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**DEVELOPING A FORMALISM FOR GIBSON'S AFFORDANCES USING
COLORED PETRI NETS**

A Thesis in

Industrial Engineering

by

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ABSTRACT

Gibson (1979/1986) proposed affordance theory to represent and model what the environment offers an animal for good or ill. Since its inception by Gibson, affordance theory has undergone several refinements. A few affordance theory-based formalisms are reviewed in this proposal to demonstrate their potential advantages and disadvantages and to motivate an overarching formalism to model problems within dynamic environments.

The purpose of this research is to provide a computational formalism for Gibson's affordance theory based on characteristics of dynamic environments to include concurrency, stochasticity and spatio-temporality. A Colored Petri Net (CPN)-based model is proposed as a suitable instrument for developing this formalism. A mathematical model, graphical representation and computational model for this CPN model is developed within the context of a driving problem. The affordances offered by this driving environment are analogous to those offered by a set of highway lanes. A formative analysis technique is also introduced along with an overall data analysis procedure to analyze the precision of the actualized actions and the niche of lane affordances that become available to the driver within the highway lane-driver system.

An empirical study was conducted using a team of two expert drivers to elicit various behaviors that would help resolve the precision of the CPN model. Four output metrics were defined that represent the deviation between the empirical human performance and model predicted data: lane position, turn direction of the subject driver's vehicle, time taken by the subject driver to move from the starting lane to the exit lane

and the total utilization of the exit lane by the subject driver. The significance of the results is then explained with reference to research implications and future work.

TABLE OF CONTENTS

LIST OF FIGURES	viii
LIST OF TABLES	x
NOMENCLATURE	xii
ACKNOWLEDGEMENTS	xiv
Chapter 1 INTRODUCTION	1
1.1 Gibson’s Affordance Theory.....	1
1.2 Colored Petri Net (CPN)	3
1.3 Research Objectives	4
Chapter 2 LITERATURE REVIEW	7
2.1 Ecological Approach to Visual Perception.....	7
2.2 Gibson’s Affordance Theory.....	8
2.2.1 Evolution of Affordance Theory.....	9
2.2.2 Properties and Characteristics of Affordances.....	11
2.2.2.1 Concurrency	13
2.2.2.2 Stochasticity	14
2.2.2.3 Spatio-Temporality.....	14
2.2.3 Existing Formalisms for Affordance Theory	15
2.2.3.1 Shaw and Turvey (1981):.....	16
2.2.3.2 Turvey (1992):.....	18
2.2.3.3 Greeno (1994):	20
2.2.3.4 Wells (2002):.....	21
2.2.3.5 Stoffregen (2003):.....	22
2.3 CPN Formalism for Gibson’s Affordance.....	23
2.3.1 Need for New Affordance Formalism.....	24
2.3.2 Suitability of the CPN formalism for Gibson’s Affordance Theory....	24
2.4 Research Motivation.....	25
2.4.1 Characteristics of the Affordance Formalism	28
2.4.2 Implications of this Formalism	29
2.5 Chapter Summary.....	30
Chapter 3 MODEL DEVELOPMENT	31
3.1 Research Questions	31
3.2 Problem Statement	32
3.3 Mathematical Model.....	35
3.3.1 Case 1 – CD is on the Left Extreme Physical Bound of SD.....	38

3.3.2 Case 2 – CD between Left Extreme Physical Bound of SD and +X-axis	40
3.3.3 Case 3 – CD on +X-axis.....	42
3.3.4 Case 4 – CD between +X-axis and Right Extreme Physical Bound of SD	44
3.3.5 Case 5 – CD on Right Extreme Physical Bound of SD	45
3.4 Conceptual Model	47
3.5 Developing a New Formalism: Colored Petri Net (CPN) Approach.....	48
3.5.1 Affordance-based CPN Model.....	49
3.5.1.1 Analysis Overlay for the Model.....	49
3.5.1.2 Highway Exit Problem Space (HEPS)	50
3.5.1.3 Lane Model (LM)	53
3.5.1.4 Driver Model (DM)	55
3.5.1.4.1 Confederate Driver Model (CDM)	55
3.5.1.4.2 Subject Driver Model (SDM)	57
3.5.1.5 Actualization Model (AM).....	58
3.5.1.5.1 Driver-Lane Interface Model (DLIM)	60
3.5.1.5.1.1 Set Turn Probabilities (STP) Module	63
3.5.1.5.1.2 Compute Lane Affordances (CLA) Module	66
3.5.1.5.1.3 Juxtaposition Function (j)	68
3.5.1.5.2 Lane-Driver Interface Module (LDIM)	69
3.5.2 Computational Representation of the CPN Model.....	70
3.5.3 Random CPN Model.....	74
3.6 Formative Analysis.....	79
3.7 Chapter Summary.....	81
Chapter 4 HYPOTHESIS	83
Chapter 5 METHODOLOGY	86
5.1 Participants	86
5.2 Equipment and Tools.....	87
5.3 Experimentation Protocol.....	90
5.4 Independent Variables	92
5.5 Description of Test Scenarios.....	94
5.6 Dependent Variables	94
5.7 Chapter Summary.....	97
Chapter 6 RESULTS AND ANALYSIS	99
6.1 Data Analysis Procedure	99
6.2 Deviation in Lane Position (ΔLP)	103
6.3 Deviation in Turn Direction (ΔTD).....	108
6.4 Deviation in Time to Exit (ΔTTE).....	114
6.5 Deviation in Utilization of the Exit Lane (ΔU).....	120
6.6 Hypothesis Testing and Model Comparison	126

6.7 Chapter Summary.....	128
Chapter 7 DISCUSSION AND CONCLUSION.....	129
7.1 Pivot Table Analysis	129
7.2 Formative Analysis.....	131
7.3 Research Limitations	132
7.4 Future Research.....	133
BIBLIOGRAPHY.....	136
Appendix A CPN BASICS	140
Appendix B CPN MODEL DECLARATIONS AND FUNCTIONS	141
Appendix C GPS CONVERSIONS.....	146
C.1 WGS84 Conversions	146
C.2 Transformation with respect to the Secondary Reference Point.....	147
Appendix D VBOX DATA SUBSAMPLING METHOD.....	149
Appendix E DRIVER INSTRUCTIONS	152
E.1 Instructions provided to the drivers during the experiment	152
Appendix F DRIVER SURVEY AND CONSENT FORMS.....	161
F.1 Post-experiment Driver Survey and Informed Consent Form	161
Appendix G TEST RESULTS	164

LIST OF FIGURES

Figure 1-1: A Sample CPN for <i>Salt-Water System</i>	4
Figure 3-1: Highway Lane Driver System with One Exit Lane	33
Figure 3-2: Visual and Physical Angles for SD.....	36
Figure 3-3: Perceptual Angles for SD	37
Figure 3-4: Affordance Pockets for SD.....	38
Figure 3-5: Case 1 – CD on Left Extreme Physical Bound of SD.....	39
Figure 3-6: Case 2 – CD between Left Extreme Physical Bound of SD and +X-axis.....	41
Figure 3-7: CD on +X-axis	42
Figure 3-8: Case 4 – CD between +X-axis and Right Extreme Physical Bound of SD.....	44
Figure 3-9: Case 5 – CD on Right Extreme Physical Bound of SD.....	46
Figure 3-10: Conceptual Model for Highway Exit Problem Space.....	47
Figure 3-11: Analysis Overlay for Highway Lane Driver System.....	50
Figure 3-12: Block Representation of Highway Exit Problem Space	51
Figure 3-13: CPN for Highway Exit problem Space	52
Figure 3-14: CPN for Lane Model Showing Affordances for Lane 3	54
Figure 3-15: CPN for Scripted Confederate Driver Model	56
Figure 3-16: CPN for Autonomous Subject Driver Model	57
Figure 3-17: CPN for Actualization Model.....	59
Figure 3-18: CPN for Computing Next Location of CD	61
Figure 3-19: CPN for Computing Next Location of SD.....	62
Figure 3-20: CPN for Set Turn Probabilities Module	64
Figure 3-21: CPN for Calculate Lane Affordances Module.....	66

Figure 3-22: CPN for Juxtaposition Function Module (<i>j</i>)	68
Figure 3-23: CPN for Current Location of Driver in Lane 1	69
Figure 3-24: CPN for Setting Random Turn Probabilities for SD while in Lane 1	75
Figure 3-25: CPN for Setting Turn Probabilities for SD while in Lane 2	76
Figure 3-26: CPN for Setting Turn Probabilities for SD while in Lane 3	77
Figure 3-27: CPN for Compute Lane Affordances Module in Random Model.....	78
Figure 5-1: Topographical Map of the Test Track (Source: PTI, University Park, PA).....	87
Figure 5-2: Layout of the Test Track.....	88
Figure 5-3: Experimentation Protocol	91
Figure 6-1: Data Analysis Procedure.....	100
Figure 6-2: Graphical Representation of Deviation in Lane Position	105
Figure 6-3: Graphical Representation for Deviation in Turn Direction.....	110
Figure 6-4: Graphical Representation for Deviation in Time to Exit.....	116
Figure 6-5: Graphical Representation for Deviation in Utilization of Exit Lane	122

LIST OF TABLES

Table 2-1: Exiting Formalisms for Gibson’s Affordance	16
Table 2-2: Affordance formalisms and their limitations	29
Table 3-1: Criteria for Existence of AES Characteristics.....	34
Table 3-2: Algorithm for Computing Niche of Lane Affordances and Actualized Action.....	63
Table 3-3: Static Turn Probabilities for SD based on the Current Lane Position.....	65
Table 3-4: Formative Analysis Overlay for Lane Affordances	80
Table 5-1: Independent Variables and their Different Levels	93
Table 5-2: Test Scenarios	94
Table 5-3: Description of the Dependent Variables	95
Table 6-1: Scenario Classifications	101
Table 6-2: Scenario Grouping Using the Pivot Table	102
Table 6-3: Descriptive Statistics for ΔLP	103
Table 6-4: Descriptive Statistics for ΔLP After Aggregating by Trials	104
Table 6-5: Test for Effects of Scenario and Subject on ΔLP	106
Table 6-6: Estimated Marginal Means for Deviation in Lane Position.....	106
Table 6-7: Pivot Table for ΔLP	107
Table 6-8: Descriptive Statistics for ΔTD	108
Table 6-9: Descriptive Statistics for ΔTD After Aggregating by Trials	109
Table 6-10: Test for the Effect of Scenario and Subject on ΔTD	111
Table 6-11: Estimated Marginal Means for Deviation in Turn Direction.....	112
Table 6-12: Pivot Table for ΔTD	113
Table 6-13: Deviation in Time to Exit (ΔTTE).....	114

Table 6-14: Descriptive Statistics for Δ TTE After Aggregating by Trials	115
Table 6-15: Test for the Effects of Scenario and Subject on Δ TTE.....	116
Table 6-16: Estimated Marginal Means for Deviation in Time to Exit.....	117
Table 6-17: Pivot Table for Δ TTE.....	119
Table 6-18: Deviation in Utilization of Exit Lane (Δ U)	120
Table 6-19: Descriptive Statistics for Δ U After Aggregating by Trials	121
Table 6-20: Test for the Effects of Scenario and Subject on Δ U	122
Table 6-21: Estimated Marginal Means for Deviation in Utilization of Exit Lane	124
Table 6-22: Pivot Table for Δ U.....	125
Table 6-23: Comparison Between CPN Model and Random Model	126
Table 6-24: Dependent Paired t-Test Statistics for Comparing Means of Affordance-based and Random CPN Models	127
Table 7-1: Sample Formative Analysis for SD2 Data (on Scenario 4, Trial 2).....	131

NOMENCLATURE

Abbreviations:

ACT	– Action-type Token
AES	– Animal Environment System
AT	– Affordance-type Token
AM	– Actualization Model
CD	– Confederate Driver
CDM	– Confederate Driver Model
CPN	– Colored Petri Net
DGPS	– Differential Global Positioning System
DLIM	– Driver Lane Interface Model
DM	– Driver Model
FSM	– Finite State Machine, also known as Finite State Automata (FSA)
ET	– Effectivity-type Token
HEPS	– Highway Exit Problem Space
HLDS	– Highway Lane Driver System
IM	– Initialization Model
j	– Turvey’s Juxtaposition function
LDIM	– Lane Driver Interface Model
LM	– Lane Model
SD	– Subject Driver
SDM	– Subject Driver Model

Driver Attributes:

- A_{curr} – Current acceleration of a driver
- Driver # – Driver with index indicating the specific driver
- P_{new} – New lane and block position of a driver
- TD_{curr} – Current turn direction of a driver
- V_{curr} – Current velocity of a driver

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“It is not the critic who counts: not the man who points out how the strong man stumbles or where the doer of deeds could have done better. The credit belongs to the man who is actually in the arena, whose face is marred by dust and sweat and blood, who strives valiantly, who errs and comes up short again and again, because there is no effort without error or shortcoming, but who knows the great enthusiasms, the great devotions, who spends himself for a worthy cause; who, at the best, knows, in the end, the triumph of high achievement, and who, at the worst, if he fails, at least he fails while daring greatly, so that his place shall never be with those cold and timid souls who knew neither victory nor defeat.”

Theodore Roosevelt, The Man in the Arena,
“Citizenship in a Republic” Speech at
the Sorbonne, Paris, April 23, 1910

*Adapted from PhD Thesis of Greg Gerling,
University of Iowa (2005)*

Chapter 1

INTRODUCTION

Ecology has always had an impact on the existence of living systems over time. Ecological psychologists believe that the interaction of an animal with its environment can be reduced to several relations, which correspond to ecological laws. These relations govern their survivability and adaptability, and are fundamental to the existence of that animal within that environment. This research focuses on developing a formalism for representing the concept of affordance proposed by Gibson (1979/1986) using a computational approach based on Colored Petri Nets (CPN).

Chapter 1 consists of these parts. Section **1.1** provides a brief introduction on Gibson's Affordance Theory. A refresher on Colored Petri Nets (CPN) is presented in **1.2**. The objectives of this research are presented in section **1.3**.

1.1 Gibson's Affordance Theory

James Gibson (1979/1986) proposed that affordance refers to properties of the environment that are offered to an animal for either good or ill. Gibson (1979/1986, p.127) states that:

“The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, but the noun

affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment.”

According to this definition, *affordance* is a property of the environment taken with respect to an animal and provides an opportunity for the animal to take an action within this environment. Furthermore, he adds that affordances are constantly perceived based invariant combination of certain higher order variables, such as stimulus energy, ratios and proportions, which do not change and exist even in the absence of the animal. Animals usually perceive and utilize a set of affordances (within their environment), known as a *niche*. Gibson (1979/1986, p.128) sums up that:

“Ecologists have the concept of a *niche*. A species of animal is said to utilize or occupy a certain niche in the environment. This is not quite the same as the *habitat* of the species; a niche refers more to *how* an animal lives rather than to *where* it lives. I suggest that a niche is a set of affordances.”

Therefore, the environment offers different set of affordances that may or may not be concurrently available to multiple animals that reside within this animal environment system (AES)¹. For instance, a road provides the affordance of “*is-drivable*” for a car driver and “*is-crossable*” for a pedestrian attempting to cross the road. In this research, we propose a new formalism using Colored Petri Nets (CPN) for representing elements of an AES that enables the actualization of a specific affordance into an action.

¹ AES is also referred to as “ecosystem”

1.2 Colored Petri Net (CPN)

Petri Net (Balbo et al., 2000; Girault and Valk, 2003; Petri, 1962 and Murata, 1989) was introduced by Carl Adam Petri in 1962, to handle concurrency issues in discrete distributed systems in a convenient manner. Since then, Petri Net has been applied to a number of modeling applications and has evolved into several variants (e.g., Colored Petri Net, Timed Petri Net and Stochastic Petri Net).

In this research, my attention will be focused on modeling the AES using Colored Petri Net (CPN). A CPN is an extension of a Finite State Machine (FSM) and graphically denotes a directed bipartite graph with annotations. It has place nodes, transition nodes and directed arcs that connect a place node with a transition node or a transition node with a place node. Any directed arc within a Colored Petri Net never connects two place nodes or two transition nodes together. A directed arc can have arc conditions implemented based on specific cases. Each place node can hold zero or more tokens depending upon their maximum capacity. A Colored Petri Net (CPN) (Jensen, 1992 and Jensen, 1995) is different from a regular Petri Net in that each token within a CPN has a specific value, known as token color. These tokens are derived from a large “color set” that enumerates the possible values for that token. A detailed illustration of CPN can be found in Jensen (1992). When a transition fires, incoming tokens from the preceding input place nodes are consumed by this transition node and output tokens are created and transferred to the output place nodes that succeed this transition. A transition fires only when the required number of tokens (based on the arc constraints) becomes available at the preceding place nodes. Figure 1-1 shows a sample CPN for *Salt-Water* system.

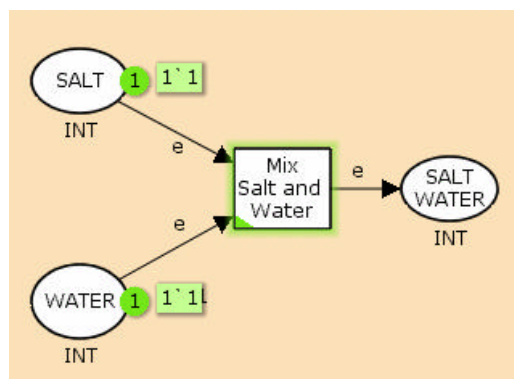


Figure 1-1: A Sample CPN for the *Salt-Water* system

This CPN indicates that there are three place nodes (*Salt*, *Water* and *Salt Water*) and a single transition node (*Mix Salt and Water*). There are two tokens one for each place *Salt* and *Water*, which represents the initial marking. Note that, since both preceding place nodes contain at least one token, the succeeding *Mix Salt and Water* transition can fire during the next update. When this transition fires, these two tokens are consumed by the transition to spawn a token, which is sent to the *Salt Water* place node. This CPN represents a system where salt is mixed with water to form salt water.

1.3 Research Objectives

The intention of this research is to provide a formalism for representing Gibson's affordances based on a CPN approach, which includes fundamental characteristics of AES such as *concurrency*, *stochasticity* and *spatio-temporality*. In order to accomplish this goal, the formalism must adopt an ecological approach and relate to both the animal and its environment. The primary research objectives include the following:

1. Develop a CPN formalism to represent elements of an AES. This formalism should explicitly account for characteristics such as concurrency, stochasticity and spatio-temporality that are ubiquitous within the AES.
2. Apply the CPN formalism to model the “Highway Exit” problem space, which includes characteristics such as concurrency, stochasticity and spatio-temporality within the driver and highway lane (AES) system.
3. Develop a graphical representation, mathematical notation and computational model for this CPN formalism.
4. Verify the CPN model by applying empirical methods situated within this driver and highway lane system.
 - a. Test the deviation in model-predicted driver behavior from the actual driver behavior to examine whether the affordance-based CPN model is an accurate means for representing affordance and driver behavior within this driver and highway lane system. This test would allow us to ascertain the precision of the model in predicting the actualized action that emerges from juxtaposing the driver action opportunities with highway lane affordances.
 - b. Compare the deviation in driver performance predicted by the affordance-based CPN model with another random CPN model that includes random turn preferences (probabilities) that are generated at each update for the driver. This comparison would help us test the hypothesis that the affordance-based CPN model is a better fit for predicting the driver performance than another random behavior model.

5. Conduct a formative analysis to elicit the set of affordances (niche) that become dynamically available to the driver within the driver and highway lane system. This would enable us to establish the niche for the driver within our formalism.

Chapter 2

LITERATURE REVIEW

In this section, an overview of the literature review relevant to this research is provided. Section **2.1** discusses the ecological approach to visual perception of Gibson's affordances. In section **2.2**, an overview of existing literature on Gibson's affordance theory is provided. This section also explores the evolutionary roots of affordance theory, identifies the properties of affordances and the characteristics of the animal environment system (AES) in addition to presenting some existing formalisms. Section **2.3** provides an overview of the Colored Petri Net (CPN) formalism along with a description of how a CPN meets the requirements of affordance theory. Section **2.4** discusses the motivation for this research.

2.1 Ecological Approach to Visual Perception

According to Gibson (1979/1986), the physical world is different from the environment (or ecology) as it encompasses everything from atoms through terrestrial objects to galaxies. On the contrary, environment is defined at the level of millimeters and meters, which correspond to ordinary familiar things of the earth. The sizes of things in the environment also coincide with sizes of animals that are limited to intermediate

terrestrial scale (which ranges from a fraction of a millimeter to a few meters). On a similar note, the masses of the animals lie within a range of milligrams to a few kilograms. Therefore, in an environment, the size and masses of things are comparable to those of the animals that reside within it.

Physical reality, however, has structure at all levels of metric size from atoms to galaxies. A nesting occurs within the intermediate band of terrestrial sizes that corresponds to various forms or shapes of our familiar world. For instance, a mountain appears at the kilometer level, boulders and rocks are nested within a mountain at the meter level, while pebbles are nested at the millimeter level. Animals perceive and act within such a world (environment), for example, avoiding a steep mountain or collision into a big rock or even a path of sharp pebbles while we walk, run or sprint on the surface of earth. Environment is persistent and comprises of events that occur as layout of time scale within them. Some layouts change while others exhibit permanence. Animals sense changes in their layout through the motion of things in the environment or from motion of bodies in space (for instance, through self-locomotion like walking).

2.2 Gibson's Affordance Theory

In this section, a chronological account on the evolution of Gibson's affordance theory is presented. Existing theories on formalizing affordance are also discussed in order to demonstrate their pitfalls and establish a need for a new formalism that would address the shortcomings of these earlier formalisms.

According to Gibson (1979/1986), anything of interest within the environment is referred to as object. Affordances are properties of objects within the environment taken relative to the animal. Turvey (1992) claims that effectivities, which are complementary dual properties of the animal, exist for these affordances offered by the environment. Effectivities essentially represent the capabilities of the animal. Corresponding affordances and effectivities juxtapose (combine), under suitable circumstances, to actualize the affordance into action.

Events occur as changes within the spatio-temporal layout of the environment and act as a structure that represents the permanence or changes in the layout of the environment. Bingham (2000) argued that events (like objects) are things that can have affordance properties, and can be perceived. It is important to distinguish an ecological event from a physical event because they are defined at different scales of the environment.

2.2.1 Evolution of Affordance Theory

Gibson's theories on visual perception have constantly evolved over the years and are manifest in his works (Gibson, 1950; 1966; 1977; 1979/1986; 1994). Jones (2003) provides a detailed account of how Gibson's thinking evolved on the concepts that relate to visual perception and affordances of real world objects. Gibson (1950, p.212) believed that meanings and spatial properties cannot be divorced from one another, which implies that there exists a possibility of perceiving *spatial-temporal meanings* at any given time. This also provides evidence in favor of the conjecture that before introducing the notion

of affordances Gibson was trying to understand how observers instantly perceive the possibilities that are afforded by the environmental objects.

