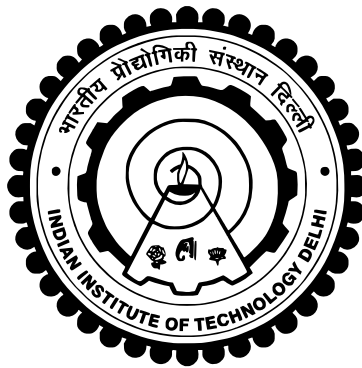


# CELLULAR AUTOMATA MODELLING OF MULTILANE SIGNALIZED JUNCTIONS WITH HETEROGENEOUS TRAFFIC

Mohit Kumar Singh



DEPARTMENT OF CIVIL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY DELHI

APRIL, 2021

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*by*

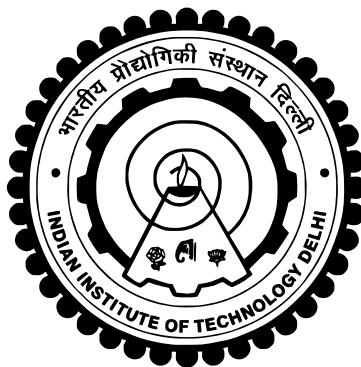
*MOHIT KUMAR SINGH*

DEPARTMENT OF CIVIL ENGINEERING

*submitted*

*In fulfilment of the requirement of the degree of Doctor of Philosophy*

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

April, 2021

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*Dedicated to My Parents.*

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# Certificate

This is to certify the thesis entitled **Cellular Automata Modelling of Multilane Signalized Junctions with Heterogeneous Traffic** being submitted by **Mr. Mohit Kumar Singh** to the Indian Institute of Technology, Delhi, India, for the award of the degree of **Doctor of Philosophy**, is a record of original bonafide research work carried out by him.

Mr. Singh has worked under my guidance and supervision. To the best of my knowledge, the thesis has reached the requisite standard.

The material contained in this thesis has not been submitted, in part or in full to any other University or Institute for the award of any degree or diploma.

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# Abstract

Intersections are an inevitable part of the road traffic system. If these are not designed properly, it can lead to several problems such as excessive delays, emissions and crashes. It is known that there are several points of conflict at the intersections that could cause crashes. Almost 49% of the total traffic crashes have been seen near intersections (MoRTH, 2016). Furthermore, studies also show that vehicle emissions are relatively higher during the acceleration or deceleration phase, which occurs at the intersections. It is difficult to understand traffic behaviour at the intersection as different activities, such as phase changes, multi-directional movements of vehicles, etc., occur at the same time. Proper intersection design can help to reduce delays, queues, emissions and crashes.

Various models are used to understand the traffic behaviour, such as microscopic, mesoscopic, and macroscopic models. Microscopic models consider traffic as individual drivers-vehicles objects, whereas macroscopic traffic models analyze aggregated traffic. Mesoscopic models are hybrid of macroscopic and microscopic models. This study attempts to simulate the signalized intersections in multi-lane heterogeneous traffic environment with microscopic simulation approach. The simulation was done in order to understand the driver behaviour at signalized junction and to estimate the delays and emissions occurring at intersections. The simulation model developed in this research was built with the help of modified Cellular Automata (CA) rules in the MATLAB<sup>®</sup> environment.

This research consists of five parts: The first is the boundary selection of the

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simulation model. Second, the modelling of signalised intersections with multi-lane heterogeneous traffic. In the third part, the rules for cellular automaton near and away from the intersection were formulated. Fourth is the modelling of driver behaviour. Finally, the emission estimation was also included in the model.

Cellular automation models may have two types of boundaries: open boundaries where the vehicles are deleted at the end of the approach; closed boundaries where the number of vehicles is fixed for the complete simulation time. There are several problems associated with the modelling of intersections using closed boundary CA models. Some of the problems such as: low simulation speeds and excessive warm-up times can be overcome with open boundary CA models. Hence, the open boundary models were further investigated in this study.

