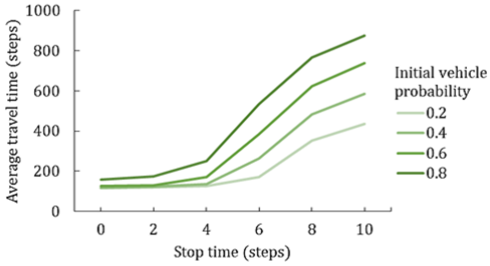

Fig. 8. Graph of average travel time from Table 1 for $V = 12$ (steps)

Table 4. Standard deviation of travel number in Experiment A

V	I	S					
		0	2	4	6	8	10
4	0.2	0.46	1.44	2.43	2.49	2.33	2.83
4	0.4	0.62	3.09	3.38	3.72	3.34	2.94
4	0.6	3.45	3.88	3.68	3.70	3.53	3.35
4	0.8	3.87	3.09	3.25	3.27	2.60	3.20
8	0.2	0.39	0.39	0.71	2.74	2.58	2.66
8	0.4	0.47	0.50	3.06	3.58	3.19	3.86
8	0.6	0.50	0.56	3.66	3.29	3.26	3.36
8	0.8	1.21	0.89	3.08	3.36	3.11	3.01
12	0.2	0.41	0.34	0.39	1.49	2.44	2.61
12	0.4	0.50	0.48	0.52	3.18	2.94	3.03
12	0.6	0.49	0.49	0.54	3.65	3.81	3.71
12	0.8	0.67	0.70	0.65	2.82	3.19	2.91

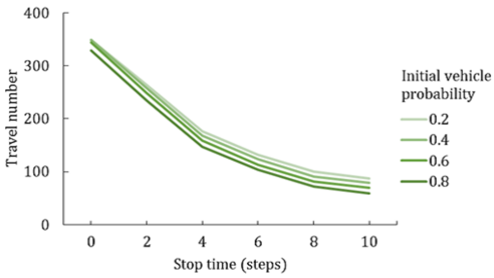

Fig. 9. Graph of travel number from Table 3 for $V = 4$ (steps)

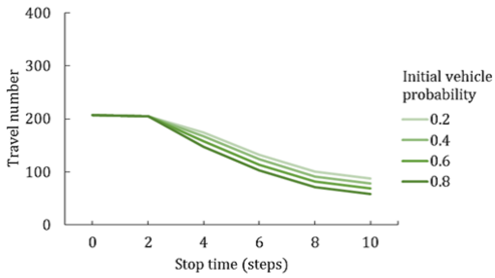

Fig. 10. Graph of travel number from Table 3 for $V = 8$ (steps)

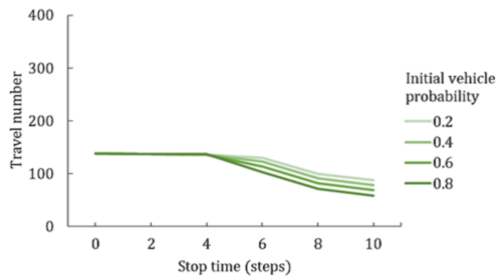

Fig. 11. Graph of travel number from Table 3 for $V = 12$ (steps)

3.2 Experiment B: Interval of Interception 320, Interception Time 120

In this experiment, we assume that the railroad gate comes down five times instead the interception time is twice as long as Experiment A.

Table 5 shows the average travel time for each $V = 4l$ $(1 \leq l \leq 3)$, $I = 0.2m$ $(1 \leq m \leq 4)$, and $S = 2n$ $(0 \leq n \leq 5)$ in Experiment B.

From Table 1 and Table 5, the tendencies of the average travel time is similar to those in Experiments A. By the annotation in Table 5, the traffic condition gets slightly worse than Experiment A.

Table 5. Average travel time in Experiment B

V	I	S					
		0	2	4	6	8	10
4	0.2	193.0†	277.4†	401.8*	526.7*	635.3*	719.6*
4	0.4	195.1†	291.2*	426.6*	569.9*	692.2*	802.3*
4	0.6	202.9†	307.7*	455.9*	603.4*	747.1*	875.6*
4	0.8	220.0†	333.4*	486.6*	661.3*	806.1*	957.6*
8	0.2	138.2	147.0†	270.4†	444.2*	548.6*	646.1*
8	0.4	140.3	148.2†	330.1*	514.7*	641.8*	748.7*
8	0.6	145.1	158.7†	399.7*	581.3*	729.3*	850.1*
8	0.8	177.5†	202.6†	454.8*	653.6*	814.6*	945.0*
12	0.2	129.5	136.3	148.9†	219.8†	378.7*	505.5*
12	0.4	132.4	138.3	158.4†	323.8*	515.8*	650.8*
12	0.6	144.2	147.8†	190.6†	445.6*	654.5*	793.4*
12	0.8	178.5†	178.8†	265.5†	590.6*	778.9*	920.9*

* The street has a traffic jam.
† The street has traffic congestion.