Shortly after that, Gibson (1966) worked on the relation between perception and action, which inspired him to develop affordance theory. Gibson (1977, p. 67) introduced affordance theory initially by defining affordance as “a specific combination of the properties of a substance and its surfaces taken with reference to an animal.” In his final book, Gibson (1979/1986) laid the foundation for affordance, by defining it to be an invariant property of the environment taken with respect to an observer², which provides an indication of what the environment offers the observer.

Since Gibson proposed affordances, proponents and opponents of affordance theory have offered several definitions of affordances. According to Jones (2003) and Shaw (2003), the theories relating to perception fall into two categories – *Direct or Indirect Perception*. Theories of direct perception assume that objects and events have inherent meanings, which an animal can exploit without any cognitive effort. Jones (2003) argues that Gibson’s affordance theory conforms to the former category. On the other hand, theories that constitute indirect perception assume that objects and events have no inherent meaning, which necessitates the internal creation of meaning that must be stored by the animal. Simon’s indirect perception theory (Simon, 1969/1996) falls under this category. Simon argues that coupling is an artifact (rule-governed) that is mediated by symbol functions essentially involving information processing.

² Throughout this manuscript, the term “observer”, “perceiver”, “agent” and “actor” refer to the “animal” and are used interchangeably, unless specified otherwise.

In addition to this, two schools of thought have evolved over the years even among proponents of affordance theory. The ecological psychologists from the first school (Greeno, 1994; Kirlik, 1995; Kirlik, 2004; Kirlik, Miller and Jagacinski, 1993; Heft, 2001; Lombardo, 1987; Reed, 1996; Shaw and Turvey, 1981 and Turvey, 1992) argue that affordances are properties of the environment of an animal that have consequences for the animal's behavior. Other ecological psychologists from the second school (Chemero, 2003; Jones, 2003; Michaels, 2003; Sanders, 1997; Stoffregen, 2000a, 2000b, 2003 and Warren, 1984) consider affordance as a higher order property of the animal environment system (AES) that refers to a mutual relation between the animal and its environment.

2.2.2 Properties and Characteristics of Affordances

According to Wells (2002), seven fundamental properties are specified for affordances.

1. Affordance is an *ecological concept* that is defined at varying ecological levels for different animal species. However, these levels are determined by the kinds of objects and events that exert selection pressure on that species.
2. Affordances are *relational*, and are attributed to two or more things taken together. Lombardo (1987) suggested the notion of reciprocity to be the essential component of Gibson's ecological approach to affordances. Reciprocity implies distinguishable yet mutually supportive realities, which relate to asymmetric interdependence, since the relation between the animal and its environment is

interdependent yet asymmetric. The environment exists even in the absence of the animal and is a fundamental information source of perceptual structure other than the animal. The reciprocity also leads to the complementary relation that exists between an animal and its environment.

3. Affordances are *both a fact of the environment and a fact of the behavior*, which according to Gibson (1979/1986, p.223), informs the perceiver (animal) on how to navigate among things and what to do with them.
4. *Sets of affordances constitute niches* that specify how an animal lives rather than where it lives (its habitat).
5. Affordances possess *real meanings*, which exist for things independent of the perceiver.
6. Affordances are constantly perceived based on *invariant combinations* of certain higher order variables such as stimulus energy, ratios and proportions that do not change. They are persistent and are always present to be perceived irrespective of whether the perceiver notices them.
7. The observer *directly perceives affordances*, that are basic, and complex affordances are learned through experience.

Gibson defines “information pickup” and “ecological optics” as the tools that facilitate the visual perception of affordances, which constrain how an animal perceives things within its environment.

In addition to the properties identified earlier, the AES presents characteristics such as “Concurrency”, “Stochasticity”, and “Spatio-Temporality” to the resident animal,

which makes the concept of affordance very rich. Each of these characteristics is explained in more detail below.

2.2.2.1 Concurrency

Gibson (1979/1986) explained that many animals co-exist within the environment. A niche represents a set of affordances that are invariant, directly perceived, and existent even in the absence of the perceiver. Consider the case where two drivers (who are moving parallel to each other) are attempting to exit on a two-lane highway system with a single exit lane. These drivers can be in the same state such as driving straight, turning left or right, braking or accelerating. When the drivers exhibit the same states simultaneously, it leads to “*concurrency*” within the AES. They would also perceive the affordance “*is-drivable*” concurrently for a particular lane as long as that lane is empty and does not end. Therefore, the affordance offered by that lane is concurrently available to and perceived by both drivers on the highway until a driver ceases that affordance (i.e. moves into the lane and blocks other driver from doing the same). This characteristic of affordance is referred to as “*conflict*”. The existence of “*concurrency*” and “*conflict*” leads to state of confusion among the drivers. The affordance offered by the lane becomes unavailable to the other driver until the driver occupying it releases the lane or ceases to exist.

2.2.2.2 Stochasticity

Although Gibson's affordances are persistent and directly perceived, its availability is stochastic in nature; that is, the next state of the environment is not fully determined by the previous state of the driver or environment independently. Instead, the availability of an affordance depends upon the mutual relationship between the effectivities and the affordances that become randomly available to the animal within this dynamic environment. This issue is termed as the problem of "*Stochasticity*". This mutual relationship between the animal and its dynamic environment results in the stochasticity within the AES. Revisiting the driver example, when the exit lane is occupied by another driver the affordance (*is-drivable*) ceases to exist for that lane. The act of moving into the exit lane can occur at random time within the duration of a given scenario, which makes the AES stochastic. Furthermore, the location of the exit lane can be randomly altered within each scenario by adjusting the vertical and horizontal proximity of the driver to that lane and the relative velocity with respect to the other, thereby making the environment, stochastic.

2.2.2.3 Spatio-Temporality

Gibson (1979/1986) states that the artifacts of space and time must be founded upon ecological realities, which would include the layout of the surfaces and nesting of events within that layout. As an event occurs if the layout of the environment changes, the spatio-temporal specification of an animal within its environment becomes vital. This is critical to visual perception of affordance because animals perceive the changes in the

spatio-temporal layout of the environment in order to perform an action within their environment. In the earlier driver example, if a driver is further away from another driver to exit lane, then the affordance available to occupy the exit lane depends upon spatio-temporal characteristics such as the drivers' current locations and time required to reach the exit lane. It is also probable that the driver closest to the exit lane would occupy it before the other driver could ever reach it, thereby making the affordance unavailable. The characteristic associated with the specification of such spatio-temporal properties is termed "*spatio-temporality*". The perception of such spatio-temporal properties is critical to the actualization of affordance as demonstrated by Oudejans et al. (1996) through an experiment for catching fly balls.

2.2.3 Existing Formalisms for Affordance Theory

A description of some existing formalisms for Gibson's affordance, including their treatment of affordance and inherent pitfalls are described in Table 2-1. A synopsis of these formalisms and their shortcomings is presented in detail in the subsequent sections in order to motivate the need for new formalism.

Table 2-1: Existing Formalisms for Gibson's Affordance

Model	Gibson (1976/1989)	Shaw and Turvey (1981)	Turvey (1992)	Greeno (1996)	Wells (2002)	Stoffregen (2003)
<i>Affordance is treated as:</i>	what an environment offers an animal for ill or good	Coalitional model	Dispositional property of the environment.	Relevant properties of the environment in agent-environment interactions that are graded.	Ordered pair (q, a) configuration, where q is an animal referential term and a is an environment referential term.	Emergent property of the animal-environment system
<i>Affordance is at:</i>	Environment Level	Environment Level	Environment Level	Environment Level	Environment Level	Animal Environment System (AES) Level
<i>Pitfalls:</i>	NA	Not all duals used to represent mutual reciprocity of the animal and its environment, may exist; Model also lacks substantive duality	Juxtaposition Function is not defined	Affordance is defined as constraints that link situation types, which relaxes the definition of affordance proposed by Gibson	Defines affordance only with respect to a single animal within AES.	Places no constraints on the basis by which relational or emergent properties can be treated as affordance; Behavior and intention functions are not defined

2.2.3.1 Shaw and Turvey (1981):

A model based on the concept of “coalition” is offered by Shaw and Turvey (1981), which suggest that perceptual organization is an activity of the (epistemic) ecosystem. This is in contrast to the Gestalt psychology (Koffka, 1935) viewpoint, which states that it is an achievement of the nervous system of the animal. A “Coalition” according to Shaw and Turvey (1981, p.344) is:

“a superordinate system (relational structure) consisting of eight pairs of subsystems (with 1024 states) nested at four exclusive “grains” of analysis (bases, relations, orders, values) and closed at each grain under a (duality) operation that specifies how the two complementary subsystems act as reciprocal context of mutual constraint”.

The coalition model represents the symmetry of such constraints that exist within the ecosystem between the animal and its environment. In summary, the coalition model suggests that the organization of perception and action within the ecosystem is not a mere achievement of the animal’s nervous system but rather an activity of the environment. This model is motivated by the nature of realism that exists in environment and addresses issues associated with realism by contending that objects of perception and their organizations exist even in the absence of the perceiver (when no perception occurs). This formalism has some disadvantages as it leaves some critical questions unanswered.

Firstly, they provide no explanation of how their formalism handles affordances that are concurrently available to multiple animals that dwell within the ecosystem. In other words, how does a single affordance or niche (that is concurrently available) become actualized into actions by some (but not all) animals that inhabit the ecosystem?

Second, there is a lack of explanation about the stochastic nature of AES. Their formalism does not address how affordances randomly evolve within the dynamic environment.

Third, the spatio-temporal specification of affordance is not realized through this formalism. Wells (2002) remarks that another issue associated with this formalism is the lack of specificity that is revealed through the absence of substantive duals. He also adds that coalitions provide an explanation of affordances through syntactic duals. Syntactic

duals are created by stipulative definitions, but substantive duals depend on the prior existence of deeper relations that provide meaning and yet will also contain syntactic duals. However, in order to explain affordance, substantive duals (that depend on the prior existence of deeper mutual relations) are required. The failure to provide substantive duals leads to a circular argument within the definition of affordance using coalitions. The circular argument is that, if substantive duality between affordance and effectivity exists then there will be syntactic duality. There is (by definition) a syntactic duality, which leads to a substantive duality. Finally, an inconsistency exists in the bounding of the set of dual covariate variables, which is bounded (Shaw and Turvey, 1981 p.390) as well as unbounded (Shaw and Turvey, 1981 p.392), within the same coalitional model.

2.2.3.2 Turvey (1992):

Turvey presents a materialist and dynamicist perspective on the ecological ontology of affordance with links to prospective control. Turvey bases the definition of affordance in terms of dispositional properties. A disposition is a property of a thing that is potential or latent or possible (i.e. not occurrent). Dispositions occurs in pairs, therefore Turvey argues that affordance is a property with a real meaning that occurs as a disposition in the environment, which is complemented by another property of the animal known as *effectivity*. He states that affordance and effectivity (which reflects an animal's capability) differ qualitatively (Vicente and Rasmussen, 1990) and have equal importance. He

concurs with Gibson's definition that affordances can be directly perceived, are invariant and persistent. Turvey (1992, p.180) offers a formal definition for affordance as follows:

Let Wpq (e.g., a person-climbing-stairs system) = $j(Xp, Zq)$ be composed of different things Z (person) and X (stairs). Let p be a property of X and q be a property of Z . Then p is said to be affordance of X and q the effectivity of Z (i.e. the complement of p), if and only if there exists a third property t such that

- (i) $Wpq = j(Xp, Zq)$ possesses t
- (ii) $Wpq = j(Xp, Zq)$ possesses neither p nor q
- (iii) Neither Z nor X possesses t

The operator j is the juxtaposition function and acts as the function that maps the environmental affordances with an animal's effectivities. In retrospect, affordances specified by this definition imply what can possibly happen, not what must happen.

Some of the problems associated with Turvey's definition as noted by Stoffregen (2003) are as follows.

Firstly, Turvey states that dispositions never fail to be actualized when conjoined with suitable circumstances. Disposition and suitable circumstances equals actuality. Stoffregen believes that this poses a problem because if dispositions never fail to be actualized when conjoined with suitable circumstance, a number of affordances would still be actualized; however, a filter that prevents some affordances from being actualized must be used. This filter is the juxtaposition function. Turvey's juxtaposition function needs further specification in order to be practically applied.

Second, Turvey's formalism does not address how concurrency, stochasticity and spatio-temporality can be handled with this definition. The only argument, which Turvey makes with reference to spatio-temporality, is that space and time are not autonomous

and represent relation among facts. They do not constitute the elementary substances that are foundational blocks all things. Furthermore, he concludes that there are no “spaceless things” and “thingless spaces”. Similarly, there are no “durationless things” and “thingless durations”. These arguments exist as ecological laws, but do not attend to the problem of specifying the spatio-temporal relationship between an animal and its environment.

2.2.3.3 Greeno (1994):

Greeno (1994) discusses the interactionist perspective of affordances through situation theory (Barwise and Perry, 1983; Suchman, 1987). The interactionist view primarily relies on the agent-situation interactions in reference to affordances. Affordances and abilities are pivotal to this line of research, where the abilities in activity of the agent depend upon attunement to constraints to which the agent is exposed and attuned. By grounding affordances within situation theory, Greeno provides a partial solution to the issue of spatio-temporality by treating affordances as changes in layout of situations.

The shortcomings of Greeno’s model are that it does not explicitly handle concurrency or stochasticity and provides a partial treatment of spatio-temporal property specification through constraints. It also conflicts with Gibson’s theory, which posits that affordances have meanings, which are directly perceptible. As a result, it would be plausible to think of affordances as constraints that link situation types rather than as conditions under which these constraints hold.

2.2.3.4 Wells (2002):

Wells (2002) addresses the parallels between Gibson's affordance and Turing Machine Theory (Turing, 1936). He suggests that both theories have similar roots that are grounded well within ecological theories. Wells (2002, p.161) quotes that "Turing machines have both structure and dynamics and are, thus, capable of providing models of the animal, the environment, and behavior." He adds that Ullman (1980) demonstrated a case for representing direct perception using computational theories.

Wells provides an analysis of his formalism on a traditional problem in computational theory, known as "Hapless Prisoner (HP)" problem and claims that a Finite State Machine (FSM) could be developed to explain the abstractly defined set of functional states for the HP system based on constraints (affordances) and states (effectivities). He developed a FSM for the HP problem along with a machine table and graphical representation in terms of constraints (affordances), states, and their transitions. Although, this formalism addresses the issues associated with stochasticity and spatio-temporality, it fails to analyze how the FSM formalism handles affordances that are concurrently available to multiple animals. For instance, if two prisoners are writing into the same sheet of paper divided into squares, how could the model represent their turn taking policies and current states within the ecosystem?

2.2.3.5 Stoffregen (2003):

Stoffregen (2003) treats affordance as an emergent higher-level property of the AES. He offers an alternative definition, which is a refinement to Turvey's (1992) original definition. Stoffregen (2003, p.123) states:

Let Wpq (e.g., a person-climbing-stairs system) = (Xp, Zq) be composed of different things Z (e.g., person) and X (e.g., stairs).

Let p be a property of X and q be a property of Z .

The relation between p and q , p/q , defines a higher order property (i.e., a property of the animal–environment system), h .

Then h is said to be an affordance of Wpq if and only if

- (i) $Wpq = (Xp, Zq)$ possesses h
- (ii) Neither Z nor X possesses h

Affordances are what one *can* do, not what one *must* do. In contrast to Turvey's (1992) assumption, Stoffregen claims that effectivities are not qualitatively distinct complements of affordances but are subordinate to affordances. Stoffregen (2003, p.124) also claims that affordances are “opportunities for action; they are properties of the animal–environment system that determine what can be done.”

Stoffregen claims that defining affordances as emergent properties of the AES preserves the prospective nature while supporting the fact that opportunities for action arise out of extant reality. For instance, if there is water in the pool and a person can swim, then swimming is possible; that is, it may happen in the future. Furthermore, his formalism describes *behavior* as what happens at the conjunction of complementary affordances and intentions or goals. A given behavior b (e.g., swimming) will occur if and only if, an affordance and its complementary intention co-occur at the same point in

the space-time continuum, where they are selected using a psychological choice function, m . Many affordances exist and persist but it does not mean that every one of them would be exploited at any given place or time. From the unlimited set of affordances, intentions select those behaviors that will be attempted (Van Orden and Holden, 2002). In defining behavior, there is a need to determine which intentions will be acted on and this is done by the psychological choice function. Both behavior and intentions are properties of the AES. In contrast, Turvey (1992) suggests the use of a filter (juxtaposition function j) to prevent the actualization of some affordances, which can prevent only emergent but not persistent affordances.

Once again, the problem associated with this formalism is that there is no consideration provided to characteristics such as concurrency and stochasticity. The psychological choice function in this formalism is not clearly defined. Furthermore, Kirlik (2004) argues that Stoffregen's definition does not place any constraints on which relational or emergent properties deserve to be treated as affordances thus allowing any relational property based on the AES to be considered as affordance. This causes a missing link between affordances and the notion of "*opportunity for action*".

2.3 CPN Formalism for Gibson's Affordance

In this section, some fundamental concerns that address how CPN formalism is suitable for modeling Gibson's affordance theory are answered. The basic elements of the CPN models are shown in Table A-1 (Appendix A).

2.3.1 Need for New Affordance Formalism

Turvey provides a formalism that relates closely to Gibson's affordances, but does not address issues such as concurrency, stochasticity and spatio-temporality within the environment. The formalism proposed by Wells (2002) uses FSM but it does not adequately address concurrency in the environment. The following questions remain unanswered in Wells's formalism.

- What would happen if there were two prisoners writing onto the same piece of paper that is separated into small squares?
- How could these prisoners write onto the paper in a concurrent fashion?
- How can they keep track of the affordances (indicating the current state of the system), in light of such concurrency?

Therefore, we need a new formalism that adequately addresses Gibson's affordances including characteristics such as concurrency, stochasticity and spatio-temporality.

2.3.2 Suitability of the CPN formalism for Gibson's Affordance Theory

The CPN formalism fits within a natural context of ecology because it possesses the structure that offers representation capabilities for the dynamics within the environment. CPN is an extension of the finite state Machine (FSM) with a provision for handling concurrency. It can be used to model stochasticity and spatio-temporal properties within the AES by means of the inherent colors or values that can be assigned to each token. Therefore, they are theoretically well-ordained for modeling the characteristics of affordances.

2.4 Research Motivation

“Like many other profound ideas, the concept of affordances is intuitively simple, but its richness makes it hard to pin down precisely - A. J. Wells (2002).”

Given the richness of affordance, many researchers have developed formalisms, which have yielded diverse theories. Wells (2002) scrutinized the models proposed by Shaw and Turvey (1981), Turvey (1992) and Greeno (1994) and proposed a FSM-based model for formalizing affordance theory. Other formal definitions for affordances have also been proposed in areas such as Human Computer Interaction (Norman, 1988), mobile robots (Murphy, 1999; Sarawagi and Horiguchi, 2000) and product design (Maier and Fadel, 2001; Galvao and Sato, 2005).

Shaw and Turvey (1981) used coalitions as mathematical model of an ecosystem in order to explain the duality relation, which they claim, exists between affordances and effectivities. They proposed an affordance schema and used a transform function, however Wells (2002) states that their formalism lacks substantive duality (which is fundamental to the transform function, which transforms affordances into effectivities and vice versa) and adds that their definition is not trivial and leads to a circular argument. Their schema also leads to open question, such as, “should one always expect to find affordances equal to the complete enumerations of the orderings within their schema?” Turvey and Shaw (1995) rejected plain dualism and urged that the relation between an animal and its environment be modeled in terms of the concept of reciprocal contexts.

Turvey (1992) explained affordances within the context of prospective control and treated it as a real dispositional property that is complemented by another property of the animal. The fundamental basis of Turvey's definition, which states that dispositions never fail to be actualized when conjoined with suitable circumstances, contradicts what happens in reality. He claims that disposition and suitable circumstances equals actuality; however, in reality, there exist many affordances (dispositions) and suitable circumstances that are not actualized by the animal despite suitable circumstances. Turvey fails to provide a clear definition for the juxtaposition function used to actualize an affordance into an action.

Greeno (1994) described affordances in the context of situation theory. He argues that affordances are relevant properties in the agent-environment interactions and used the term "ability" to describe the contribution of the agent. Greeno cites Warren and Whang (1987), and argues that their empirical work has treated affordances as a "graded property" that allows degrees of presence. He links affordance theory with situation theory and comments that meanings evolve from the interactions of real, living things and their actual environment. Additionally, he cites Barwise (1989) to underpin his argument. A notion of "situation type" is introduced to group a class of situations that have one or more specific relational properties. He contends that affordances and abilities can be characterized into conditional constraints, which can then be analyzed within the context of situation theory. The main drawback with this approach is that it conflicts with Gibson's theory, which suggests that affordances have real meanings that are directly perceived from the environment. In Greeno's case, it would be plausible to think of

affordances as constraints that link situation types rather than as conditions under which constraints hold.

Wells (2002) provided the most comprehensive theory by recognizing the parallels between Alan Turing's Abstract Machine Theory (Turing, 1936-1937/1965) with affordance theory. He argues that both theories are founded based on the concepts that constitute the laws of an ecological approach. A Finite State Machine (FSM) provides a natural means of expressing affordances and effectivities based on the characteristics of the animal and its environment. An example is provided using the Hapless Prisoner (HP) problem, which exemplifies how a machine table can be generated with reference to the affordances (treated as configurations) in the environment and effectivities of the animal. A temporal analysis of the HP problem is also furnished in terms of state transitions. The problem, however is this FSM-based formalism does not address the issues related to concurrency, which exists within the environment.

Stoffregen (2003) proposed the formalism based on a modification to Turvey's (1992) original definition of affordance theory. He contended that affordances are higher-level relational or emergent properties that belong to the AES in contrast to Turvey's treatment of affordances as dispositional properties of the environment, which occurs as a complementary dual to effectivity (property of the animal). Kirlik (2004) argues that one of the fundamental pitfalls of this definition is that it places no constraints on the basis by which such relational or emergent properties can be treated as affordances of the AES. Consequently, any relational property (even though meaningless) which can be established within an AES could be included as an affordance. Kirlik explains that this causes a missing link between affordances and the notion of "*opportunity for action*" and

introduces a problem for specification of meaningful affordances. Kirlik (2004) quotes that:

“As such, Stoffregen’s definition lacks any substantive linkage to the “opportunity for action” notion that has accounted for the scientific utility of the concept to date, a linkage I suggest should be preserved in any definition of affordances.”