Once the boundary conditions were determined, the simulation model with multi-lane and heterogeneous traffic was modelled with the help of CA. The model was designed to allow vehicles to use neighbourhood gaps to move. As a result, some important interactions taking place near the intersections such as seepage behaviour, was incorporated into the model. In the seepage behaviour the smaller vehicle sees through the gaps between large vehicles and reaches the stop line near the intersection. Seepage behaviour is one of the important phenomena frequently observed at the signal intersection when the signal turns red.

The model developed in this study considers the zone of influence to segregate the behaviour of drivers at mid-block to those near the stop line. Zone of influence was calculated with the GPS data collected on 300 vehicles of three types: Car, Two-wheeler, Motorized-three-wheeler. A total of 100 data samples for each of the vehicle types were collected for generating trajectories. These trajectories were used to identify the vehicle driving behaviour such as speed and acceleration. Different rules for the vehicles before and after the intersection were proposed.

It was found that the zone of influence of intersection is different for various vehicles. The average of distances when vehicles start reducing their speed before intersection after seeing the red signal at the intersection is 90.67 m. Many studies classified drivers

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into broad categories based on accelerations such as aggressive, timid or normal drivers. In this study it was found there were no such distinct groups based on field observations. Instead, there could be more categories which follow a distribution rather than the distinct categories.

Further, the GPS data was also used to classify the drivers, but no particular number of groups of drivers were found, hence a different data set through video was collected at the intersections in Delhi and Mumbai, India. An attempt was made to model the driver behaviour as a distribution. A video data extractor tool was developed to extract traffic data such as trajectories, flow and speeds of vehicles.

The final model was calibrated and validated with the data collected in Delhi and Mumbai (India). Seepage behaviour and trajectories were compared with a simulator VISSIM and it was found that it does not satisfactorily simulate these behaviours. Delays obtained from several highway capacity manuals were compared with field and simulated data. Delays obtained from Indonesian and Canadian manuals were comparatively closer to the delays obtained in the field, whereas delays obtained from Indo-HCM and HCM were overestimates. Moreover, the delays obtained from the proposed model were found to be closer to the field delays. Further this study can also be applied to simulate driver behaviour, signal timing optimization etc.

Overall, this study focuses on the simulation of heterogeneous, non-lane-based traffic conditions. It includes seepage, and driver behaviour. It has been calibrated and validated with Delhi and Mumbai data. This model can be useful for the comprehensive analysis of a signalised intersection.

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# संक्षेप

सड़क यातायात प्रणाली का एक अपरिहार्य हिस्सा है। यदि इन्हें ठीक से डिज़ाइन नहीं किया गया है, तो यह कई समस्याओं जैसे अत्यधिक विलंब, प्रदूषक का उत्सर्जन और दुर्घटनाओं का कारण बन सकता है। यह ज्ञात है कि चौराहों पर टकराव की कई जगहें हैं जो दुर्घटनाओं का कारण बन सकते हैं। कुल टैफ़िक क्रैश का लगभग 49% चौराहों (MoRTH, 2016) के पास देखा गया है। इसके अलावा, अध्ययनों से यह भी पता चलता है कि वाहन उत्सर्जन त्वरण या मंदन के चरण के दौरान अपेक्षाकृत अधिक है, जो चौराहों पर होता है। चौराहे पर टैफ़िक व्यवहार को समझना मुश्किल है क्योंकि विभिन्न गतिविधियाँ, जैसे कि चरण परिवर्तन, वाहनों के बहु-दिशात्मक गमनागमन आदि, एक ही समय में होती हैं। उचित चौराहे का डिज़ाइन देरी, कतार, उत्सर्जन और दुर्घटनाओं को कम करने में मदद कर सकता है।