Actually the result of Experiment B is quite similar to the one of Experiment A, thus we omit here other results for Experiment B. See Appendix I for more results. Graphs of Table

5 are also in Appendix I.

3.3 Experiment C: Interval of Interception Random, Interception Time 60

In this experiment, we assume that the railroad gate comes down randomly ten times and each interception time is set as 60 steps.

Table 6 shows the average travel time for each $V = 4l$ $(1 \leq l \leq 3)$, $I = 0.2m$ $(1 \leq m \leq 4)$, and $S = 2n$ $(0 \leq n \leq 5)$ in Experiment C.

By the annotation in Table 6, the traffic condition gets slightly worse than Experiment A.

From Table 1 and Table 6, the tendencies of the average travel time is similar to those in Experiment A. Actually the result of Experiment C is quite similar to the one of Experiment A, thus we omit here other results for Experiment C. See Appendix II for more results.

Table 6. Average travel time in Experiment C

V	I	S					
		0	2	4	6	8	10
4	0.2	205.5†	277.9†	414.3*	542.5*	664.3*	765.7*
4	0.4	205.2†	290.2†	444.1*	589.5*	736.6*	852.3*
4	0.6	217.0†	315.9*	471.8*	628.9*	784.3*	921.8*
4	0.8	245.0†	335.6*	511.6*	670.6*	839.4*	995.8*
8	0.2	129.3	167.5†	324.3*	467.0*	589.4*	695.4*
8	0.4	134.5	167.7†	368.2*	542.0*	675.8*	797.3*
8	0.6	132.7	189.4†	419.9*	598.6*	753.8*	895.6*
8	0.8	166.2†	267.7†	482.2*	674.2*	832.6*	1001.9*
12	0.2	117.2	125.8	161.7†	289.9	455.9*	565.3*
12	0.4	120.6	126.7	184.4†	395.1*	577.8*	713.5*
12	0.6	126.8	136.6	262.1†	511.9*	697.8*	845.8*
12	0.8	172.6†	182.9†	377.1*	634.7*	816.5*	979.0*

4 Conclusion

In the present paper, we presented a cellular automaton model to simulate the traffic flow on Kashii Sando. We found that the street has a worse traffic jam when the stop time is longer. Our result concerning the stop time shows that the legally mandated stops in front of the railroad crossing cause serious traffic jams. Therefore, railroad crossing signals that reduce the stop times in front of the railroad crossing would help to reduce traffic jams. However, for the case that the car flow is extremely heavy, the reduction of stop times is no longer effective. This result implies that having railroad crossing signals is ineffective.

From the actual traffic data in Kashii Sando presented by Fukuoka City [7], when we convert the traffic data into the vehicle inflow time, it is almost in between 8 and 12. Therefore, the proposed use of crossing signals should be effective on Kashii Sando.

Our future work is to simulate and analyze the complicated simulation in Kashii Sando by taking into account the traffic flow of the crossing next to the railroad crossing and the torii, the guard frame.

Acknowledgment

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Appendix I: Experimental result for Experiment B

We show our experimental results for Experiment B in Subsection 3.2.

Figure 12, 13, 14 show the graphs of Table 5 for the average travel time. Table 7 shows the travel number in Experiment B. Figure 15, 16, 17 are the graphs of Table 7 for the travel number.