In his reply to Kirlik’s (2004) commentary, Stoffregen (2004) agrees that affordances should be restricted to opportunities for action. In addition, Stoffregen defends that the affordances, which are specified by his definition, are bounded, and action could and should include the greater majority of behavior exhibited by animals.

The downsides of prior formalisms clearly emphasize the need for an overarching formalism that explains and models affordance theory within the context of both the environment and the animal. This formalism must be consistent with what Gibson intended the theory to be and must represent the characteristics such as concurrency, stochasticity and spatio-temporality that persist within the environment. This research is motivated by a need for a new formalism that would enable us to model affordances from the perspective of its fundamental properties including concurrent, stochastic and spatio-temporal characteristics that prevail within the AES.

2.4.1 Characteristics of the Affordance Formalism

Several formalisms have been proposed earlier based on the continually evolving comprehension about affordance theory. The formalisms reviewed in the previous section address some but not all of these issues in their entirety. Table 2-2 shows the limitation of the various formalisms of affordances discussed earlier.

Table 2-2: Affordance formalisms and their limitations

Formalism Type	Is Concurrency Handled?	Is Stochasticity Handled?	Is Spatio-Temporal Properties Specified?
Shaw and Turvey (1981)	No	No	No
Turvey (1992)	No	No	No
Greeno (1994)	No	No	Yes
Wells (2002)	No	Yes	Yes
Stoffregen (2003)	No	No	No

The nonexistence of a current formalism that would adequately deal with all three characteristic issues collectively necessitates a need for a new formalism. This new formalism should allow verification within the context of the ecosystem.

2.4.2 Implications of this Formalism

The new formalism would enable us to analyze affordances within the context of the AES and illustrate how concurrency can be handled within this formalism. The new formalism would also promote an understanding of the stochastic nature of the affordances within the AES. Moreover, the new formalism would also allow one to envisage the affordances, effectivities and their actualizations within the AES, in terms of state space and time. Overall, the formalism would allow one to generate a graphical representation, develop mathematical notations and computational model of Gibson's affordance.

2.5 Chapter Summary

In this chapter, the ecological approach to visual perception of Gibson's affordances was discussed. Then, the existing formalisms for affordance were discussed. The shortcomings of these current formalisms were also highlighted in coherence with the properties of affordances including characteristics such as concurrency, stochasticity and spatio-temporality that persist within the environment. Then, a need for developing a new formalism based on CPN techniques was established along with its implications.

Chapter 3

MODEL DEVELOPMENT

In this chapter, research questions relevant to affordance-based CPN model development are raised in section **3.1**, followed by the description of the problem statement in section **3.2**. Section **3.3** proposes a mathematical basis for Gibson's affordances. Section **3.4** provides a conceptual model to explain the computational representation for the affordance-based CPN formalism provided in section **3.5**. The details of an alternative random CPN model used for comparison are discussed in this section. The formative analysis overlay for the set of affordances offered by the environment is described in section **3.6**.

3.1 Research Questions

After having established the motivation and implications of this research, it is important to ponder questions that would enable us to understand the purpose of this research. The following questions relevant to Gibson's affordance theory are answered through this research.

1. Is CPN an adequate formalism for representing Gibson's affordances, while including characteristics such as concurrency, stochasticity and spatio-temporality?
2. Could such a model predict the niche and actualized action based on the set of affordances and effectivities assumed within the problem space?
3. How could the precision of this CPN model be verified based on the subset of affordances, effectivities and actions assumed within the problem space?
4. Could this CPN model be generalized using a mathematical notation?

A CPN model that addresses these research questions and represents the properties of affordance including characteristics such as *concurrency*, *stochasticity* and *spatio-temporality* is presented in the subsequent sections within this chapter. This CPN model can also be run as an executable simulation using "CPN Tools" (Jensen, 1992 & 1995; CPN Group, 2005) to generate the driver related performance metrics. The precision of the model is verified by analyzing the deviation between the empirical and model predicted driver performance data.

3.2 Problem Statement

Consider a *Highway-Lane-Driver System* (HLDS) animal environment system with two highway lanes and an exit lane as shown in Figure 3-1. Assume that, there are two drivers sharing the HLDS, a *confederate driver* (CD: driver 1) and a *subject driver* (SD: driver 2). While CD follows a scripted predetermined path, a SD is allowed to drive freely

within the HLDS. This enables us to elicit various driving behaviors from SD by controlling CD's path.

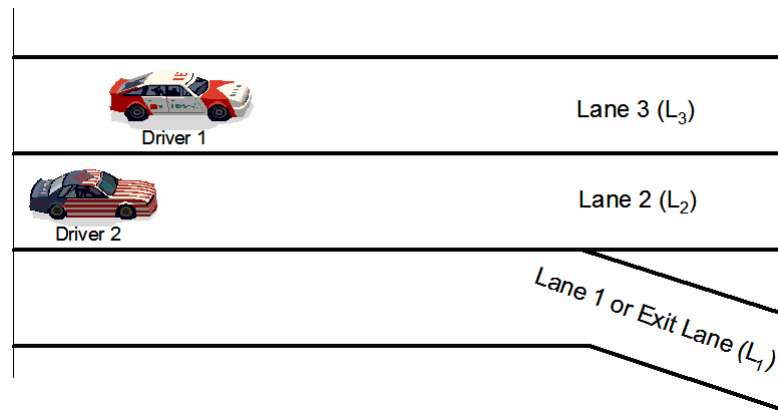


Figure 3-1: Highway Lane Driver System with One Exit Lane

A lane (L_i) within the HLDS provides the affordance “*is-drivable*” to a driver (d_j), if and only if, the lane is empty for at least three car lengths (assumed safety factor for moving into lane without crashing) at any given time. It is assumed that the drivers possess the capability to perceive the affordances offered by the environment in a concurrent manner, and would therefore be able to decide whether their adjacent lane provides the affordance “*is-drivable*” or not. In addition to this, a driver is also capable of perceiving the availability of multiple affordances with respect to other driver (animal) that are part of the HLDS. The spatio-temporal location is inherently specified within the HLDS representation, as the driver would be able to perceive the current lane, as well as the position within the lane occupied by the other driver. Let us now assume that the goal of both drivers is to exit the HLDS from their respective lanes by maintaining their target speed without crashing into each other. In order to reduce the complexity of this problem space, we also assume that the drivers do not accelerate or decelerate during the course of

the scenario. In other words, they are instructed to reach and maintain their target velocity provided to them at the beginning of each test scenario. This problem of exiting the highway is referred to as “Highway Exit” problem space (HEPS). Given this problem description, a consummate formalism is required to represent the affordance structure that exists among these drivers, based on their effectivities and the affordances offered by the highway lanes. The criteria for the existence of AES characteristics including concurrency, stochasticity and spatio-temporality are described in Table 3-1.

Table 3-1: Criteria for Existence of AES Characteristics

CRITERIA FOR EXISTENCE OF AES CHARACTERISTICS FOR THE DRIVER (ANIMAL) AND HIGHWAY LANE SYSTEM (ENVIRONMENT)	
<i>AES CHARACTERISTICS</i>	<i>CRITERIA DESCRIPTION (UNIT OF ANALYSIS: SUBJECT DRIVER)</i>
CONCURRENCY (WITH CONFLICT)	<i>CONCURRENCY</i> : Two or more effectivities (driver capabilities) afford an action for a driver at the same time.
	<i>CONFLICT</i> : Both drivers have concurrent access to an affordance (lane-block position) within the environment.
STOCHASTICITY	The location of the exit is not fixed and is randomly altered within each scenario by adjusting the vertical and horizontal proximity of both drivers to the exit lane and the relative velocity of the subject driver with respect to the confederate driver.
SPATIO-TEMPORALITY	The location (lane and block position) of the confederate driver is known with reference to the environment of the subject driver.

These AES characteristics are included within the experimental scenarios, while empirically evaluating driver behavior data.

3.3 Mathematical Model

In this section, a mathematical model based on trigonometric modeling techniques is presented to generalize the representation of affordances within HEPS domain. The fundamental assumption is that a driver is capable of visually perceiving other drivers within the HLDS environment. However, the capability of a driver to perceive a blind spot is not considered within the mathematical model to reduce the complexity of the model. In order to understand the model better, we must first clarify the parameters associated with the model. The visual and physical angles associated with the subject driver are shown in Figure 3-2. The Center of Gravity (CoG) of SD's car, also known as the observation point for SD is located about at the same point as the SD's eyes. The black circle around CoG of SD represents the distance (d_1) covered by SD in unit time (i.e., 1 second). The angles between the red lines above and below the horizontal +X-axis represent the left (a_1) and right (a_2) extreme physical bound angles. These angles also depict the physical turning radius of the wheels of SD's car in both left and right directions. On the other hand, the angles between the blue lines above and below the horizontal +X-axis represent the left (β_1) and right (β_2) extreme visual bound angles, which indicates the visual range of sight that can be perceived by SD while looking straight ahead. *The location of CD affects the affordances of SD, if and only if, CD lies within the extreme physical bounds of SD.*

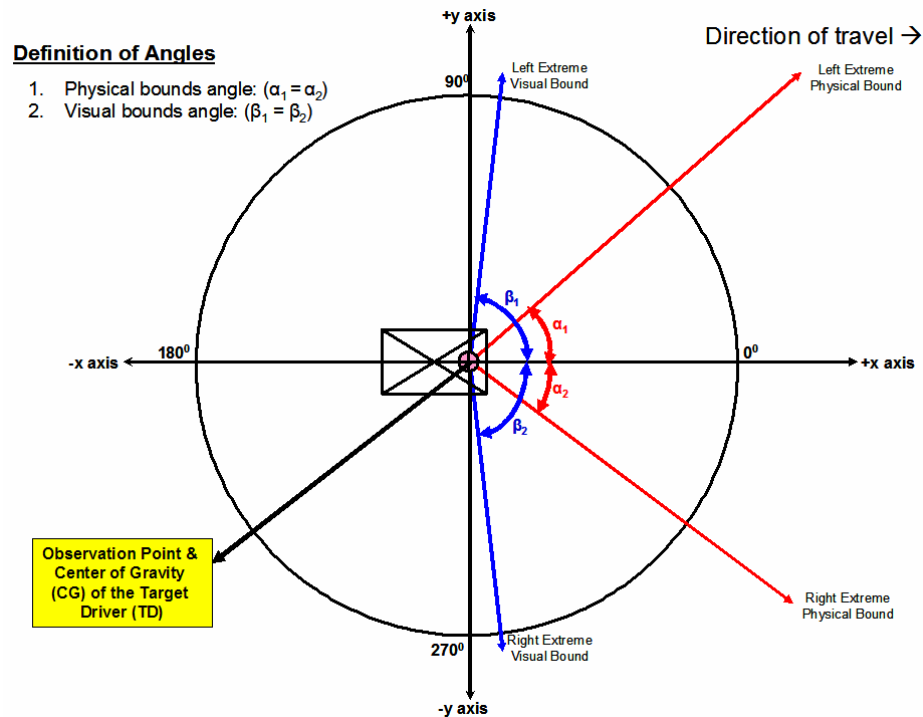


Figure 3-2: Visual and Physical Angles for SD

The perceptual angles associated with SD while perceiving a CD who lies straight ahead are shown in Figure 3-3. The perceptual angle between the horizontal +X-axis to the left most and right most rear-edge of CD's car is denoted by θ_1 and θ_2 , respectively. Similarly, the perceptual angle between the horizontal +X-axis to the left most and right most front-edge of CD's car is denoted by the angles θ_3 and θ_4 . It may not always be possible to perceive all the edges of CD's car directly. Therefore, a perceptual angle for an edge that is not directly visible to SD is indicated by a dash (') after the angle. For instance, in Figure 3-3 the perceptual angle θ_3' is same as θ_3 and indicates that the left most front-edge of CD's car is not directly visible to SD.

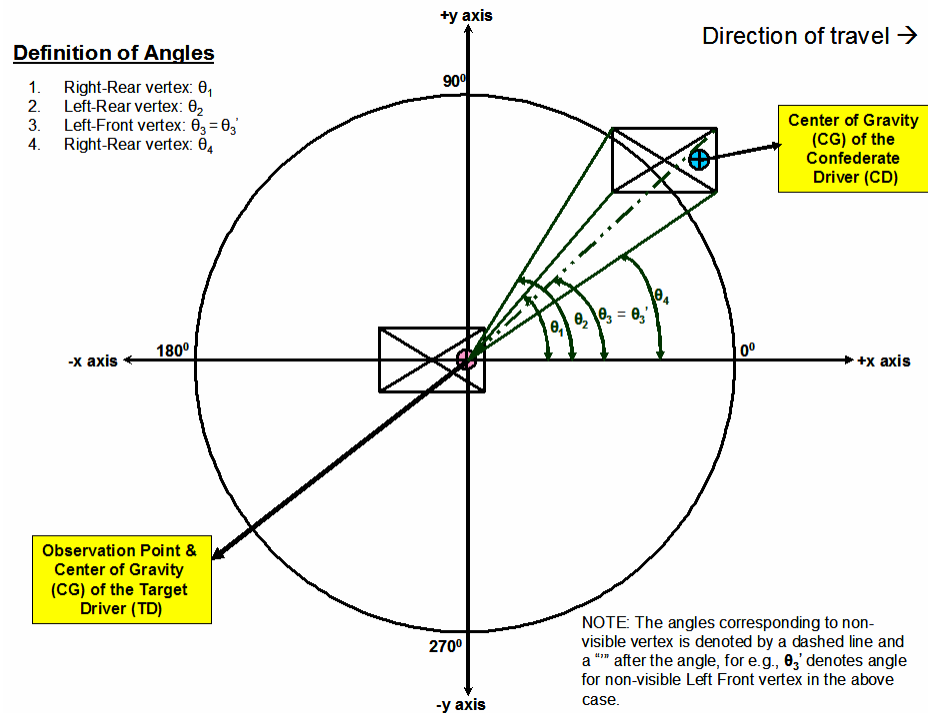


Figure 3-3: Perceptual Angles for SD

The CD affects the affordances of SD only when the CD lies within the physical bounds for SD. An affordance pocket represents a region within the highway lane that allows a driver to travel through the HLDS. An affordance pocket is said to be “open”, when it allows the driver to travel safely without crashing into an obstacle. On the other hand, an affordance pocket is “closed”, when travel through this region leads to potentially unsafe conditions such as crashing into another driver or the guardrails on the highway lane. The affordances pockets that remain available (open) and unavailable (closed) for SD are illustrated in Figure 3-4.

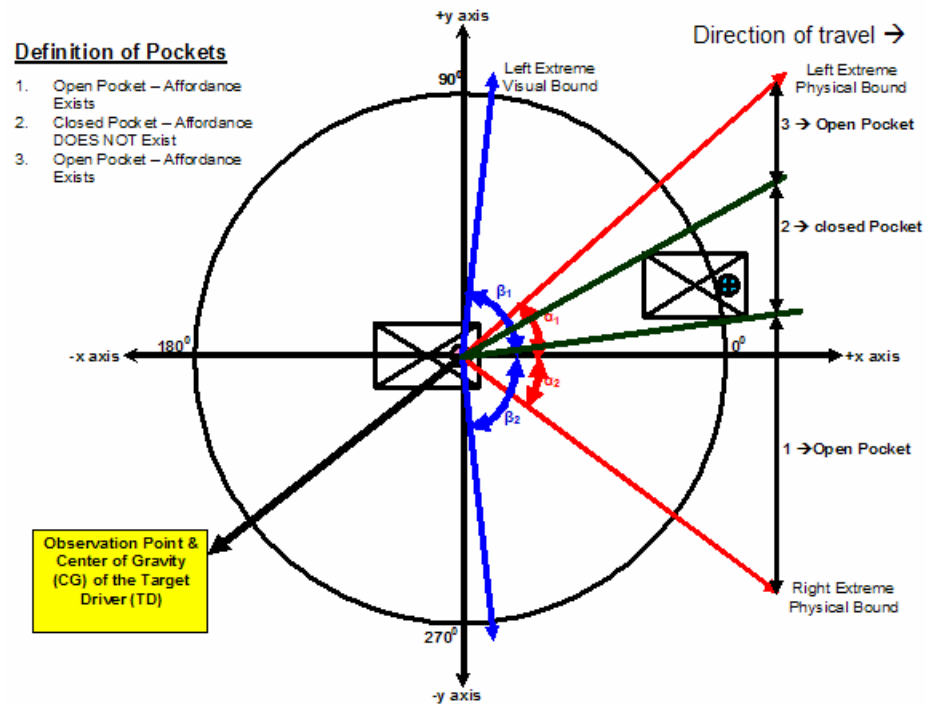


Figure 3-4: Affordance Pockets for SD

The mathematical models for the five cases that reflect the ways in which CD affects the affordance pockets associated with SD are discussed further in the rest of this section.

3.3.1 Case 1 – CD is on the Left Extreme Physical Bound of SD

Figure 3-5 shows the case where CD is located on the left extreme physical bound of SD. Let the length and width of the SD's car be denoted by L_1 and W_1 , respectively. The horizontal distance between the front-edge of SD's car and SD's CoG (also known as observation point) is denoted by L_3 . Similarly, the length and width of the SD's car is denoted by L_2 and W_2 , respectively and the distance between the front-edge

of CD's car and CD's CoG is denoted by L_4 . The distance traversed by SD in unit time t is given by d_1 .

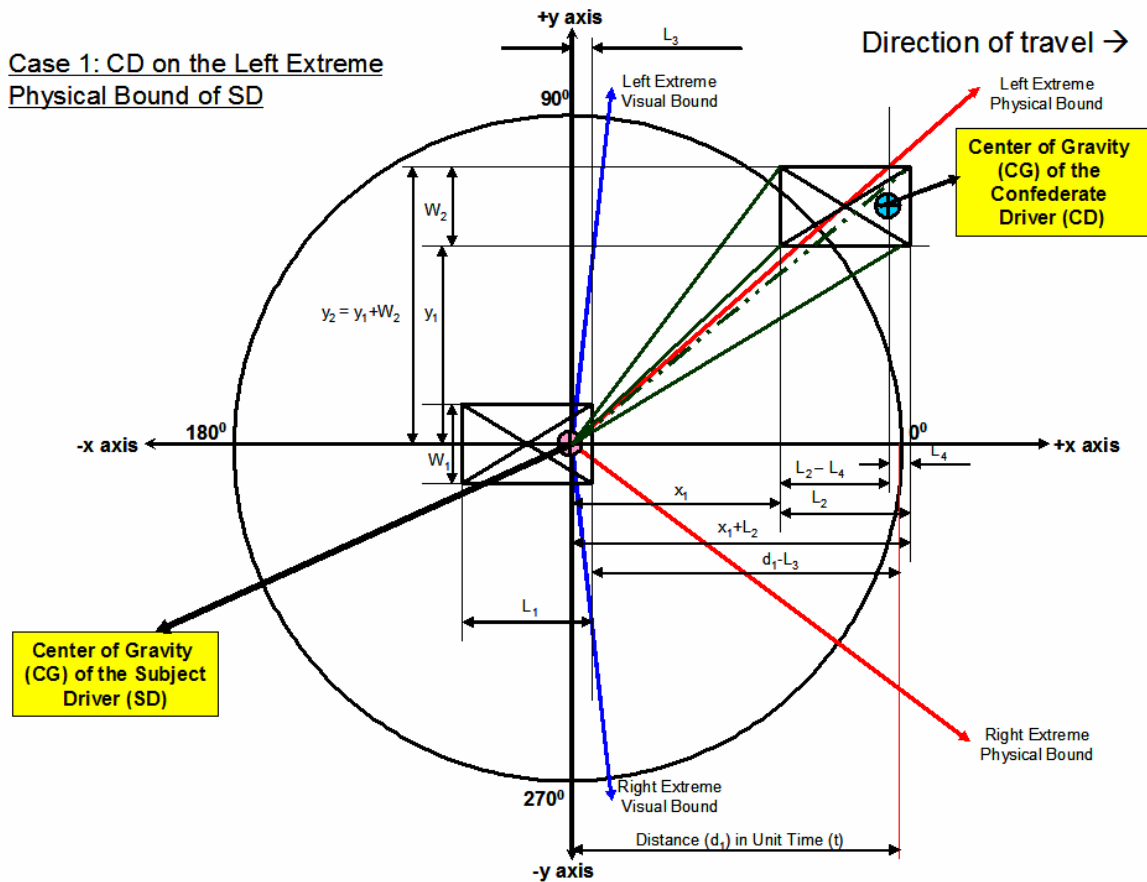


Figure 3-5: Case 1 – CD on Left Extreme Physical Bound of SD

The assumptions regarding the length and width of SD's car and CD's car will be consistently used throughout the rest of this mathematical modeling section unless specified otherwise. Let x_1 be the horizontal distance between SD's CoG and the rear-edge of CD's car. Similarly, let y_1 denote the vertical distance between SD's CoG and the right-edge of CD's car, and y_2 denote the vertical distance between SD's CoG and the left-edge of CD's car.

Based on the earlier assumptions about CD's location, one open and one closed affordance pocket are created for case 1. The perceptual angles (θ_1 , θ_2 and θ_3) and the angle (θ_4) that separates the open pocket from the closed pocket are computed as follows.

$$\begin{aligned} \text{Given : } y_2 &= y_1 + W_2 \\ \mathbf{q}_1 &= \tan^{-1}\left(\frac{y_1}{x_1}\right), \mathbf{q}_2 = \tan^{-1}\left(\frac{y_1 + W_2}{x_1}\right) \\ \mathbf{q}_3 = \mathbf{q}_3' &= \tan^{-1}\left(\frac{y_1 + W_2}{x_1 + L_2}\right), \mathbf{q}_4 = \tan^{-1}\left(\frac{y_1}{x_1 + L_2}\right) \end{aligned}$$

Note that, the angle θ_3' ($= \theta_3$) is not directly perceivable angle for SD as the edge associated with this angle is hidden from SD's view.

The open affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from θ_4 to a_2 . Similarly, the closed affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from a_1 to θ_4 .

3.3.2 Case 2 – CD between Left Extreme Physical Bound of SD and +X-axis

The physical location of CD with respect to SD is shown in Figure 3-6. In this case, CD is between the left extreme physical bound of SD and the horizontal +X-axis. The assumptions about the length and width of the cars driven by SD and CD are similar to those specified in the previous case. Similarly, the definition of x_1 , y_1 and y_2 are identical to those provided in the previous case. However, in this case three affordance pockets are created: two available (Open) and one unavailable (Closed).