यातायात के व्यवहार को समझने के लिए विभिन्न मॉडलों का उपयोग किया जाता है, जैसे कि माइक्रोस्कोपिक और मैक्रोस्कोपिक मॉडल। माइक्रोस्कोपिक मॉडल टैफ़िक को व्यक्तिगत ड्राइवर-वाहन ऑब्जेक्ट के रूप में मानते हैं, जबकि मैक्रोस्कोपिक टैफ़िक मॉडल समग्र टैफ़िक का विश्लेषण करते हैं। मेसोस्कोपिक मॉडल मैक्रोस्कोपिक और मैक्रोस्कोपिक के संकर हैं। यह अध्ययन सूक्ष्म अनुकरण दृष्टिकोण के साथ बहु-लेन विषम यातायात वातावरण में संकेतित चौराहों को अनुकरण करने का प्रयास करता है। यह सिमुलेशन सिग्नल पर चालक के व्यवहार को समझने और चौराहों पर होने वाली देरी और उत्सर्जन का अनुमान लगाने के लिए किया गया था। इस शोध में विकसित सिमुलेशन मॉडल MATLAB® वातावरण में संशोधित सेलुलर ऑटोमेटा (CA) नियमों की मदद से बनाया गया था।

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इस शोध में पाँच भाग शामिल हैं: पहला अनुकरण मॉडल का सीमा चयन है। दूसरा, मल्टी लेन विषम यातायात वाले सिग्नल वाले चौराहों का मॉडलिंग। तीसरे भाग में, चौराहे के पास और दूर CA के नियम तैयार किए गए थे। चौथा ड्राइवर व्यवहार का मॉडलिंग है। अंत में, उत्सर्जन का अनुमान भी मॉडल में शामिल किया गया था।

सेलुलर स्वचालन मॉडल में दो प्रकार की सीमाएं हो सकती हैं: खुली सीमाएं जहां वाहनों को दृष्टिकोण के अंत में हटा दिया जाता है; बंद सीमाएं जहां वाहनों की संख्या पूर्ण सिमुलेशन समय के लिए तय की जाती है। बंद सीमा सीए मॉडल का उपयोग करके चौराहों के मॉडलिंग से जुड़ी कई समस्याएं हैं। कुछ समस्याओं जैसे: कम सिमुलेशन गति और अत्यधिक वार्म-अप समय को खुली सीमा सीए मॉडल के साथ दूर किया जा सकता है। इसलिए, इस अध्ययन में खुली सीमा के मॉडल की जांच की गई।

एक बार सीमा की स्थिति निर्धारित होने के बाद, CA की मदद से मल्टीलेन और विषम यातायात वाले सिमुलेशन मॉडल को मॉडल किया गया था। मॉडल को वाहनों को पड़ोस के रिक्ति का उपयोग करने की अनुमति देने के लिए डिज़ाइन किया गया था। नतीजतन, चौराहों के पास होने वाले कुछ महत्वपूर्ण सूचना जैसे कि स्राव व्यवहार, मॉडल में शामिल किया गया था। स्राव व्यवहार में छोटे वाहन बड़े वाहनों के बीच रिक्ति के माध्यम से देखता है और चौराहे के पास स्टॉप लाइन तक पहुंचता है। स्राव व्यवहार एक महत्वपूर्ण घटना है जो अक्सर सिग्नल चौराहे पर देखी जाती है जब सिग्नल लाल हो जाता है।

इस अध्ययन में विकसित मॉडल स्टॉप लाइन के पास मध्य-ब्लॉक में ड्राइवर्स के व्यवहार को अलग करने के लिए प्रभाव क्षेत्र को मानता है। प्रभाव क्षेत्र की गणना तीन प्रकार (कार, दोपहिया और मोटोराइज्ड तिपहिया वाहन) के 300 वाहनों पर एकत्र किए गए GPS डेटा के साथ की गई थी। वाहन के प्रत्येक प्रकार के लिए कुल 100 डेटा नमूने प्रक्षेपवक्र उत्पन्न करने के लिए एकत्र किए गए थे। इन प्रक्षेपवक्रों का उपयोग वाहन चालन व्यवहार जैसे गति और त्वरण की पहचान करने के लिए किया गया था। चौराहे से पहले और बाद में वाहनों के लिए अलग-अलग नियम प्रस्तावित थे। यह पाया गया कि विभिन्न वाहनों के लिए चौराहे का प्रभाव क्षेत्र अलग है। जब चौराहे पर लाल सिग्नल देखने के बाद 90.67 मीटर हो जाता है, तो चौराहे से पहले वाहन अपनी गति कम करना शुरू कर देते हैं। कई अध्ययनों ने चालकों को व्यापक श्रेणियों में वर्गीकृत किया, जैसे कि आक्रामक, डरपोक या सामान्य ड्राइवर। इस अध्ययन में यह पाया गया