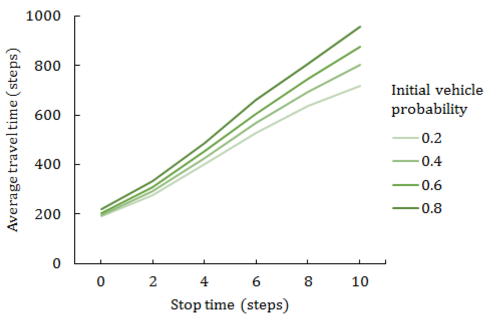

Fig. 12. Graph of average travel time from Table 5 for $V = 4$ (steps)

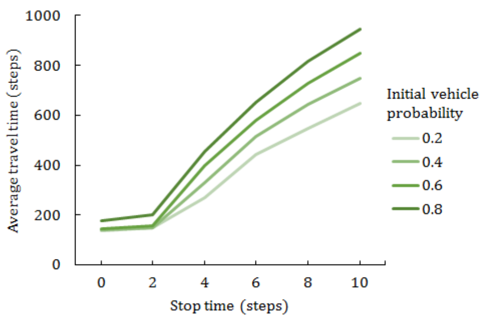

Fig. 13. Graph of average travel time from Table 5 for $V = 8$ (steps)

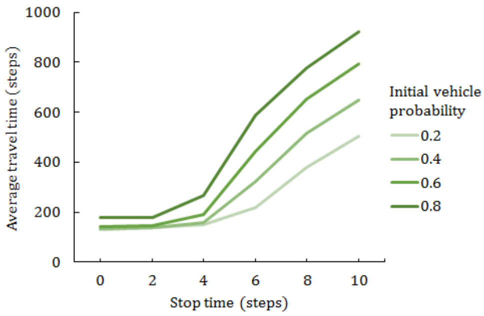

Fig. 14. Graph of average travel time from Table 5 for $V = 12$ (steps)

Table 7. Travel number in Experiment B

V	I	S 0	2	4	6	8	10
4	0.2	344.3	263.5	176.1	128.0	100.1	84.1
4	0.4	344.2	256.2	167.8	119.2	91.1	74.2
4	0.6	339.3	247.6	158.2	110.1	81.9	64.2
4	0.8	323.8	234.2	147.2	99.0	71.6	54.4
8	0.2	207.2	206.2	173.9	127.7	101.0	83.8
8	0.4	207.4	206.4	167.3	119.0	91.3	74.5
8	0.6	207.5	206.5	157.7	109.2	80.7	64.4
8	0.8	207.0	206.0	147.1	99.7	71.7	54.8
12	0.2	138.3	137.2	137.2	126.5	100.4	83.5
12	0.4	138.5	137.4	137.4	118.6	91.2	74.3
12	0.6	138.6	137.6	137.6	109.3	81.3	64.7
12	0.8	138.5	137.6	137.6	99.3	71.6	54.9

Appendix II: Experimental result for Experiment C

We show our experimental results for Experiment C in Subsection 3.3.

Figure 18, 19, 20 show the graphs of Table 6 for the average travel time. Table 8 shows the travel number in Experiment C. Figure 21, 22, 23 are the graphs of Table 3 for the travel number.

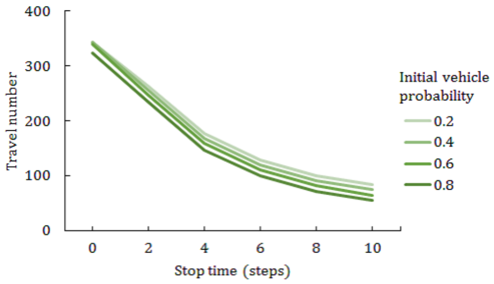

Fig. 15. Graph of travel number from Table 7 for $V = 4$ (steps)

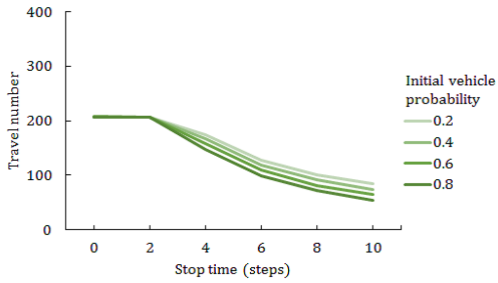

Fig. 16. Graph of travel number from Table 7 for $V = 8$ (steps)

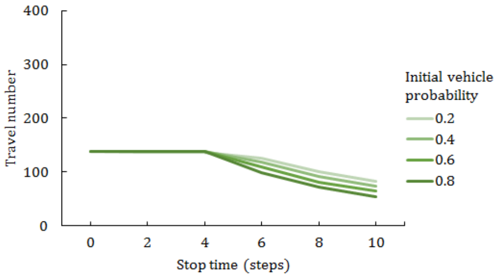

Fig. 17. Graph of travel number from Table 7 for $V = 12$ (steps)