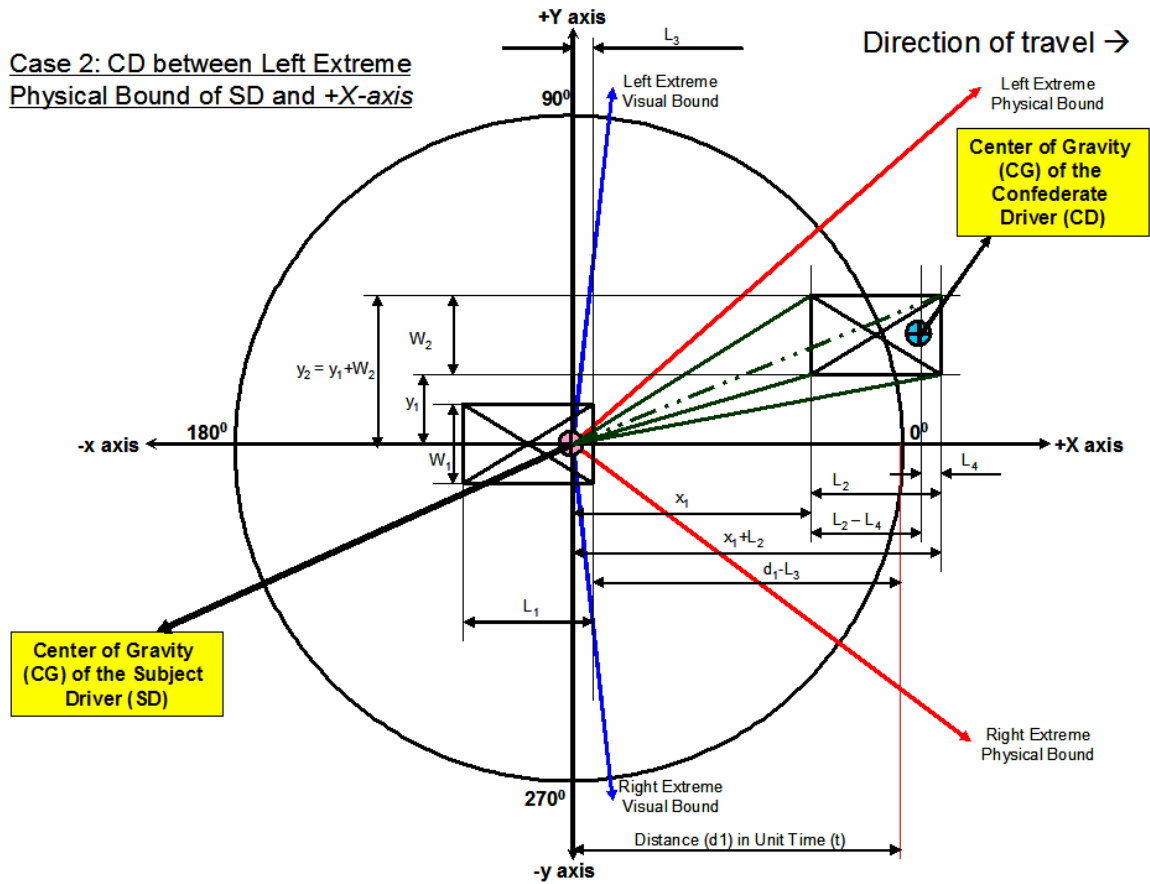


Figure 3-6: Case 2 – CD between Left Extreme Physical Bound of SD and +X-axis

The perceptual angles (q_1 and q_3) and the angles (q_2 and q_4) that separate the two open pockets from the closed pocket are computed as follows.

$$\text{Given : } y_2 = y_1 + W_2$$

$$q_1 = \tan^{-1}\left(\frac{y_1}{x_1}\right), q_2 = \tan^{-1}\left(\frac{y_1 + W_2}{x_1}\right)$$

$$q_3 = q_3' = \tan^{-1}\left(\frac{y_1 + W_2}{x_1 + L_2}\right), q_4 = \tan^{-1}\left(\frac{y_1}{x_1 + L_2}\right)$$

Note that, the angle q_3' ($= q_3$) is not directly perceivable angle for SD as the edge associated with this angle is hidden from SD's view.

The first open affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from a_1 to θ_2 . Similarly, the second open affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from θ_4 to a_2 . The closed affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from θ_2 to θ_4 .

3.3.3 Case 3 – CD on +X-axis

Figure 3-7 shows the location of CD with respect to SD for case 3.

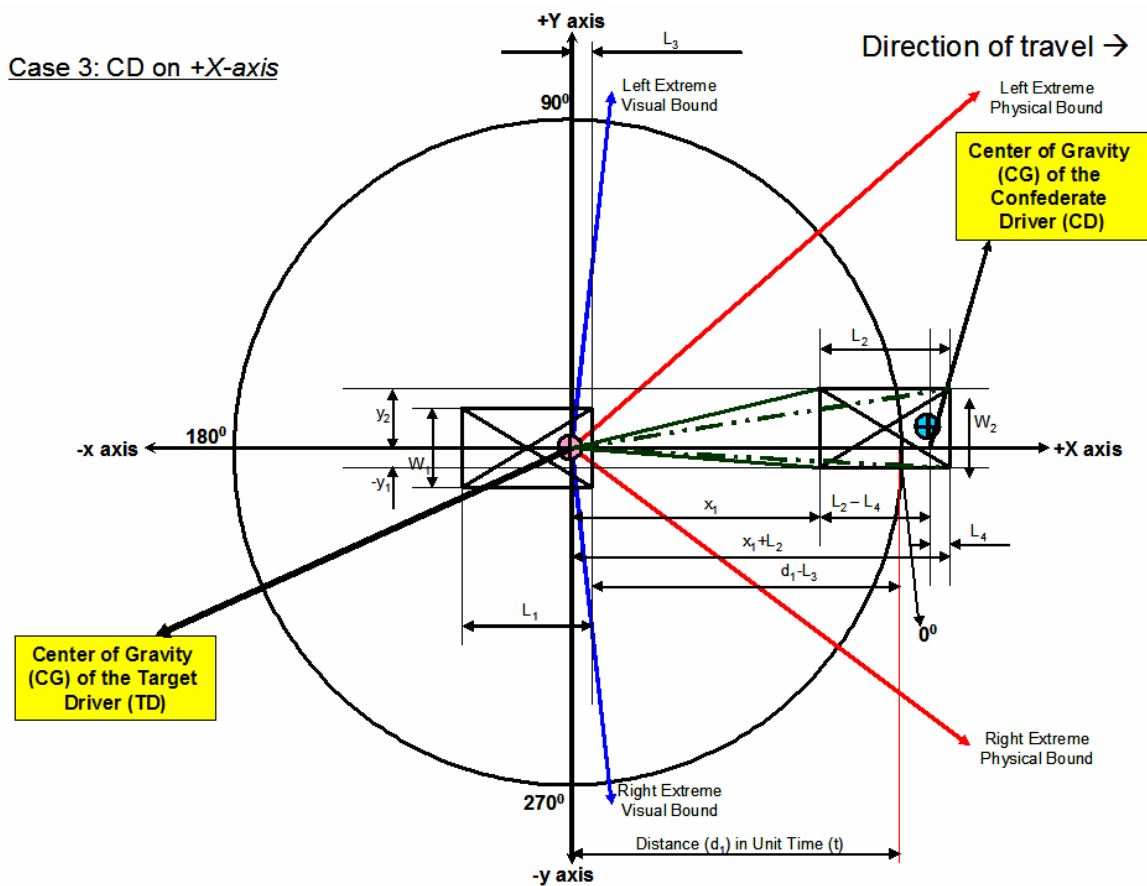


Figure 3-7: CD on +X-axis

In this case, CD lies directly ahead on the $+X$ -axis of SD creating two open pockets and one closed pocket. Therefore, SD can pass CD on either the left or the right side. The length and width of the cars driven by CD and SD are assumed as stated in case 1. As before, x_1 denotes the horizontal distance between SD's CoG and the rear-edge of CD's car. Similarly, y_1 denotes the vertical distance between SD's CoG and the left edge of CD's car. However, $-y_2$ represents the vertical distance between the SD's CoG and the right edge of CD's car. Note that, this value is negative as the right edge of CD lies below the X -axis. This case affects the affordances associated with SD, as CD lies completely within the physical angles (a_1 and a_2) at distance d_1 . We can calculate the perceptual angles ($?_3$ and $?_4$) and the angles ($?_1$ and $?_2$) that separate the two open pockets from the closed pocket as follows.

$$\mathbf{q}_1 = \tan^{-1}\left(\frac{-y_1}{x_1}\right), \mathbf{q}_2 = \tan^{-1}\left(\frac{y_2}{x_1}\right)$$

$$\mathbf{q}_3 = \mathbf{q}_3' = \tan^{-1}\left(\frac{y_2}{x_1 + L_2}\right), \mathbf{q}_4 = \mathbf{q}_4' = \tan^{-1}\left(\frac{-y_1}{x_1 + L_2}\right)$$

Note also that, the angles $?_3'$ ($= ?_3$) and $?_4'$ ($= ?_4$) are not directly perceivable angles for SD as the edges associated with these angles are hidden from SD's view.

The first open affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from a_1 to $?_2$. Similarly, the second open affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from $?_1$ to a_2 . The closed affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from $?_1$ to $?_2$.

3.3.4 Case 4 – CD between +X-axis and Right Extreme Physical Bound of SD

In the fourth case, CD is located within a distance of d_1 between the +X-axis and the right extreme physical bound of SD as shown in Figure 3-8.

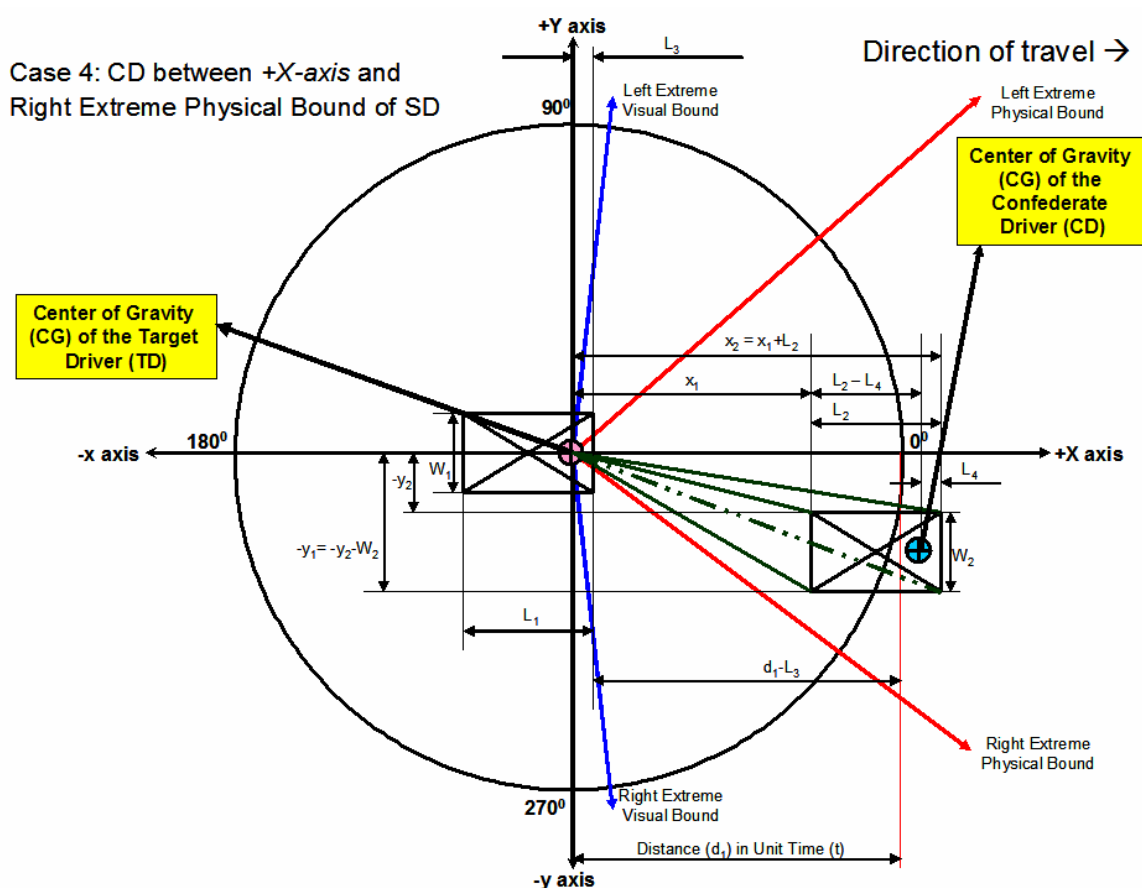


Figure 3-8: Case 4 – CD between +X-axis and Right Extreme Physical Bound of SD

The length and width of the cars driven by CD and SD are assumed as stated in case 1. Let x_1 represent the horizontal distance between SD's CoG and the rear edge of CD's car. However, in this case the values for both y_1 and y_2 are negative and represent the vertical distances between SD's CoG and the left and right edges of CD's car, respectively. This case results in two open and one closed affordance pockets for SD.

Therefore, the perceptual angles (θ_2 and θ_4) and the angles (θ_1 and θ_3) that separate the two open pockets from the closed pocket are computed as given below.

$$\begin{aligned} \text{Given : } -y_1 &= -y_1 - W_2 \\ \mathbf{q}_1 &= \tan^{-1}\left(\frac{-y_1}{x_1}\right), \mathbf{q}_2 = \tan^{-1}\left(\frac{-y_2}{x_1}\right) \\ \mathbf{q}_3 &= \tan^{-1}\left(\frac{-y_2}{x_1 + L_2}\right), \mathbf{q}_4 = \mathbf{q}_4' = \tan^{-1}\left(\frac{-y_1}{x_1 + L_2}\right) \end{aligned}$$

Note also that, the angle θ_4' ($= \theta_4$) is not directly perceivable angle by SD as the edge associated with this angle is hidden from SD's view.

The first open affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from a_1 to θ_3 . Similarly, the second open affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from θ_1 to a_2 . The closed affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from θ_1 to θ_3 . Note that, this case describes the exact opposite situation of case 2.

3.3.5 Case 5 – CD on Right Extreme Physical Bound of SD

Figure 3-9 shows the location of CD with respect to SD for case 5. In this case, CD lies on the right extreme physical bound of SD, which characterizes the exact opposite case for case 1. As before, the length and the width of SD and CD car as assumed in case 1. Similarly, x_1 specifies the horizontal distance between SD's CoG and the rear edge of CD's car. Also, let y_1 and y_2 represent the vertical distances between SD's CoG and the left and right edges of CD's car, respectively.

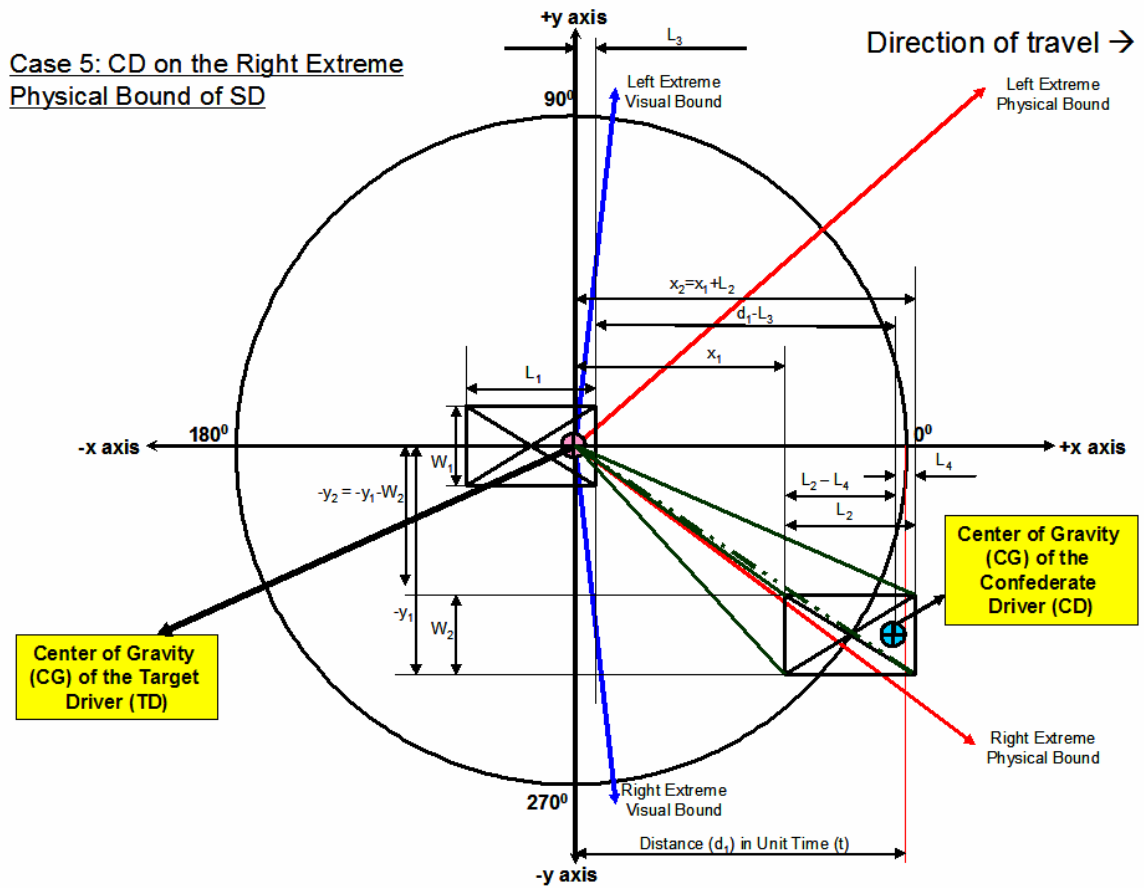


Figure 3-9: Case 5 – CD on Right Extreme Physical Bound of SD

There is one open and one closed pocket that results from this case. The perceptual angles (θ_1 , θ_2 and θ_4) and the angle (θ_3) that separates the open pocket from the closed pocket can be calculated as given below. Note that, the angle θ_4' ($= \theta_4$) is not directly perceivable angle for SD as the edge associated with this angle is hidden from SD's view.

$$\text{Given : } -y_1 = -y_2 - W_2$$

$$\mathbf{q}_1 = \tan^{-1}\left(\frac{-y_1}{x_1}\right), \mathbf{q}_2 = \tan^{-1}\left(\frac{-y_2}{x_1}\right)$$

$$\mathbf{q}_3 = \tan^{-1}\left(\frac{-y_2}{x_1 + L_2}\right), \mathbf{q}_4 = \mathbf{q}_4' = \tan^{-1}\left(\frac{-y_1}{x_1 + L_2}\right)$$

The open affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from a_1 to $?_3$. Similarly, the closed affordance pocket is represented by the angular area traced by a vector of length d_1 , centered on SD's CoG, from $?_3$ to a_2 .

3.4 Conceptual Model

The conceptual model for the HEPS in terms of affordance, effectivity and actualization is shown in Figure 3-10.

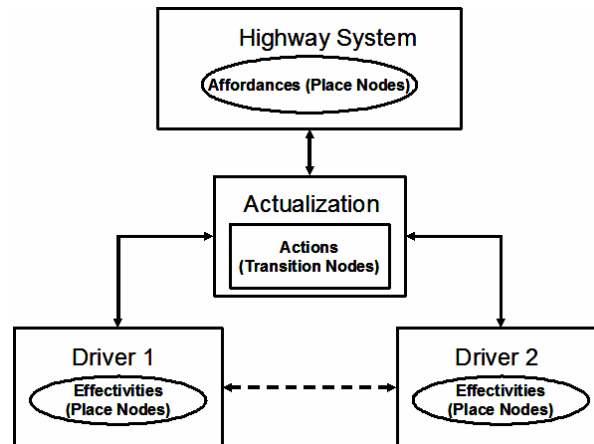


Figure 3-10: Conceptual Model for Highway Exit Problem Space

The drivers possess capabilities (effectivities) that enable them to turn left or right, head straight, accelerate or decelerate. The affordances offered by the HLDS include unoccupied locations on lane 1 (exit lane), lane 2 or lane 3. An invariant combination results from juxtaposing the effectivities of each driver with the lane affordances that are currently available to that driver. This juxtaposition leads to a subset of actions that depict what actions are possible within the current realm of the environment. An actualized action emerges from the driver's willingness (desire) to execute a specific action from this subset of possible actions.

In the CPN model, the highway lanes affordances and driver effectivities are represented as place nodes that hold *Affordance-type Token* (AT) and *Effectivity-type Token* (ET), respectively. The actualization mechanism is a function represented by a transition node that consumes AT and ET, to produce an *Action-type Token* (ACT), which indicates the actualized action resulting from the juxtaposition function (j).

3.5 Developing a New Formalism: Colored Petri Net (CPN) Approach

The CPN formalism presented in this section aims at representing environmental affordances, driver effectivities and actions that can be actualized. The graphical representation and computational model for the CPN formalism of HEPS are also provided in this section.

In order to design and develop the computational CPN model, a tool known as "CPN Tools" (Jensen, 1992 & 1995; CPN Group, 2005) is used. CPN Tools replaced its predecessor "Design/CPN", to become the most popular tool used for designing,

developing and testing CPN. The tool uses a standard language called CPN ML (CPN Markup Language), which is an extension of SML or Standard Markup Language.

3.5.1 Affordance-based CPN Model

In this section, the details of an affordance-based CPN model (Thiruvengada and Rothrock, 2006a and 2006b) are discussed and along with its graphical and computational representations. The CPN model computes the set of affordances offered to the SD within the HDLS environment. Then, the model picks an affordance to be actualized during the subsequent update cycle from the set of affordances using the juxtaposition function (j). The specific details of variable declarations and functions used within the affordance-based CPN model are provided in Appendix B.

3.5.1.1 Analysis Overlay for the Model

In order to understand each of the individual component models within the CPN model, we must first clarify the analysis overlay for the HLDS environment. The HLDS system is represented using the analysis overlay shown in Figure 3-11. The rows labeled L1, L2 and L3 represent lane 1 (exit lane), lane 2 and lane 3, respectively. Each lane spans a width of 2.5 meters (Standard US Highway lane width). The columns labeled 1 – 80 represent blocks of equal size and span a length of 4.5 meters (an average car length). The entire length of this HLDS system is equal to 360 meters (which is 42 meters short of a quarter mile track).