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कि क्षेत्र के अवलोकन के आधार पर ऐसे कोई अलग समूह नहीं थे। इसके बजाय, अधिक श्रेणियां हो सकती हैं जो अलग-अलग श्रेणियों के बजाय वितरण का पालन करती हैं।

इसके अलावा, जीपीएस डेटा का उपयोग ड्राइवरों को वर्गीकृत करने के लिए भी किया गया था, लेकिन ड्राइवरों के कोई विशेष समूह नहीं पाए गए थे, इसलिए वीडियो के माध्यम से एक अलग डेटा दिल्ली और मुंबई, भारत में चौराहों पर एकत्र किया गया था। वितरण के रूप में ड्राइवर व्यवहार को मॉडल करने का प्रयास किया गया था। ट्रैफिक डेटा, वाहनों के प्रवाह और गति जैसे ट्रैफिक डेटा को निकालने के लिए एक वीडियो डेटा एक्सट्रैक्टर टूल विकसित किया गया था।

अंतिम मॉडल को दिल्ली और मुंबई (भारत) में एकत्र किए गए डेटा के साथ कैलिब्रेट और मान्य किया गया था। सीपेज व्यवहार और प्रक्षेपवक्र की तुलना एक सिमुलेटर VISSIM के साथ की गई और यह पाया गया कि यह इन व्यवहारों को संतोषजनक रूप से अनुकरण नहीं करता है। कई राजमार्ग क्षमता मैनुअलों से प्राप्त विलंब की तुलना फ़िल्ड और सिमुलेटेड डेटा के साथ की गई थी। इंडोनेशियाई और कनाडाई मैनुअल से प्राप्त विलंब तुलनात्मक रूप से क्षेत्र में प्राप्त देरी के करीब थे, जबकि Indo HCM और HCM से प्राप्त देरी को कम करके आंका गया था। इसके अलावा, प्रस्तावित मॉडल से प्राप्त विलंब क्षेत्र देरी के करीब पाए गए। आगे इस अध्ययन को चालक के व्यवहार, सिग्नल टाइमिंग अनुकूलन आदि का अनुकरण करने के लिए भी लागू किया जा सकता है।

कुल मिलाकर, यह अध्ययन विषम, गैर-लेन-आधारित यातायात स्थितियों के अनुकरण पर केंद्रित है। इसमें सीपेज, और ड्राइवर व्यवहार शामिल हैं। इसे दिल्ली और मुंबई डेटा के साथ कैलिब्रेट और वैरिफाईड किया गया है। यह मॉडल एक संकेतित चौराहे के व्यापक विश्लेषण के लिए उपयोगी हो सकता है।

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# Abbreviations and Notation

$\mu$	Mean
AD	Anderson Darling Test
AESOM	Auto Encoder Self-Organizing Maps
$A_F$	Driver Behavior Probability (Li and Sun 2016 et al)
BLCA	Brake Light Cellular Automata Model
BML	Biham, Middleton And Levine
CA	Cellular Automata
CI	Confidence Interval
CO	Carbon Mono Oxide
E	Total Emission
EF	Emission Factor
FI	Fukui Ishibashi
FL	Fraction of Long Vehicle
GA	Genetic Algorithm
GOF	Goodness of Fit
GPS	Global Positioning System
GUI	Graphical User Interface
h	Hypothesis
HC	Hydrocarbons
HMM	Hidden Markov Model
HR	High Risk