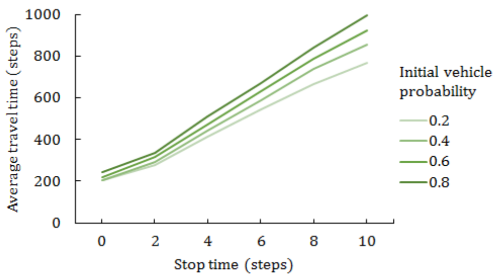

Fig. 18. Graph of average travel time from Table 6 for $V = 4$ (steps)

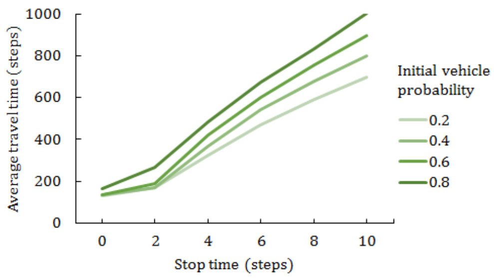

Fig. 19. Graph of average travel time from Table 6 for $V = 8$ (steps)

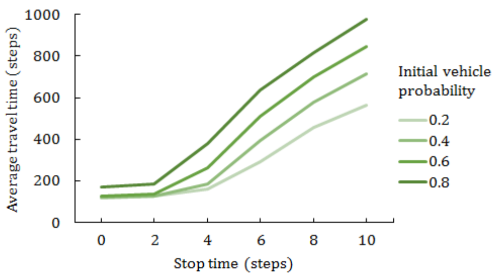

Fig. 20. Graph of average travel time from Table 6 for $V = 12$ (steps)

Table 8. Travel number in Experiment C

V	I	S = 0	2	4	6	8	10
4	0.2	328.5	266.5	177.2	131.8	104.2	86.4
4	0.4	328.3	260.4	168.3	122.5	94.3	77.3
4	0.6	323.6	250.2	158.9	112.8	85.8	67.2
4	0.8	308.2	237.4	148.1	103.2	75.8	57.9
8	0.2	207.2	206.0	174.7	131.8	104.6	86.1
8	0.4	207.3	206.2	168.3	122.2	95.5	77.1
8	0.6	207.6	206.2	158.8	113.2	85.7	67.7
8	0.8	206.8	202.4	148.2	103.4	76.0	57.3
12	0.2	138.3	137.2	137.2	130.5	104.3	86.5
12	0.4	138.4	137.4	137.3	122.6	95.2	76.9
12	0.6	138.6	137.6	137.5	113.2	85.7	67.7
12	0.8	138.5	137.6	136.8	102.7	75.6	56.9

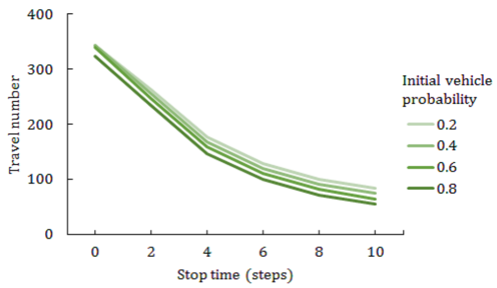

Fig. 21. Graph of travel number from Table 8 for $V = 4$ (steps)

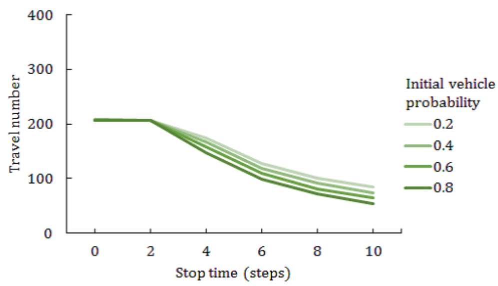

Fig. 22. Graph of travel number from Table 8 for $V = 8$ (steps)

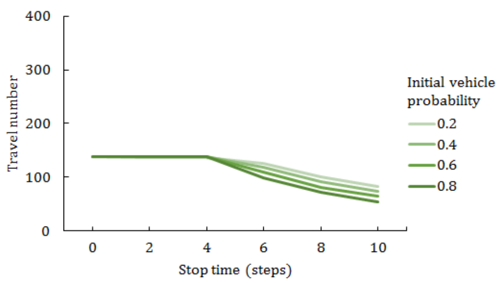

Fig. 23. Graph of travel number from Table 8 for $V = 12$ (steps)