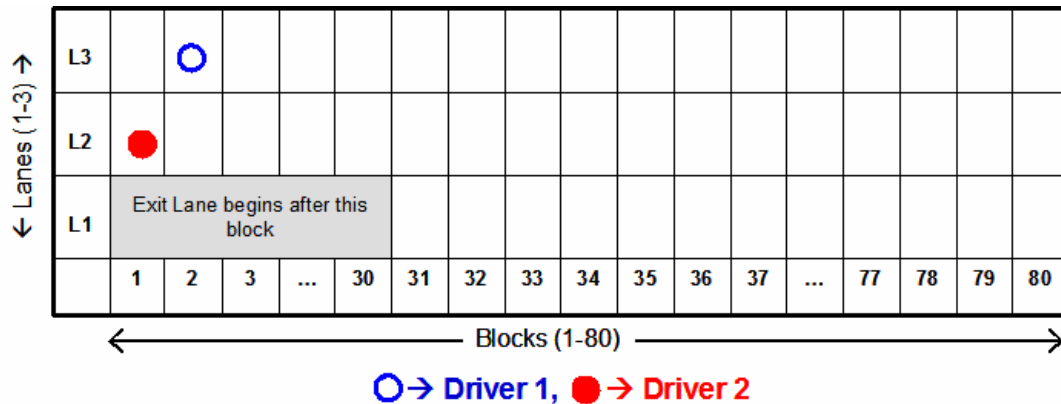


Figure 3-11: Analysis Overlay for Highway Lane Driver System

The lane-block position of CD and SD is indicated by clear (blue) and shaded (red) circle, respectively, within the analysis overlay. This analysis overlay will be consistently used throughout the rest of this document unless indicated otherwise.

3.5.1.2 Highway Exit Problem Space (HEPS)

The block representation of Highway Exit Problem Space (HEPS) is shown in Figure 3-12. The affordance-based CPN model consists of three main component models: *Lane Model* (LM), *Driver Model* (DM) and *Actualization Model* (AM). There are two types of driver models (CDM; SDM) and three identical lane models (one each for lane: Lane 1 [or Exit Lane], Lane 2, and Lane 3). There is also an Initialization Module (IM), which is used to initialize the LM based on the driver attributes in CDM and SDM.

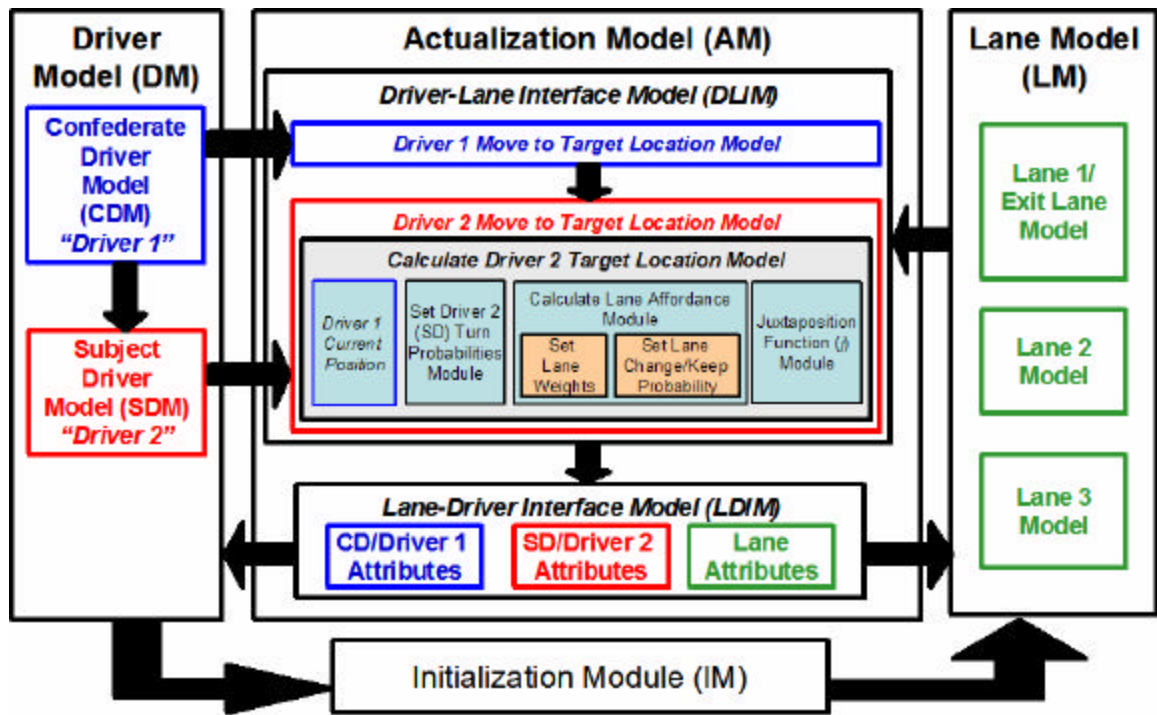


Figure 3-12: Block Representation of Highway Exit Problem Space

The CPN model representation for the Highway Exit Problem Space (HEPS) is shown in Figure 3-13. During the first step, the driver attributes and the lane-block occupancy information for each driver are initialized in the DM and LM, respectively. Then, the complete path information for CD and the initial lane-block occupancy information for SD are input through external files ("Driver1_Input.txt" and "Driver2_Input.txt"), before the model is executed using the simulation utility within CPN Tools (Jensen 1992 & 1995). In the second step, the AM consumes tokens from both DM (CDM and SDM) and LM to generate an actualized action for SD based on the set of lane affordances, turn probabilities and juxtaposition function (j). Then, during the final step, the actualized action results in the attributes of SD and CD being updated, which are then passed to the CDM and SDM, respectively.

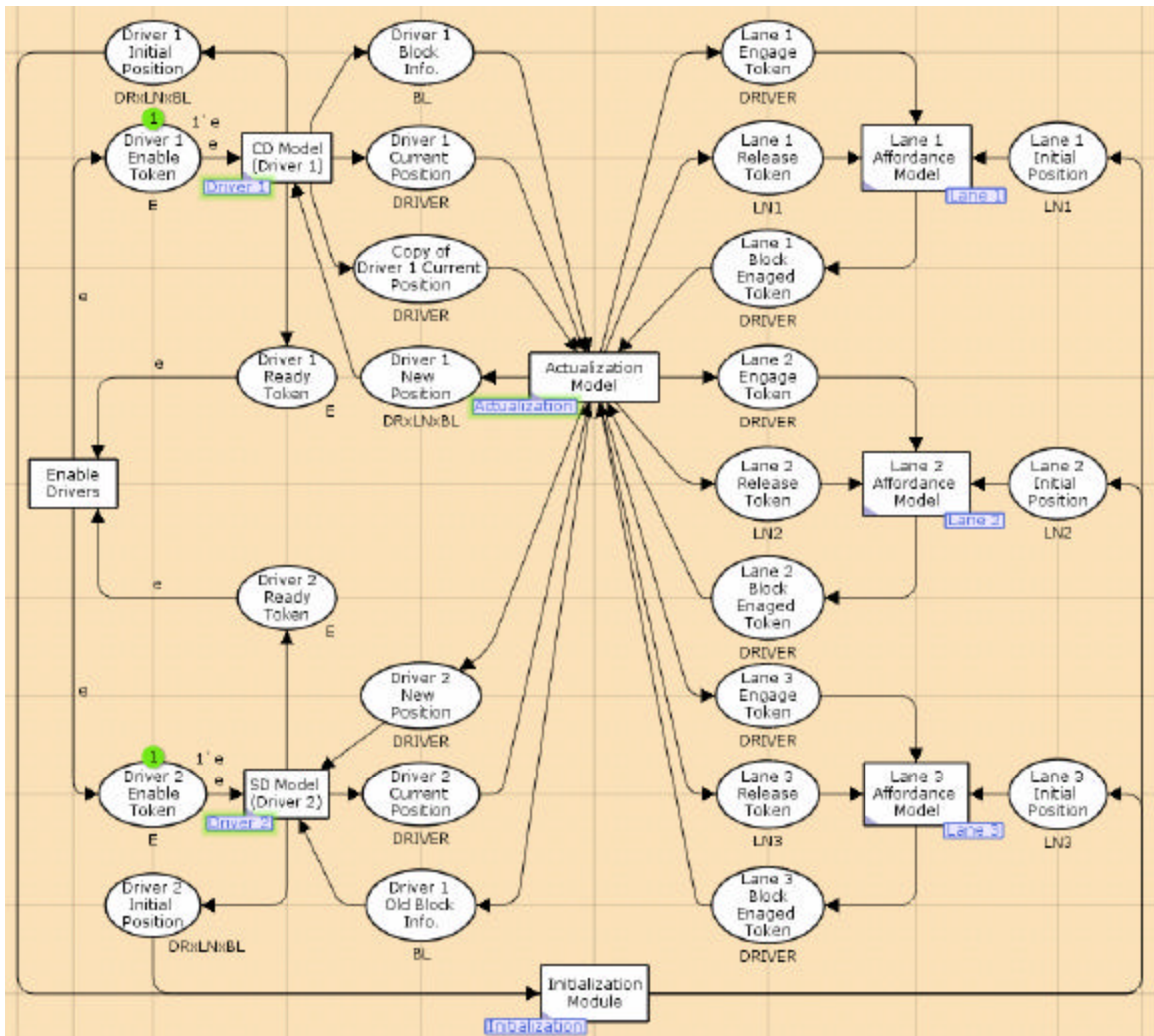


Figure 3-13: CPN for Highway Exit problem Space

The new attributes of SD are recorded using an output file (*Driver2_Output.txt*) during each update cycle for post-hoc data analysis. Steps 2 and 3 are repeated until the end of the scenario (i.e., when both CD and SD pass 80 blocks). The details of each of these models are discussed in the following sections.

3.5.1.3 Lane Model (LM)

The Lane Model (LM) for representing the affordances for Lane 3 is shown in Figure 3-14. The Lane Models for Lane 1 and Lane 2 are identical to Lane 3, and therefore are not discussed in detail here. There are two crucial place nodes within the Lane Model: “Lane n Available” and “Lane n Used”, which act as placeholders for AT and indicates the state of each block within that lane. For instance, the presence of an AT within “Lane 3 Used” indicates that the block within this lane is in use and occupied by a driver, and the presence of an AT within “Lane 3 Available” specifies that this block is available for occupancy by a driver. Therefore, an AT always specifies the spatio-temporal relationship between the driver (animal) and highway lane-block (environment) at any given time. In the above Figure, the place node “Lane 3 Available” indicates that there are 160 blocks³ (Lane 3, Blocks 1–160) that are unoccupied and currently available for occupation by any driver and 0 lane-blocks are currently used (as indicated by “Lane 3 Used” place node). In addition to this, two transition nodes (“Lane 3 Block Engage” and “Lane 3 Block Release”) transfer affordance tokens between these two place nodes. These transition nodes are triggered by the actualization model when an effectivity token becomes available from the Driver Model (see DM 3.5.1.4). The initial lane-block position of each driver is set by the transition “Initialize Lane 3 Occupied Blocks”, which transfers tokens from available state to used state. Once the simulation begins execution, this place no longer will contain any tokens.

³ Each lane is instantiated with 160 blocks ((twice the length of the course → 80 blocks) x 2) to allow the CPN model to complete its execution during simulation run without stalling. However, only SD information pertaining to the length of the course is recorded for data analysis.

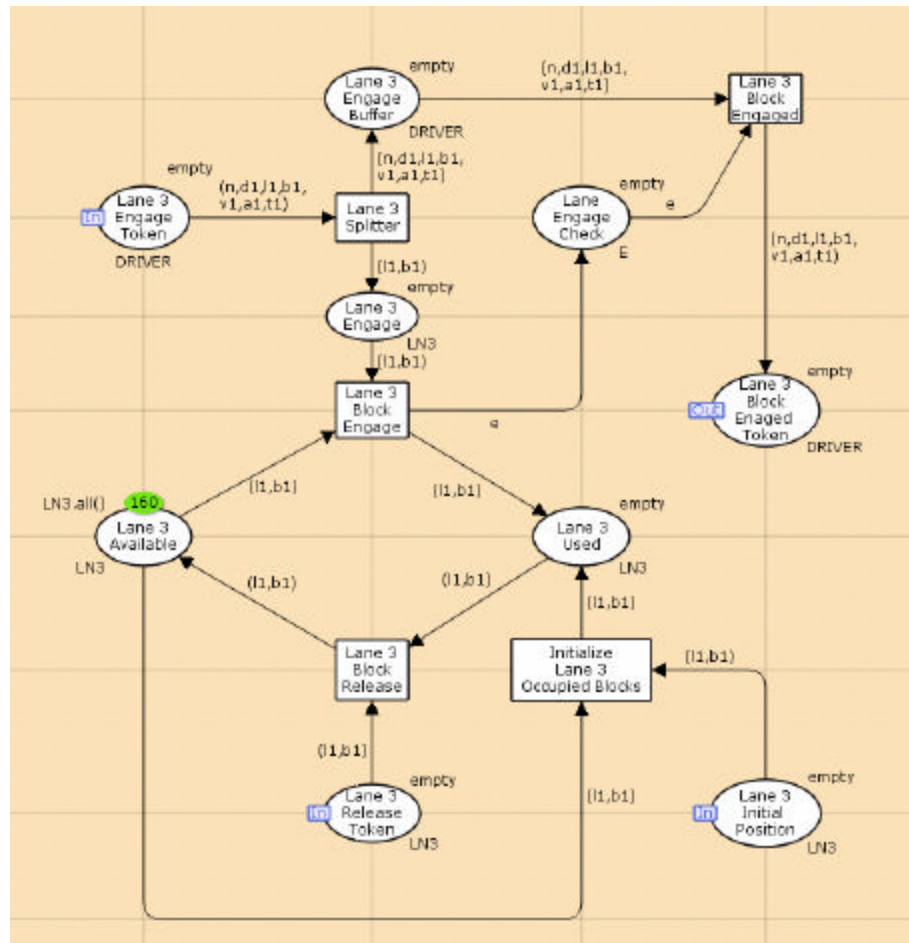


Figure 3-14: CPN for Lane Model Showing Affordances for Lane 3

“Lane 3 Engage Token” place node tracks the blocks that must be engaged within the lane due to driver maneuvers. The transition following this place node (Lane 3 Splitter) clones the engage token into two tokens, so that the current position of the driver can be retained for future use. Once a lane-block is engaged, it can only be released when the driver occupying that lane-block moves into a different location and issues a release token. Both release and engage tokens have the same format as an AT. Once a lane-block is successfully engaged, this new location information (lane-block position along with the driver index) is transferred to the appropriate driver through Lane-Driver Interface Model

(LDIM, see section **3.5.1.5.2**). Therefore, the SD is aware of the current location of the CD at all times, which allows us to include the notion of situation awareness that arises from visual perception and optic flow indirectly into the model.

3.5.1.4 Driver Model (DM)

There are two variants of the Driver Model (DM): a scripted version of the *Confederate Driver Model (CDM)* and an autonomous version of the *Subject Driver Model (SDM)*.

3.5.1.4.1 Confederate Driver Model (CDM)

The CPN model for the scripted CDM is shown in Figure **3-15**. In the scripted CDM, the driver model follows a scripted path based on a list of ET values specified by the input script file (*Driver1_Input.txt*) for Driver 1. This model is used to elicit behavioral preferences and driving maneuvers from the SD using predefined scripted paths for CD during each test scenario. The CD's attributes such as driver number (index), current position, velocity, acceleration and turn direction are specified for every time increment (1-second update interval) within the scripted input file and initialized into CDM prior to the start of execution of the current test scenario. When CD is enabled, an ET corresponding to the current simulation clock time is transferred to SDM and AM (section **3.5.1.5**).

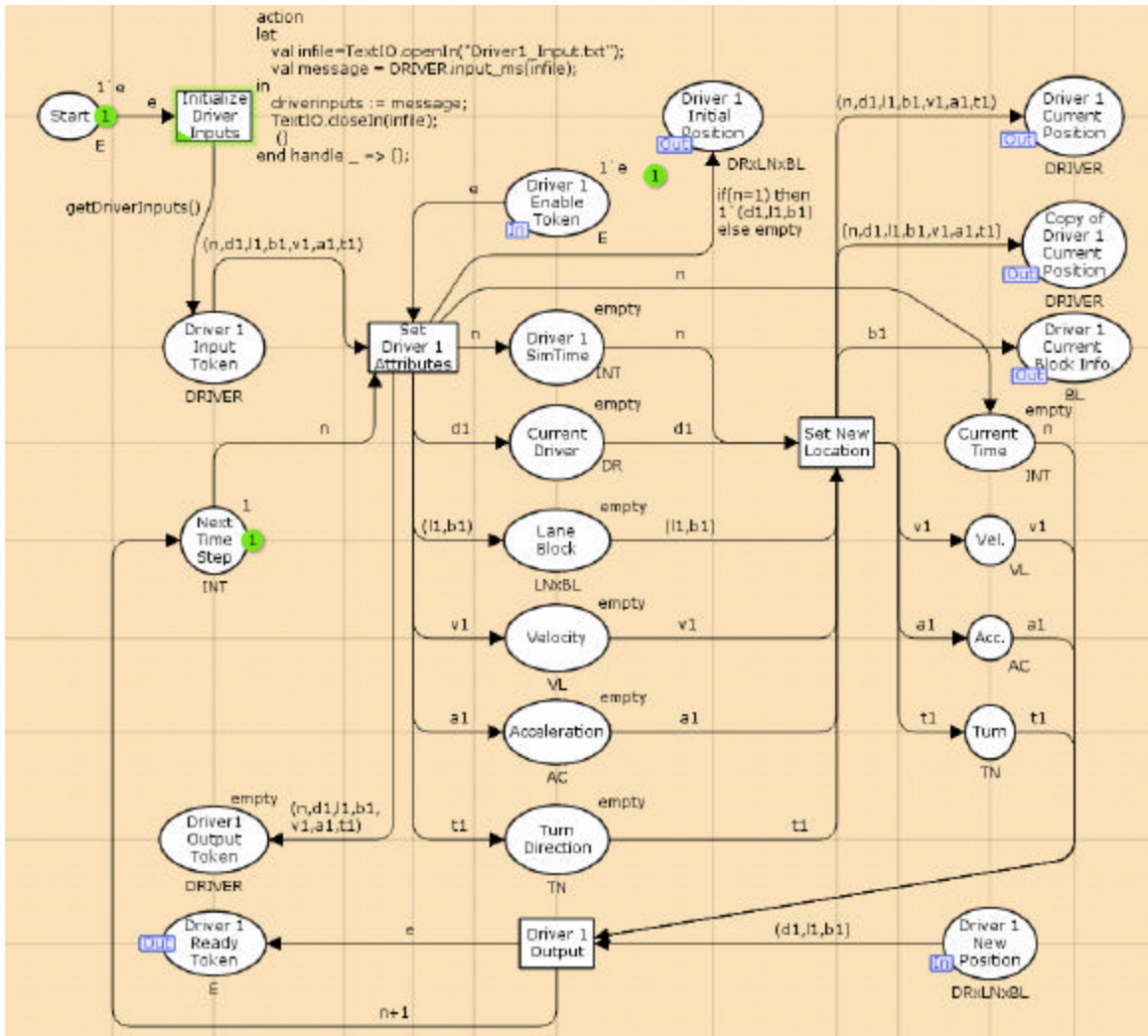


Figure 3-15: CPN for Scripted Confederate Driver Model

These ET values are obtained from the actual driver performance data gathered from the empirical testing of the same scenario. The turn direction corresponding to each turn that a confederate makes is also passed to AM. When the simulation update its current clock time, the driver attributes are updated based on the next ET in the token list. The execution of the simulation over time recreates CD’s maneuver along a path on the test track for the current test scenario.

3.5.1.4.2 Subject Driver Model (SDM)

The autonomous SDM is shown in Figure 3-16.

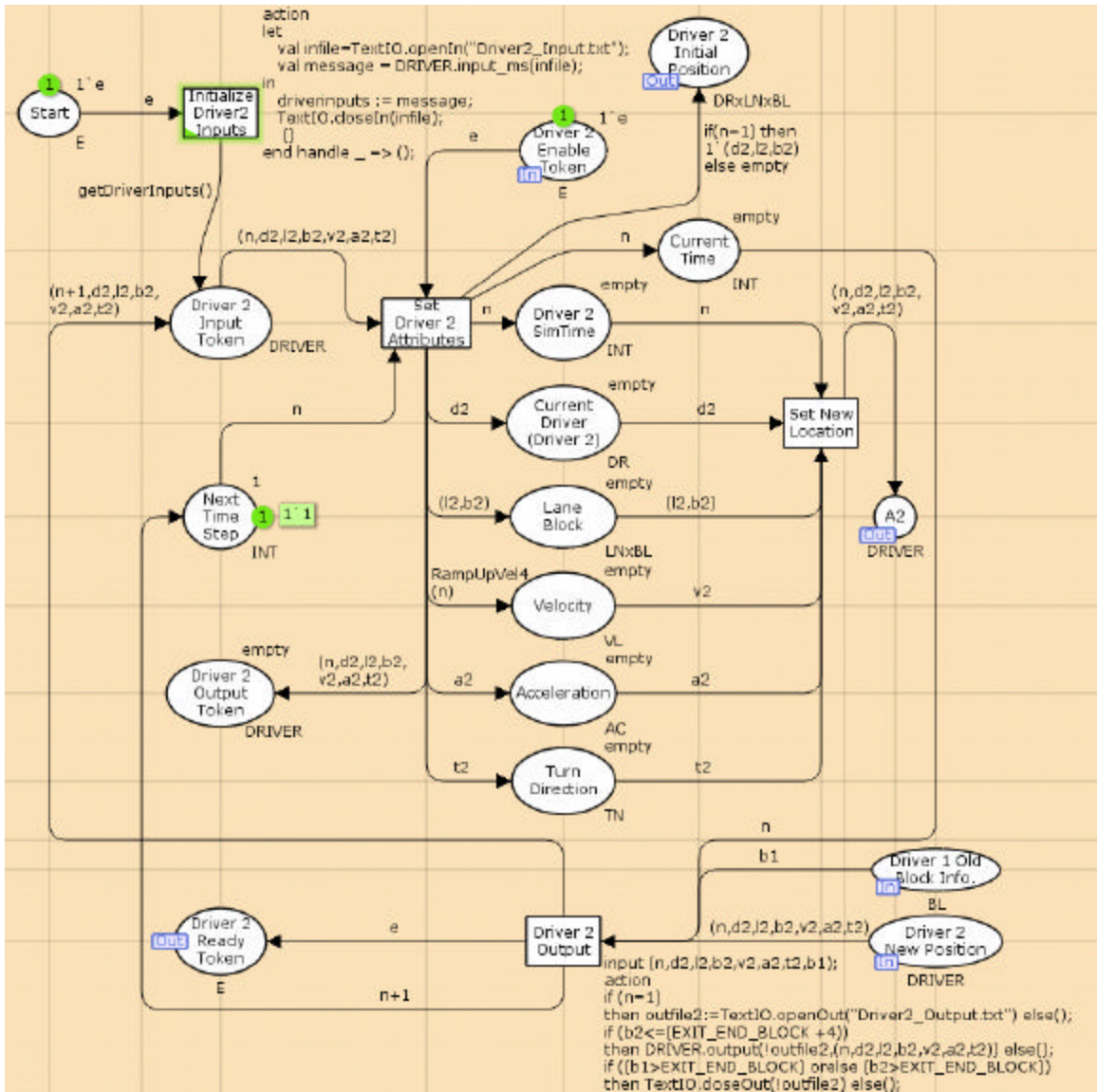


Figure 3-16: CPN for Autonomous Subject Driver Model

In this model, only the initial driver attributes for Driver 2 are set through the input file (*Driver2_Input.txt*). Although, the initial position and driver attributes are specified through the input file (before the start of the each test scenario), the SDM model behaves

autonomously once the simulation starts by interacting with the tokens generated by LM and AM, to compute the next position of SD. The model also maintains a copy of driver attributes such as driver number (index), velocity, acceleration and turn direction within the model in appropriate place nodes. The model also initializes the input tokens for AM during each update interval through place node A2. The SDM receives an ET containing information about the attributes of SD from the LDIM (see section **3.5.1.5.2**) through place node “Driver 2 New Position” at the end of each update interval. The updated attributes of SD are used to reinitialize the place nodes within SDM during the next update cycle. This process is repeated until SD and CD traverse the length of the test track (80 blocks). The SDM model records the current driver attributes at each update interval into an output file (*Driver2_Output.txt*) that records model predicted driver performance data for the entire duration of the test scenario. This output file also provides the model predicted output metrics for the current scenario, which is used to compute the deviation between the empirical human behavior data and the model predicted data for SD.