INS	Inertial Navigation System
IoV	Internet of Vehicles
ITS	Intelligent Transport System
IZOI	Intersection Zone of Influence
L	Road Length
LR	Low Risk
LVQ	Linear Vector Quantization
MATLAB <sup>®</sup>	Programming Language
MCME	Manual Count Made Easy
ME	Margin of Error
MR	Medium Risk
MTraDE	Manual Traffic Data Extractor
MTW	Motorized three-Wheeler
$NO_x$	Nitrogen Oxide
NS	Nagel and Schreckenberg 1992
PDA	Plan Decision Action
PLC	Probability Left Side
$PM_{2.5}$	Particulate matter of <2.5 mm size
PRC	Probability Right Side
RGB	Red, Green, Blue
RLCs	Red Light Cameras
SOM	Self-Organizing Maps
SSAM	Safety Assessment Model
TAI	Trajectory Aggressivity Indicator
TDE	Traffic Data Extractor
TRAZER <sup>®</sup>	TRaffic AnalyZer and EnumeratoR software ( Video Traffic data extractor)
t-test	t test
TW	Two-Wheeler
VISSIM	Verkehr In Städten – SIMulationsmodell (Traffic simulation software)

VKT	Vehicle Miles Traveled
VOC	Volatile organic content
$\sigma$	Standard Deviation
$v_{current}$	Current vehicle speed
$v_{max}$	Maximum speed of vehicles in simulation model
p	Randomization probability
$D_j$	Total Mean delay for $j_{th}$ approach
$DG_j$	Mean geometric delay for $j_{th}$ approach
$DT_j$	Mean traffic delay for $j_{th}$ approach
GR	Green ratio
g	Green time
$g_e$	Effective green interval (s)
c	Cycle time
C	Capacity
DS or $x$ or $x_1$ or X	Degree of saturation
Q	Traffic flow
$NQ_1$	PCUs remained in current phase from earlier phase
PCU	Passenger car unit
$q_{gr}/q$	Proportion of vehicles arrived in green time
$q_{gr}$	number of vehicles arrived in green time
$m$	Number of vehicles arrived in a cycle
$f_p$	Platoon arrival time adjustment factor
$d_1$	Average overall uniform delay (s/pcu)
$d_2$	Average overflow delay or Incremental delay (s/pcu)
$d_3$	Initial queue delay
$k_f$	Quality progression effect adjustment factor
$t_e$	Evaluation time
HCM	Highway Capacity manual

# Definitions

**Cycle** - A sequence of phases is called one cycle.

**Phase** - Part of cycle in which right of way is given to particular directions.

**Cycle time** - Time taken to complete one sequence of phases.

**Phase time** - Time allotted for a fixed directional movements (or a phase).

**Density** - Number of vehicles in one kilometer of road (veh/km/lane).

**Flow** - Number of vehicle passing through a section in an hour (veh/h/lane).

**Capacity** - Maximum number of vehicle that can pass through a point or segment of intersection/road in an hour (veh/h).

**Saturation flow**- Maximum number of vehicles that can pass through a junction, if green time is assumed for all the time (veh/h).

**Free flow speed** - The maximum speed that drivers want to achieve on an empty road.

**Headway** - The time gap between two vehicles crossing the same point with same

reference (such as bumper to bumper).

**Delay** - The increment in travel time due to the traffic factors such as signal, traffic flow, etc.

**Effective green time** - Green and amber time remaining after deduction of lost time.

**Lost time** - Time lost in starting and stopping of vehicles after seeing the signals.

**Geometric delay (DG)** - The delay caused by acceleration/deceleration of vehicle to make a turn at the intersection or/and delay caused by stopping at the signal.

**Traffic delay (DT)** - The delay caused by interaction of vehicles at the signalized junction.

**Green ratio** - The ratio of green time and cycle time.

**Degree of saturation** - Volume to capacity ratio.

**Phase** - Part of the cycle time in which a particular directional movements are allowed.

**Intersection zone of influence (IZOI)** - Part of road where the intersection signal starts affecting vehicles.

**Seepage** - The act of vehicles moving through small gaps left by neighbouring vehicles.

**Uniform delay** - Delay due to uniform arrival rate of vehicles.

**Incremental delay** - Delay due to random arrival rate of vehicles.

**Initial queue delay** - Delay due to queue of earlier cycle.