3.5.1.5 Actualization Model (AM)

The CPN model for AM (including DLIM and LDIM) is shown in Figure **3-17**. The Actualization Model (AM) is the central processor behind the affordance-based CPN Model, which is responsible for calculating the set of affordances and a candidate affordance that can be actualized into an action based on the juxtaposition function.

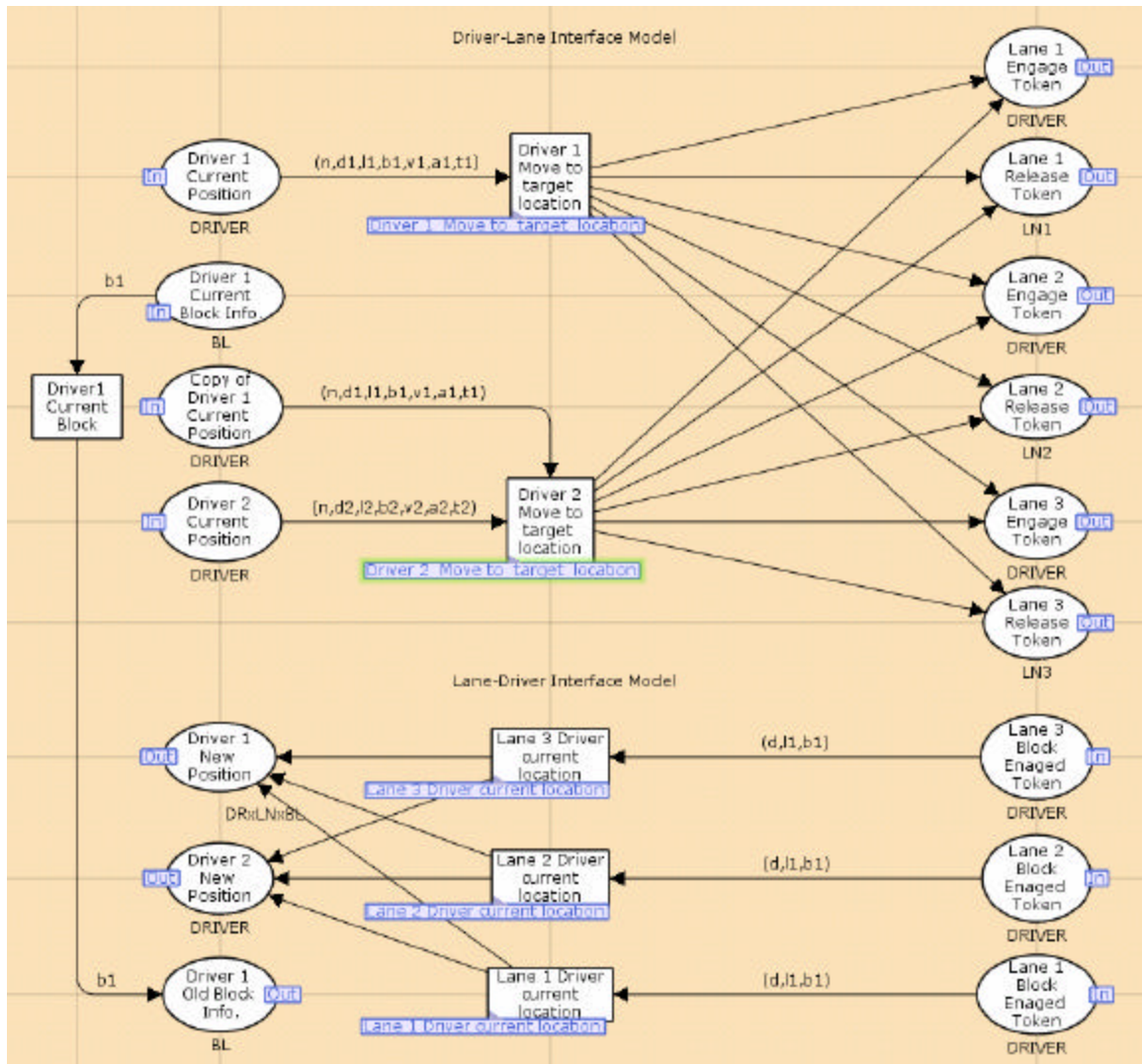


Figure 3-17: CPN for Actualization Model

This model consumes input tokens from both DM and LM to generate output tokens during each update interval. The details of the various components of AM are discussed in the following subsections.

3.5.1.5.1 Driver-Lane Interface Model (DLIM)

The Driver-Lane Interface Model (DLIM) is responsible for the interface between the output components of DM and LM, and the input component of the AM. In this model, the new position for SD is calculated by accounting for the lane affordances and the attributes of CD within HLDS. There are two CPN modules within DLIM that are responsible for accomplishing the path maneuvers for both CD (*“Driver 1 Move to Target” Module*) and SD (*“Driver 2 Move to Target” Module*). The module for computing the next position for CD (Driver 1) is shown in Figure **3-18**. In this CPN, the next location (lane-block position) is input from CDM through a place node (A2), which maintains a record of the path traversed by CD. An AT is created and transferred to LM based on the new lane-block position, in order to synchronize the driver occupancy information at the respective LM (Lane 1: C1, D1; Lane 2: C2, D2; Lane 3: C3, D3).

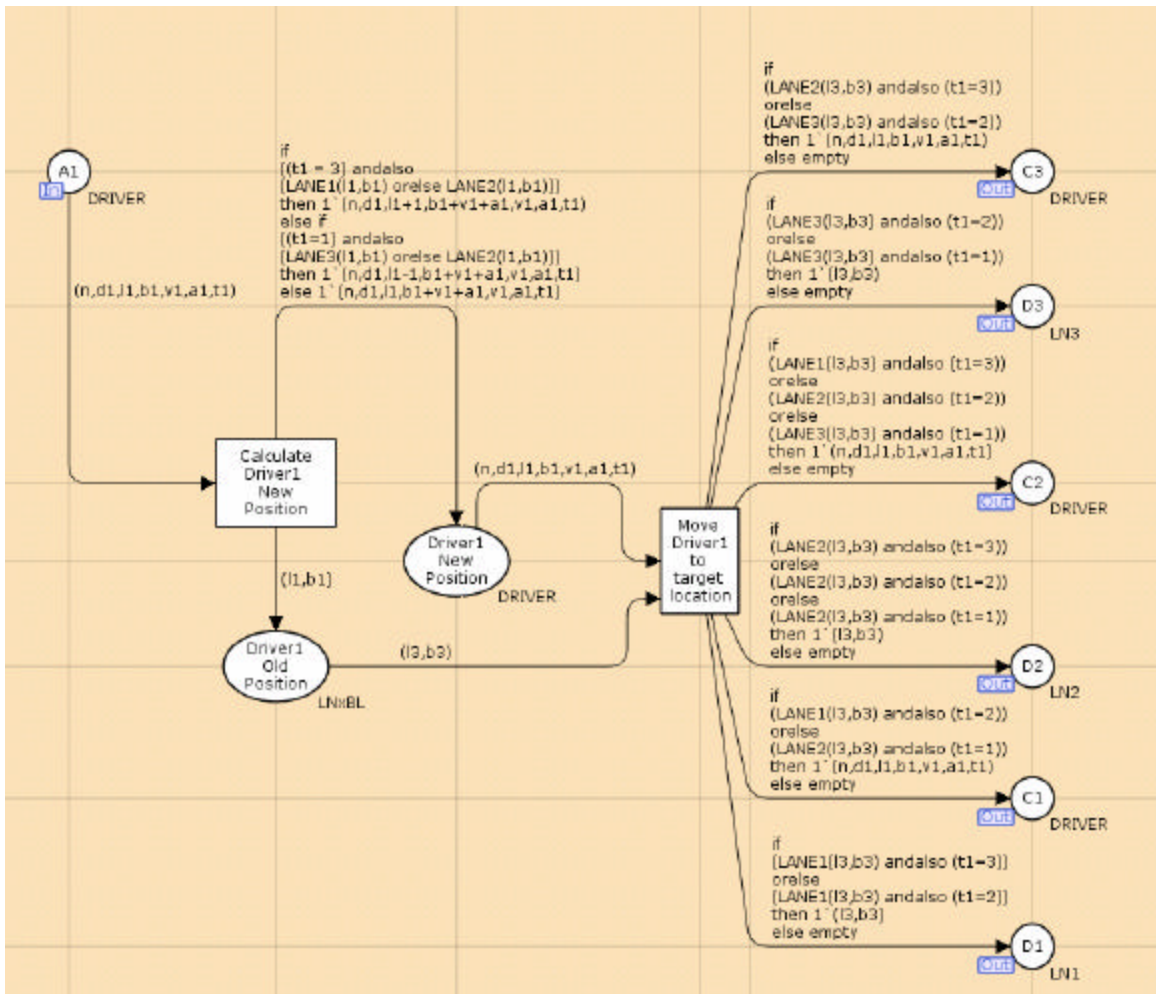


Figure 3-18: CPN for Computing Next Location of CD

The CPN for computing the next location of SD is shown in Figure 3-19. In this CPN, the next location (lane-block position) is computed by considering the current attributes of CD, which is input through the place node (A12). A stepwise algorithm-based approach is used to compute the set of possible affordances and a candidate affordance to be actualized based on the juxtaposition function (j).

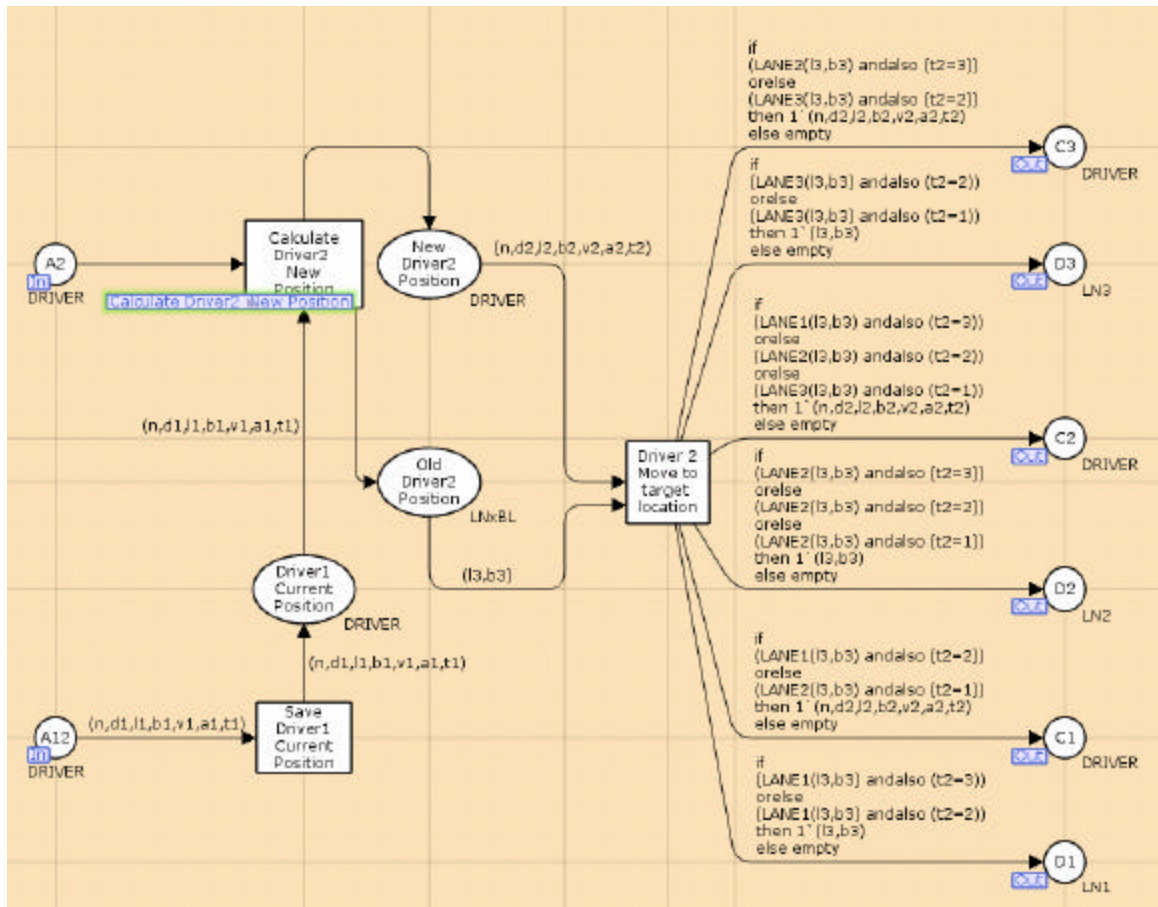


Figure 3-19: CPN for Computing Next Location of SD

The steps involved in the algorithm for computing set of lane affordances (niche) and actualized action for SD is given in Table 3-2. The steps involved in this algorithm are explained further through modules within DLIM that are accountable for accomplishing these tasks.

Table 3-2: Algorithm for Computing Niche of Lane Affordances and Actualized Action

Step #	Explanation
Step 1	Initialize the fixed turn probabilities of SD for moving from one lane to the other in the absence of CD and based on the overall goal of exiting through <i>lane 1</i> (exit lane).
Step 2	Compute the lane weights for each lane based on the current location of SD and CD and the <i>region of safe travel</i> .
Step 3	Compute the probability of <i>changing or keeping</i> the current lane based on relative position of SD and CD and the propensity for avoiding a crash.
Step 4	Compute the lane affordances for each lane by finding the product of corresponding turn probability, lane weight and <i>lane keeping/changing</i> probability for that lane.
Step 5	Use the juxtaposition function (<i>j</i>) to select a candidate action that would be actualized during the next update interval.

Three modules present within DLIM are responsible for accomplishing the various steps in the aforementioned algorithm, namely *Set Turn Probabilities*, *Calculate Lane Affordances* and *Juxtaposition Function Modules*. The details of these modules are discussed in the following sections.

3.5.1.5.1.1 Set Turn Probabilities (STP) Module

This module is responsible for accomplishing step 1 of the algorithm described in Table 3-2. This module is also known as “Set Turn Probabilities” or STP Module. The CPN model for “Set Turn Probabilities” module is shown in Figure 3-20. This module initializes the turn probabilities of SD for moving from one lane to the other, in the absence of CD, while considering the overall goal of exiting through *lane 1* (exit lane). In other words, this module reads static turn probabilities from an input file (*Turn_Probabilities.txt*) and sets these values into the nine place nodes ($L_{11} - L_{33}$) in the CPN model. For example, the place node L_{11} in Figure 3-20 indicates the probability

associated with SD moving from Lane 1 to Lane 1 (in the absence of CD) during the next update interval.

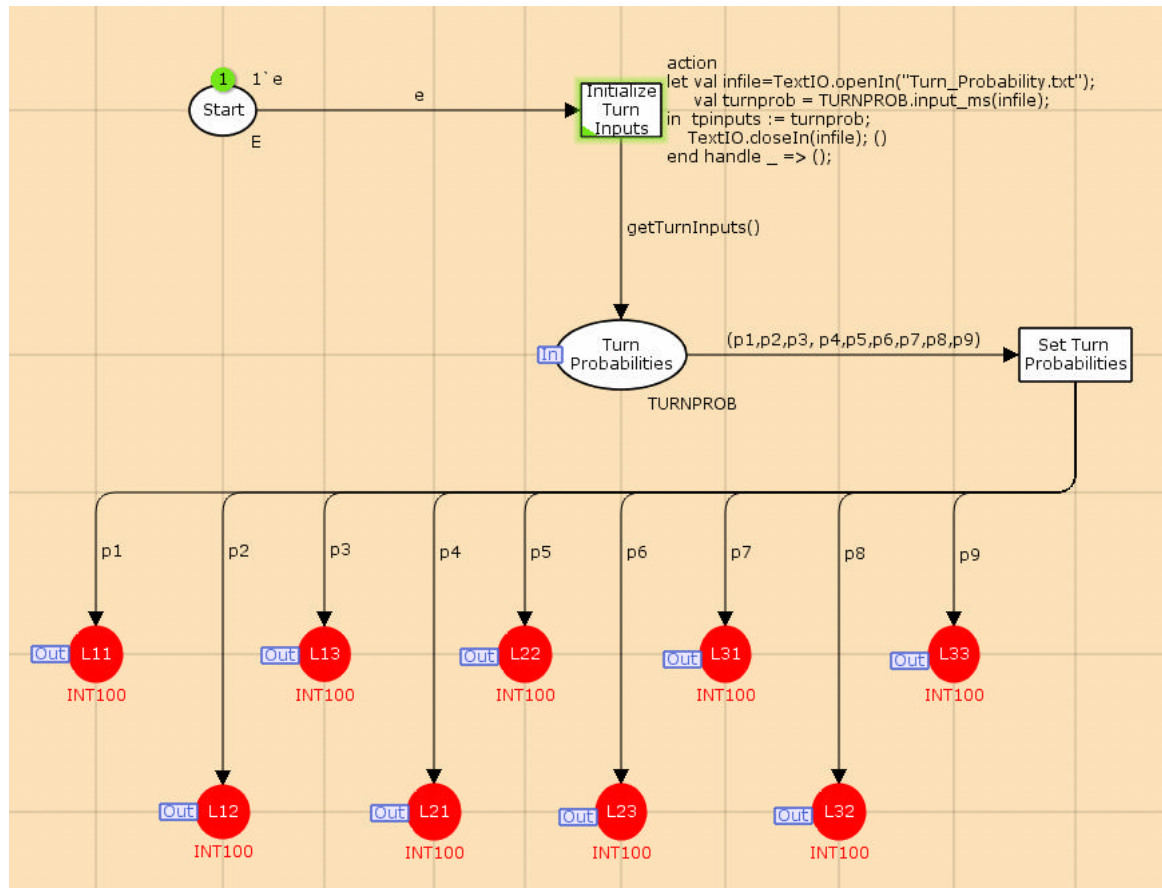


Figure 3-20: CPN for Set Turn Probabilities Module

The remaining eight place nodes ($L_{12} - L_{33}$) in the CPN module hold the rest of the turn probability values for SD. These turn probabilities remain constant for the entire duration of the scenario and portray the turn preferences of SD.

As the exit lane is toward the right side of SD, the following relationships among SD turn probabilities are required in order to accomplish the overall goal of exiting the highway lane system.

$$L_{11} > L_{12} > L_{13};$$

$$L_{21} > L_{22} > L_{23};$$

$$L_{31} > L_{32} > L_{33};$$

A comparison analysis was done using several ratios based on different turn preferences, and most effective ratio that led to the overall goal of exiting the highway was chosen.

The ratios are as follows:

When SD in lane 1 \rightarrow 2:1:0,

When SD in lane 2 \rightarrow 4:2:1,

When SD in lane 3 \rightarrow 0:2:1.

The static turn probabilities used in the CPN model with respect to the current lane position of SD, is shown in Table 3-3.

Table 3-3: Static Turn Probabilities for SD based on the Current Lane Position

	Lane 1	Lane 2	Lane 3	Total Probability
Lane 1	0.67 (=L ₁₁)	0.33 (=L ₁₂)	0.00 (=L ₁₃)	1
Lane 2	0.57 (=L ₂₁)	0.29 (=L ₂₂)	0.14 (=L ₂₃)	1
Lane 3	0.0 (=L ₃₁)	0.67 (=L ₃₂)	0.33 (=L ₃₃)	1

In this table, the turn probability for L₁₃ and L₃₁ are zero because the drivers are assumed to take at least one update cycle (1 second) to complete a lane change into an adjacent lane. Therefore, multiple lane changes within a single update cycle are not possible. In a fully random behavior model, these turn probabilities would be generated using a random generator during every update cycle to mimic random behavior for SD.

3.5.1.5.1.2 Compute Lane Affordances (CLA) Module

This module is responsible for accomplishing steps 2–4 of the algorithm shown in Table 3-2. This model computes the affordances offered by each lane to SD as shown in Figure 3-21.

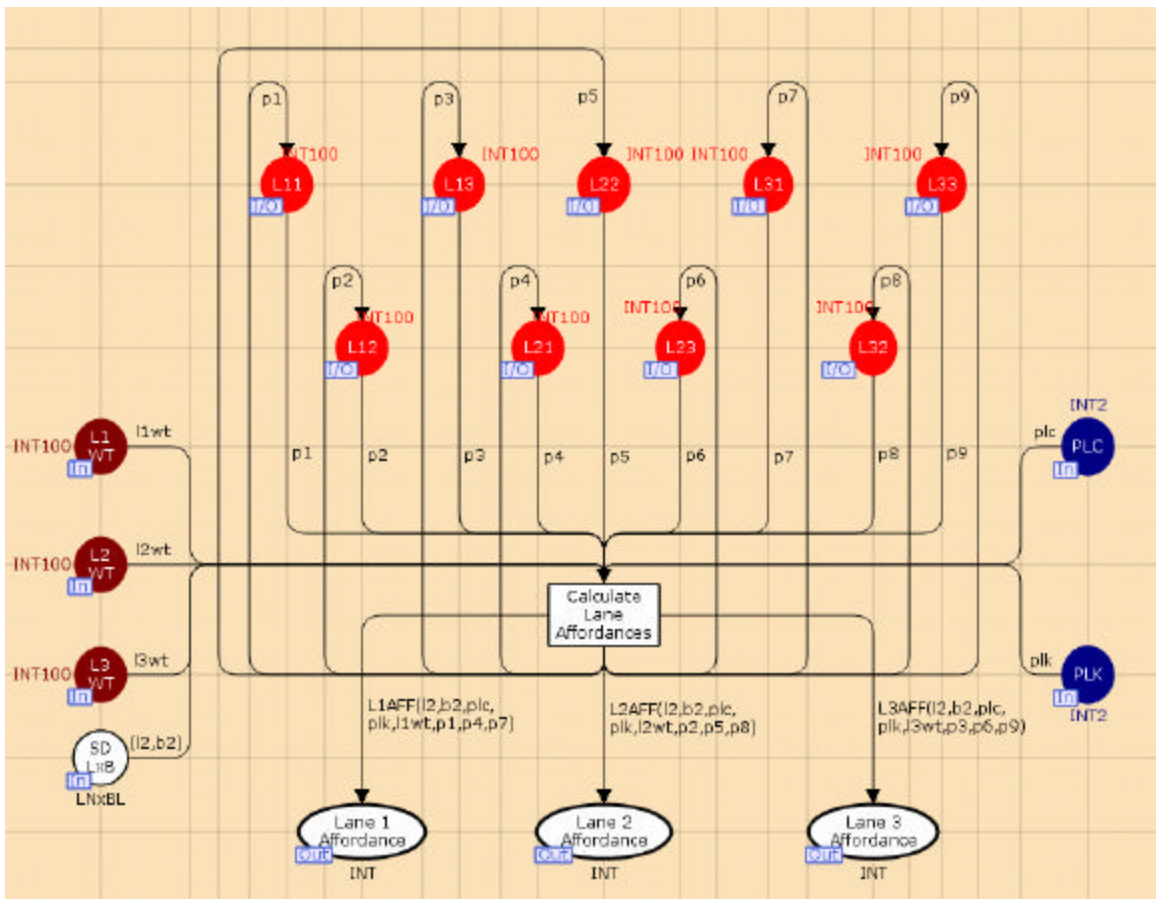


Figure 3-21: CPN for Calculate Lane Affordances Module

In step 2, the lane weights for each lane are assigned by considering the current location of SD, the relative distance between SD and CD, and the minimum safety distance that must be maintained in order to remain in the *region of safe travel*. Empirical research in transportation science (Winsum and Heino, 1996) suggests that the minimal

safety distance (in terms of time headway), that must be maintained to brake safely without crashing is 1.5 seconds. This time headway translates to a distance of greater than at least three blocks for a target velocity of 2 blocks/sec. During step 3, the probability of keeping the current lane or changing into an adjacent lane is computed based on the current location of SD, region of safe travel and target lane (exit lane) for achieving the overall goal of exiting the HLDS. The CPN function used for calculating the lane change or keep probability is described by two separate functions (PLC and PLK, see Appendix B). In step 4, the CLA module computes the lane affordances by calculating the product of respective turn probability for SD, Lane weight and the probabilities of lane change (*PLC*) or lane keeping (*PLK*) for that lane. The place nodes “Lane 1 Affordance”, “Lane 2 Affordance” and “Lane 3 Affordance” indicate the affordance value offered by Lane 1, Lane 2 and Lane 3 to SD. A zero value in this any of these place nodes indicates that no affordance is offered by that particular lane and non-zero value indicates that the lane offers an affordance. A relatively higher value in any of these place nodes indicates that the affordance offered by that lane relative to other lanes is much higher. In other words, this lane presents a positive affordance with a larger propensity of being actualized into an action than any other lane with non-zero affordance value. By plotting the affordance value of all of these place nodes over course of the test scenario, we can generate a formative space that specifies the set of affordances that become available to SD dynamically during the scenario.

3.5.1.5.1.3 Juxtaposition Function (*j*)

The CPN for the juxtaposition function module is shown in Figure 3-22.

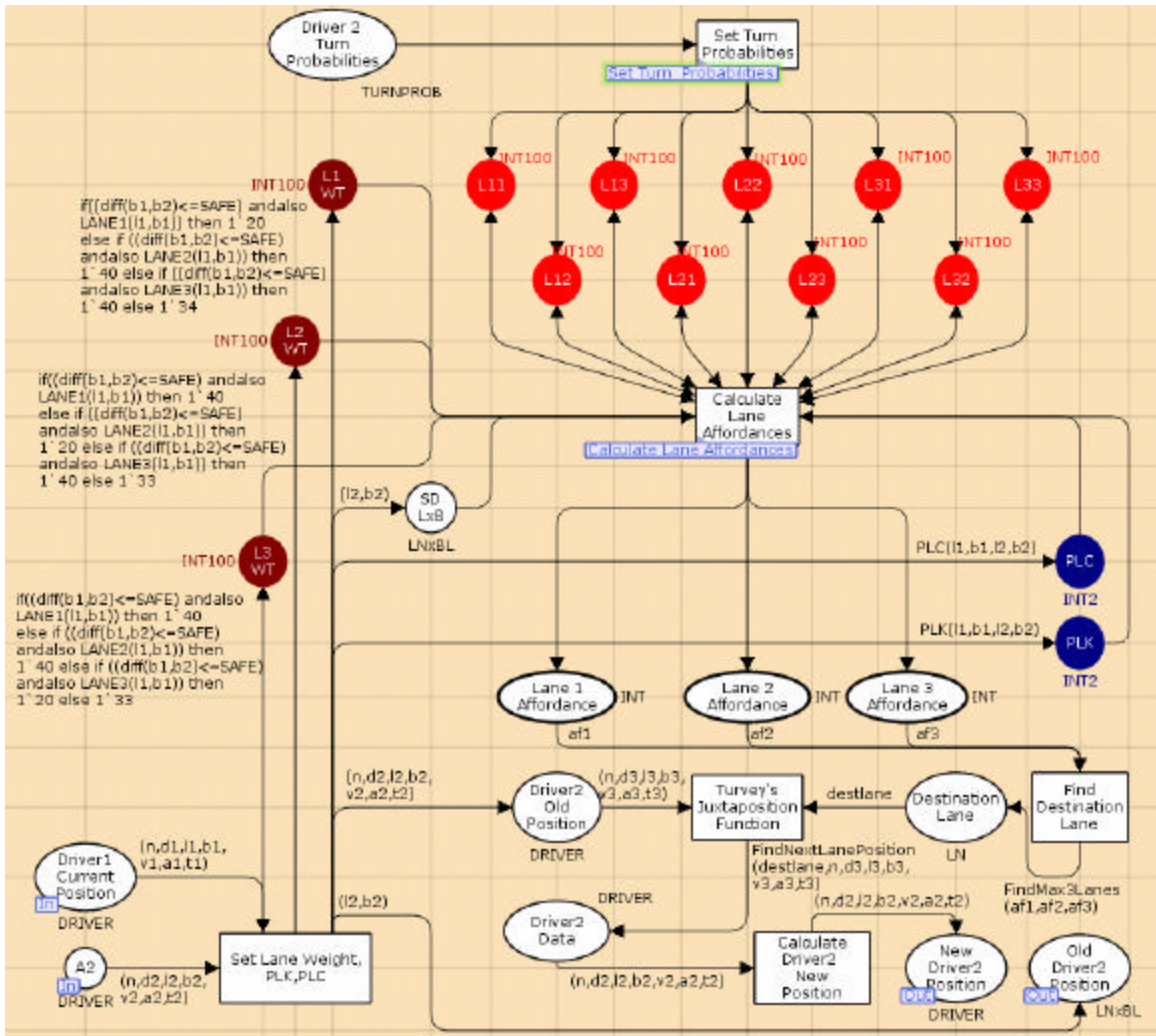


Figure 3-22: CPN for Juxtaposition Function Module (*j*)

The *Juxtaposition Function (j)* proposed by Turvey (1992) enables the CPN model to select a candidate affordance (step 5), from the set of available affordances, to be actualized into an action. In our model, we use a *maximum* function on the lane affordance values obtained from step 4 in CLA module, to pick the candidate action that

would be actualized during the next update interval. This function is similar to Turvey's Juxtaposition function (j) (Turvey, 1992) and is mathematically denoted as follows.

$$\text{Actualized Action} = \max \left(\text{Lane 1 Affordance}, \text{Lane 2 Affordance}, \text{Lane 3 Affordance} \right)$$

Once the new position is computed based on j , two ET tokens representing both old and new positions for SD are sent to the LDIM for updating the SDM.

3.5.1.5.2 Lane-Driver Interface Module (LDIM)

The Lane-Driver Interface Model (LDIM) is responsible for the interface between the output components of AM, and the input component of the DM. There are three identical modules within LDIM that transfer tokens to DM, based on the corresponding lane-block occupied by CD and SD. The CPN for transferring current location information of the driver in Lane 1 to the respective DM is shown in Figure 3-23. The modules for Lane 2 and Lane 3 are identical and are not discussed further in this section.

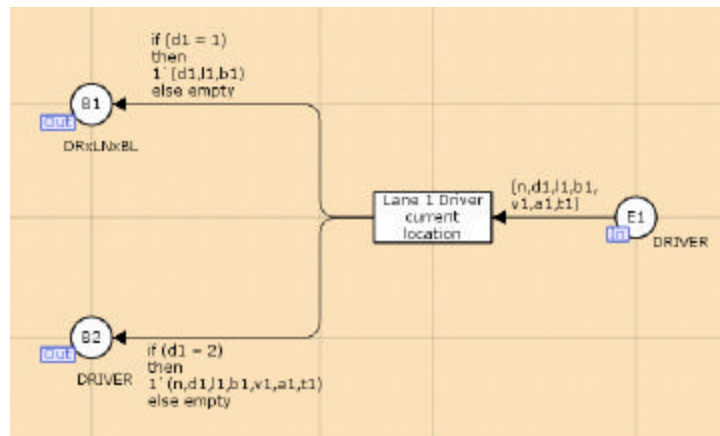


Figure 3-23: CPN for Current Location of Driver in Lane 1

In the absence of this module, the affordances available to SD cannot be tracked within the SDM. An AT that comprises of the driver index and lane-block position is sent to the input component of CDM, through place node B1. Similarly, an ET including the driver index, lane-block position, velocity, acceleration and turn direction is sent to the input component of SDM through place node B2. After the CDM and SDM models update the current attributes of CD and SD, the entire process of computing set of affordances and an actualized action for SD is repeated, until both SD and CD traverse the test track length (= 80 blocks).

3.5.2 Computational Representation of the CPN Model

Makungu, St-Denis and Barbeau (1996) provide the mathematical representation for a CPN model that could be used for modeling a Discrete Event System (DES) and state that a CPN could be represented using the following ordered tuple.

$CPN = (? , P, T, A, N, C, E, M_0)$, where

$?$ is a finite set of non-empty types, called *color sets*;

P is a finite set of *places*;

T is a finite set of *transitions*;

A is a finite set of *arcs* connecting places and transitions;

N is a *node function* that maps each arc into a pair of nodes of different kinds (i.e., one is a place, while the other is a transition);

C is a *color function* that associates a color set with each place;

E is an *arc expression function* that maps each arc into a multi-set over the color set that is attached to the corresponding place;

M_O is the initial marking.

Their mathematical notation for CPN is adopted within this research for representing a mathematical model of our formalism. It is assumed that the valid model for the CPN is one in which the color sets are finite and the contents of places are bounded.

Even though visual perception is continuous, the system can be divided into discrete time units such as $t_0, t_1, t_2, \dots, t_n$ such that the initial state is t_0 and the final state before the goal state can no longer be achieved, is t_n . The assumptions used in the mathematical formulation are given below.

Initial Time = t_0 ;

End Time = t_n (time after which the goal state cannot be achieved)

$t_0 < t_i \in T < t_n, \forall i = 1 \text{ to } n$

Driver(i) = $d_i \in D$, where $D = \{d_1, d_2\}$;

Lanes(j) = $l_j \in L$, where $L = \{l_1, l_2, l_3\}$;

Blocks(k) = $b_k \in B$, where $B = \{b_1, \dots, b_{80}\}$;

Turn Direction(m) = $td_m \in TD$, where $TD = \{1(\text{Right}), 2(\text{Straight}), 3(\text{Left})\}$;

Velocity(t) = $v_t, \forall v_0 \leq v_t \leq v_{\max}$;

Acceleration(t) = $a_t, \forall a_0 \leq a_t \leq a_{\max}$

There are three different types of tokens within our CPN formalism: *Affordance Token (AT)*, *Effectivity Token (ET)* and *Action Token (ACT)*. In order to define color set for the tokens, a modified adaptation of the convention from Wells (2002) is used.

1. An *affordance Token (AT)* is defined as the ordered pair: **(a, e)**.

$$AT \rightarrow (a, e)$$

a (animal referential term) $\in Q$,

$Q \rightarrow$ (Set of functional states of the driver)

e (environment referential term) $\in S$,

$S \rightarrow$ (Set of type of entities [lanes] in the highway system)

- a. “a” is an driver (animal) referential term that is a subset of Q that enumerates the functional states of the driver, and
- b. “e” is an highway lane system (environment) referential term that is a subset of S , which represents the types of entities (lanes) in the highway system that the driver occupies.

An example of an AT is given by the following ordered pair.

$AT \rightarrow (a, e) \rightarrow (d_1, (l_3, b_1))$, where d_1 = driver 1, l_3 = lane 3, b_1 = block 1.

2. *Effectivity Token (ET)* is defined as the ordered pair: **(p, m, b)**.

$$ET \rightarrow (p, m, b)$$

p (animal referential term) $\in Q$,

$Q \rightarrow$ (Set of functional states of the driver)

m (movement within the environment) $\in M$,

$M \rightarrow$ (Set of possible maneuvers for the driver)

b (behavior of the animal within the environment) $\in S$,

$S \rightarrow$ (Set of type of entities [lanes] in the highway system)

- a. “p” is an animal referential term, which indicates the functional state that results from “b”, that is $p \in Q$,

- b. “m” is an environment referential term used for representing the movement of driver within the highway system, and $k \in M$ (which is made up of finite set of elements), and
- c. “b” is the behavior exhibited by the driver (animal) in the highway system (environment), in other words, $b \in S$.

An example of an ET is given by the following ordered pair.

$$ET \rightarrow (p, m, b) \rightarrow (d_1, (l_2, b_2, 3, 0), 2), \text{ where}$$

d_1 = driver 1, l_2 = lane 3, b_1 = block 1, velocity = 3 blocks/sec, acceleration = 0 blocks/sec² and turn direction = 2 (heading straight).

3. An *action token (ACT)* is defined as the ordered pair (x_i, y_j) that results from actualizing an ordered pair (AT, ET) into an action, where AT is the Affordance and ET is the effectivity.

$$\begin{aligned} ACT &\rightarrow \text{actualize}(AT, ET) \rightarrow (x_i, y_j), \text{ where} \\ &\exists ((x_i \in AT) \wedge (y_j \in ET)) \wedge \\ &\exists ((x_i, y_j) \in ACT(\text{Set of Possible Valid Actions})) \end{aligned}$$

- a. x_i is an affordance token, where $x_i \in AT$,
- b. y_j is effectivity token, where $y_j \in ET$, and
- c. (x_i, y_j) is an action token, where $(x_i, y_j) \in ACT$.

The format for an ACT token is given by the following ordered pair,

$$ACT \rightarrow (\text{Driver \#, } P_{\text{new}}, V_{\text{curr}}, A_{\text{curr}}, TD_{\text{curr}}), \text{ where}$$

Driver # indicates the index for the current driver, P_{new} indicates the new position that has been computed for this driver, V_{curr} shows the current velocity, A_{curr} indicates the

current acceleration and TD_{curr} indicates the current turn direction. An example for an ACT token is $(d_1, (l_3, b_4), 3, 0, 2)$, which shows that driver 1 moved into block 4 within lane 3 with a velocity of 3 blocks/sec and an acceleration of 0 blocks/sec² by heading straight.

The sets Q and S are finite, therefore the set of affordance types (Q x S) is also finite.

3.5.3 Random CPN Model

The random CPN Model differs from the affordance-based CPN model as the turn preferences for the subject driver within the later is initialized at the beginning of the test scenario based on affordances that would lead to the goal state (i.e. exit via lane 1). The Set Turn Probabilities (STP) module (see section **3.5.1.5.1.1**) is responsible for initializing these turn probability values from a data file (*Turn Probabilities.txt*) at the beginning of the simulation.

Alternatively, in the random CPN model these turn probabilities are generated during each update interval by specific random generators for each lane within the HLDS. The CPN model for generating and setting the random turn probabilities for SD while in Lane 1 is shown in Figure **3-24**. In this CPN, an activation of the place node “Enable Rand1 in Lane1” triggers the random generator (Rand1) to create the three new turn probabilities. Only one random generator is used to generate the three turn probabilities, as SD has a zero probability of physically moving into lane 3, while occupying lane 1. The random probabilities that are generated for the moving from lane 1

into lane 1 (L_{11}), lane 2 (L_{12}) and lane 3 (L_{13}) are stored within place nodes “L11”, “L12” and “L13”, respectively, and then transferred to the CLA module.

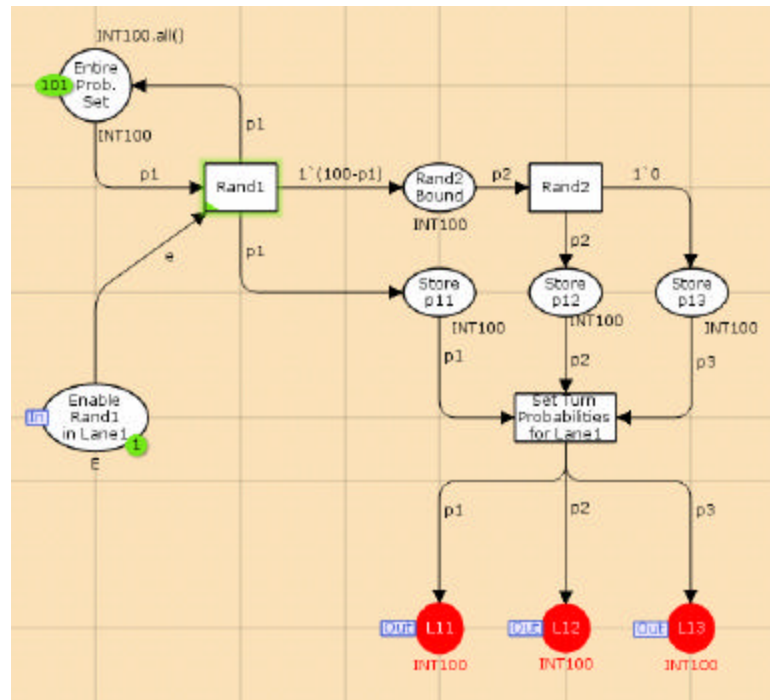


Figure 3-24: CPN for Setting Random Turn Probabilities for SD while in Lane 1

The CPN model for generating and setting the random turn probabilities for SD while in Lane 2 is shown in Figure 3-25. In this CPN, an activation of the place nodes “Enable Rand1 in Lane2” and “Enable Rand2 in Lane2” triggers two random generators (Rand1 and Rand2) to create three new turn probabilities. In this case, two random generators are used to generate these three turn probabilities as SD may have a non-zero probability of moving into each of the three lanes while occupying the middle lane (lane 2). The random probabilities that are generated for the moving from lane 2 into lane 1 (L_{21}), lane 2 (L_{22}) and lane 3 (L_{23}) are stored within place nodes “L21”, “L22” and “L23”, respectively, and then transferred to the CLA module.

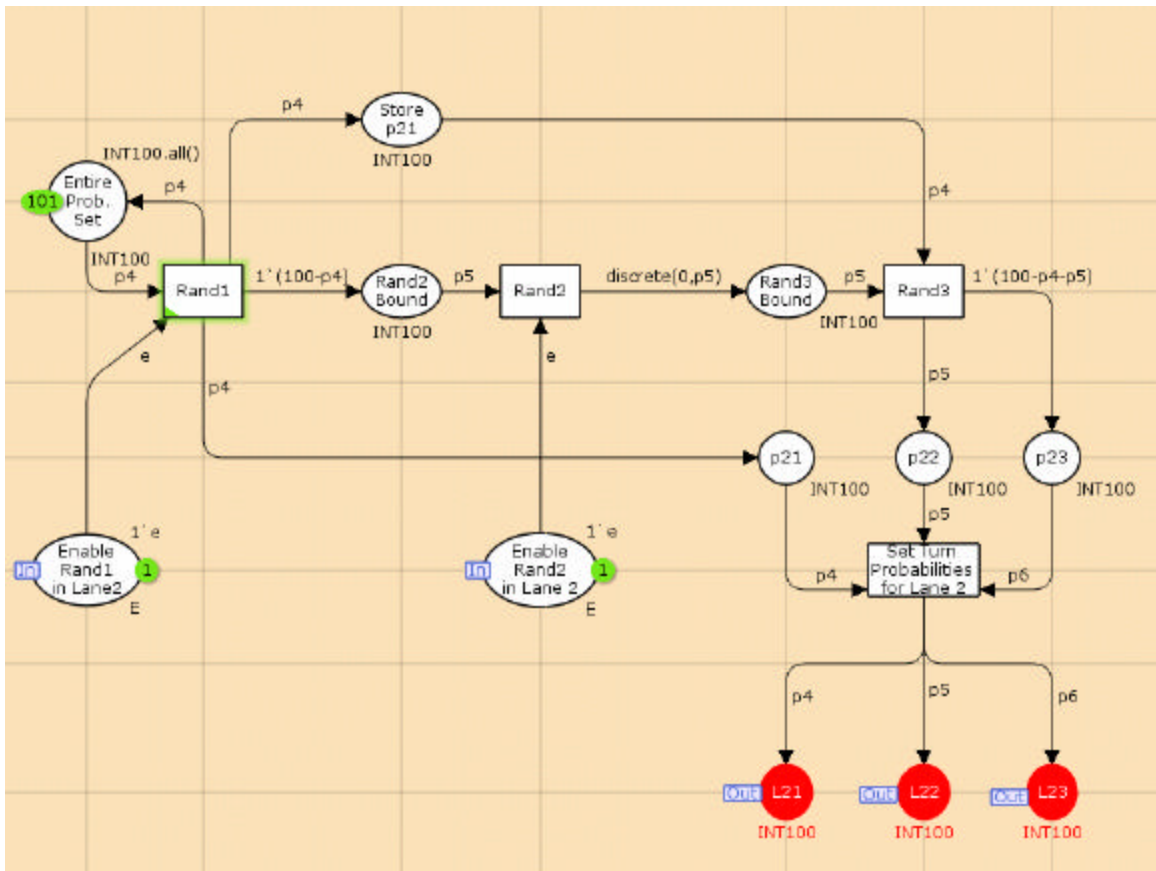


Figure 3-25: CPN for Setting Turn Probabilities for SD while in Lane 2

The CPN model for generating and setting the random turn probabilities for SD while in Lane 3 is shown in Figure 3-26. In this CPN, an activation of the place node “Enable Rand1 in Lane3” triggers the random generator to create the three new turn probabilities. Only one random generator is used to generate these turn probabilities as SD has a zero probability of physically moving into lane 1 during the next update interval, while occupying lane 3. The random probabilities that are generated for the moving from lane 3 into lane 1 (L_{31}), lane 2 (L_{32}) and lane 3 (L_{33}) are stored within place nodes “L31”, “L32” and “L33”, respectively, and then transferred to the CLA module.

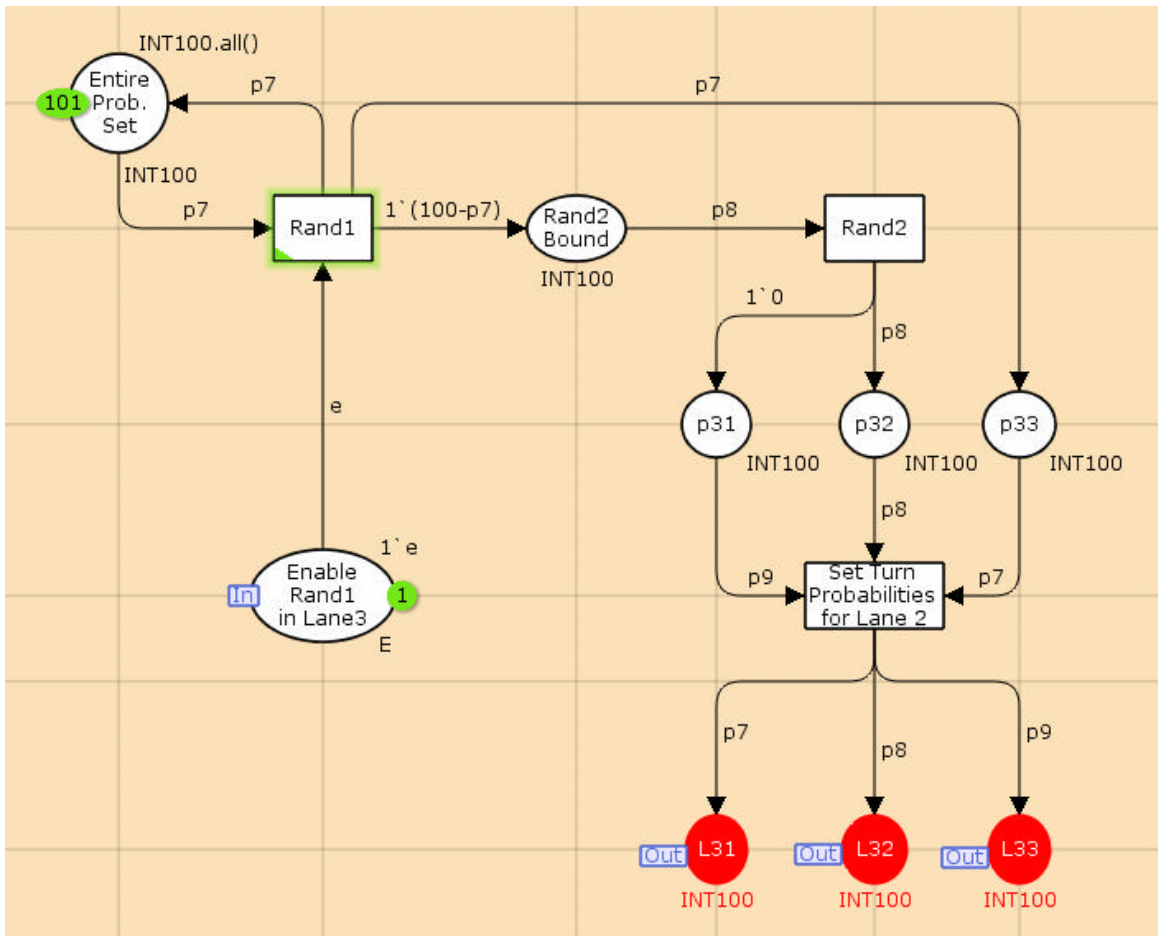


Figure 3-26: CPN for Setting Turn Probabilities for SD while in Lane 3

The CPN for the CLA module that consumes the tokens containing the nine random turn probability values is shown in Figure 3-27.

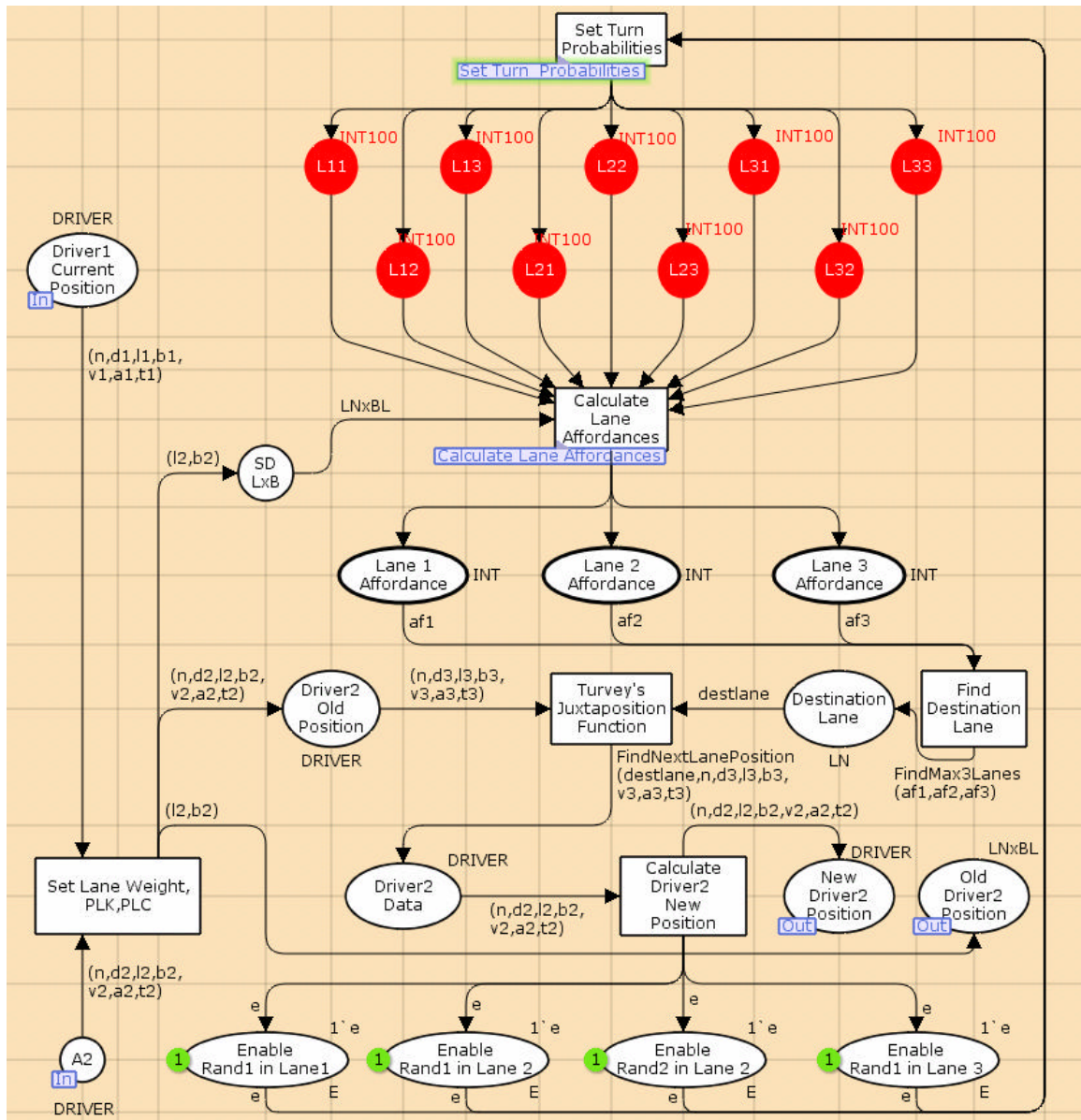


Figure 3-27: CPN for Compute Lane Affordances Module in Random Model

Note that, in the above model an activation token for generating the next set of turn probabilities is generated and transferred to the STP module for each lane after the new position of the subject driver is computed.

3.6 Formative Analysis

In this section, the formative analysis provided by CPN model is illustrated. The affordance values for all three lanes are calculated by the CLA module at each update interval (= 1 second). This allows us to analyze the affordance space from a formative perspective. For instance, let us assume that the SD starts at lane 3 and block 1 during a given scenario and the CD starts at lane 2 and block 1. In this scenario, a valid affordance (indicated by a non-zero affordance value within CLA module) becomes available for lane 3 and lane 2 for the SD, during the next update cycle. In a similar way, the affordance offered by lane 1 to SD is invalid (indicated by a zero value within CLA module), since we assume that, the driver cannot jump two lanes within one update cycle. Therefore, the affordance offered by that lane remains invalid for SD until the SD moves to lane 2. This overlay for formative analysis of affordance is shown in Table 3-4. Affordance values for each lane are generated by the CLA module within the affordance-based CPN model during every update cycle. Then, these affordance values are standardized within the range 0.0 to 1.0. In this table, the light green spaces indicate the valid affordances (non-zero affordance values) that dynamically become available based on the events that occur within the AES. For instance, when SD moves from lane 3 to lane 2 at 5 seconds (scenario time) after passing the lane change point with the target velocity, only lane 2 and lane 3 present non-zero affordance and lane 1 presents a zero affordance as the starting point of lane 1(exit lane) has not yet been reached. In other words, the exit lane has not yet begun. The tan spaces indicate the invalid affordances that are not available to SD due to the non-existence of the exit lane.

Table 3-4: Formative Analysis Overlay for Lane Affordances

Scenario Time	Affordance Values for the Niche (Set of lane affordances) available to SD			Comments	
	Lane 1	Lane 2	Lane 3		
0	Black	Black	Gray	<i>Speed up point</i>	
1	Black	Black	Gray		
2	Black	Black	Gray		
3	Black	Black	Gray		
4	Black	Black	Gray		
5	Black	Black	Gray		
6	Black	Black	Gray		
7	Black	Black	Gray		
8	Black	Black	Gray		
9	Black	Black	Gray		
10	Black	Black	Gray		<i>Exit Lane Begins</i>
11	Black	Black	Gray		
12	Black	Black	Gray		
13	Black	Black	Gray		
14	Black	Light Gray	Black		
15	Light Gray	Black	White	<i>SD moved into exit lane</i>	
16	Light Gray	Light Gray	Black		
17	Light Gray	Light Gray	Black		
18	Light Gray	Light Gray	Black		
19	Light Gray	Light Gray	Black		
20	Light Gray	Light Gray	Black		
21	Light Gray	Light Gray	Black		
22	Light Gray	Light Gray	Black		
23	Light Gray	Light Gray	Black		
24	Light Gray	Light Gray	Black	<i>Highway Lane Ends</i>	
Cells filled with BLACK color provide no affordance to SD					
Cells filled with WHITE color or shades of GRAY provide valid affordance to SD					

Typically, this table is filled with these standardized affordance values. The affordance value of each lane shown in this table corresponds to the propensity (or strength) of the lane affordance to be actualized into an action during the next update interval. A cell filled within black color is assigned a zero affordance value, as it provides no affordance for SD to move into that lane. On the other hand, a cell with white color or shades of gray is assigned a non-zero affordance value since it provides an affordance for

SD to move into that lane. An affordance with a high value (closer to white colors or lighter shades of gray) indicates a stronger propensity to be actualized during the next update cycle than an affordance with a low value. One can visualize the affordance space by inspect the color-coding scheme present within the table. Critical events are listed on the comments column. The critical events include speed up point before which the target velocity must be achieved, starting of the exit lane, SD moving into the exit lane and the ending of the highway exit lane.

In the above scenario, SD starts from lane 3 (SL2) initially and continues driving straight ahead as the exit lane has not yet begun. Then SD is unable to move from lane 3 to lane 2 until later as SD must speed up to the assigned target velocity. Since SD has a higher target velocity than CD, SD violates the safety factor after 13 seconds as CD is straight ahead on lane 3. Therefore, SD eventually moves to lane 2 at 14 seconds. Then, SD moves to the exit lane (lane 1) during the next update interval (15 seconds) and continues driving straight ahead to achieve the goal state. Generally, a contiguous set of cells filled with white color or shades of gray from the starting location to the end of the exit lane indicates that the goal state can be achieved within the highway lane system.

3.7 Chapter Summary

In this chapter, questions related to the development of affordance-based CPN model were raised and partially addressed using the CPN modeling framework. A mathematical model for Gibson's affordances was provided along with a case-based analysis within the HEPS domain. Then, a conceptual model was illustrated to develop

the computational CPN model for Gibson's affordances within HEPS. This model was then generalized for HEPS domain by specifying the standardized CPN notation for the different token types included in the affordance-based CPN model based on Gibson's affordance theory. The formative analysis for the model was also explained.

Chapter 4

HYPOTHESIS

The fundamental research hypotheses being tested in this research is that an affordance-based CPN model (formalism) that is theoretically well suited for representing Gibson's affordances, because CPN can address the modeling related challenges presented by the properties of affordance.

Fundamental Hypothesis: An affordance-based CPN model (formalism) provides the means for representing the actualized action of an animal that results from juxtaposing its effectivities with the set of affordances available within this animal-environment system.

The fundamental hypothesis mentioned earlier will be tested by statistically analyzing the performance of the affordance-based CPN model for significant effects due to test trails, drivers and scenarios. If any of the measured output metrics were found not to be significant, then this would indicate that the model appears to fit the driver performance more accurately and is a good predictor of the actualized action or path pursued by the driver.

The effectiveness of the model will also be tested by statistically comparing the performance metrics generated by the affordance-based CPN model with another random model. If any of the measured output metrics were found to be significant with a larger

mean for the random model, then this would indicate that the model appears to fit the driver performance more accurately than the random model. These tests would also confirm the following conjectures.

Conjecture 1: An Affordance-based CPN model can efficiently represent the “concurrency” that exists among affordances within the environment.

The significance of this conjecture is that affordance-based CPN model is capable of efficiently representing the behavior of a driver in scenarios, where the environment presents concurrent affordances. If any of the output metrics were found to be significant while analyzing the performance data generated by the affordance-based CPN model on scenarios involving concurrency, then this would refute the conjecture that the affordance-based CPN model is efficient in representing the concurrency involved in affordances.

Conjecture 2: An Affordance-based CPN model can efficiently represent the “stochasticity” that exists among effectivities of an animal residing within the animal-environment system.

This conjecture signifies the effectiveness and suitability of the affordance-based CPN model in representing the action alternatives available to an animal and the stochasticity involved in the dynamic environment. If any of the output metrics were found to be significant while analyzing the performance data generated by the affordance-based CPN

model on scenarios involving stochasticity, then this would refute the conjecture that the affordance-based CPN model is efficient in modeling the stochasticity involved in the HLDS system.

Conjecture 3: An Affordance-based CPN model can effectively represent the “spatio-temporality” specification and the relationship that exists between an animal and its environment.

This conjecture addresses the issues associated with the spatio-temporal specification of affordances. If any of the output metrics were found to be significant while analyzing the performance data generated by the affordance-based CPN model on scenarios involving spatio-temporality, then this would refute the conjecture that the affordance-based CPN model is efficient in representing the spatio-temporal specification of an animal within its environment.

Chapter 5

METHODOLOGY

In this chapter, the methodology used for conducting the empirical experiments and collecting driver related performance data is discussed. The demographics of the participants are described in section **5.1**, followed by an illustration of the equipment and tools used for the experiment, in section **5.2**. The experimentation protocol is explained in section **5.3**. Section **5.4** provides a description of the independent variables that are controlled during the experiment. Section **5.5** provides a description of the test scenarios and section **5.6** describes the dependent variables used for capturing driver performance during the experiment.

5.1 Participants

Four test drivers were recruited from the Pennsylvania Transportation Institute (PTI) at Penn State University. These drivers were randomly grouped into two pairs for the experiment. While one driver was randomly assigned to the role of a confederate driver (CD), the other driver was assigned to the role of the subject driver (SD). Each of these drivers was male, between the ages of 40–65 years and possessed a valid commercial driver's license at the time of the experiment. Each driver had a practical driving experience of at least 15 years on US highway lane system. Two of the four drivers had corrective glasses, which provided them with a 20/20 vision correction. The

experiment was conducted during daytime between 2:00 PM – 4:30 PM eastern standard time in the month of October 2006. Therefore, the participants had ample daylight while driving and did not require any additional light source. The subjects were provided with monetary compensation, equivalent to their hourly wages at PTI, for their participation at the end of the experiment.

5.2 Equipment and Tools

In order to conduct this experiment, an actual test track at PTI was used. The topographical map of the test track is shown in figure 5-1 (Source: PTI, University Park, PA) along with the straight stretch portion of the test track that was used during the experiment.

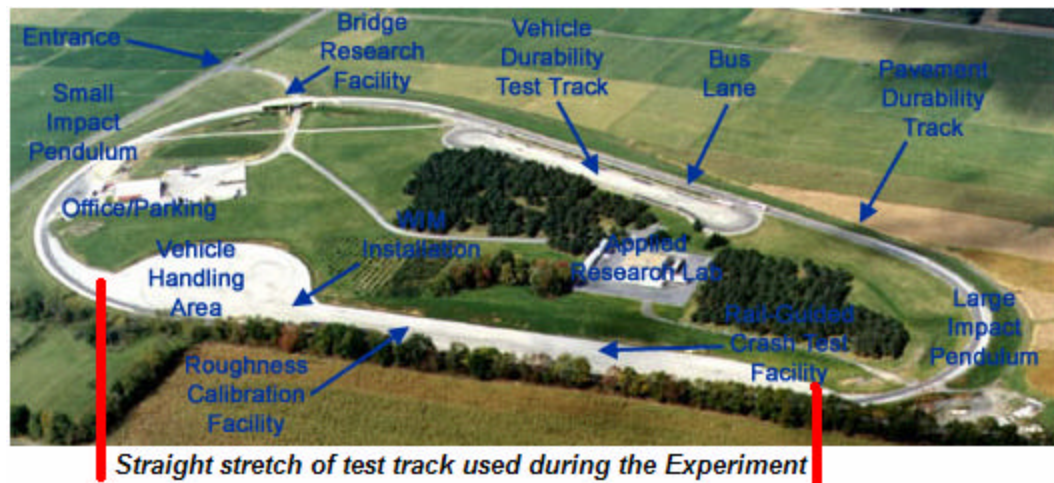


Figure 5-1: Topographical Map of the Test Track (Source: PTI, University Park, PA)

This portion of the test track spans approximately 402 meters (equivalent to a $\frac{1}{4}$ -mile stretch). However, only a span of 360 meters of this stretch was used during data

collection, which allowed the drivers to slow down after this point. This also enabled the drivers to have a runway length of 42 meters to slow down and safely come to a complete stop at a designated location.

The CD was assigned to drive a 1989 Dodge Caravan (Minivan) that was equipped with the VBOX2 Differential Global Positioning System (DGPS) unit (VBOX, 2006). A 1992 Mercury Tracer equipped with a DGPS unit was used as the test vehicle for SD. The details of the DGPS System and the test vehicle used in the car driven by SD are provided in Martini (2006). Both of these cars were equipped with automatic transmissions that require standard driving skills.

Figure 5-2 shows the overall layout for the test track along with the primary and secondary reference points.

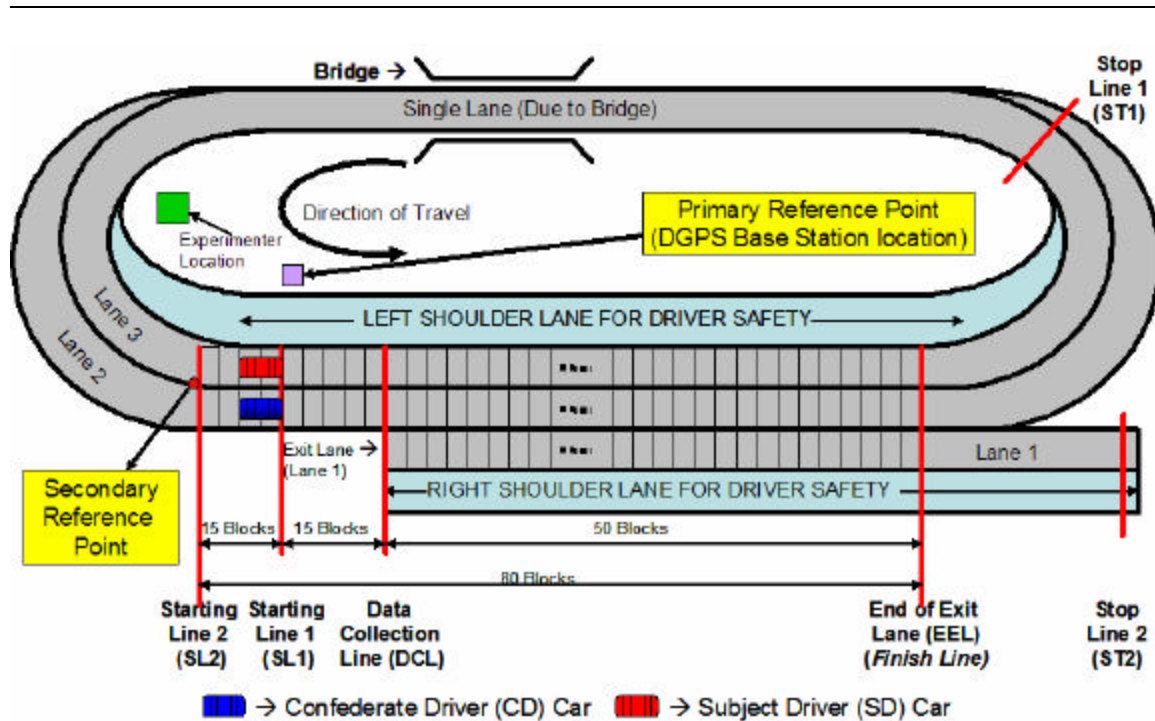


Figure 5-2: Layout of the Test Track

The primary reference point is the location of the DGPS Base Station unit. The secondary reference point is denoted as the point that lies between lane 3 and lane 2 at the beginning of the first block. Both of these DGPS units provide positional information about the respective test vehicles in terms of latitude, longitude and altitude, which is then transformed into x - y Cartesian coordinate system (with reference to the secondary reference point) using the WGS84 coordinate system (WGS84, 2007) as described in Appendix C. After calibration, it was determined that the average error radius for the Cartesian coordinates derived from the latitude, longitude and altitude information, was less than ± 0.5 meters and was acceptable for this experiment. These output metrics are measured using the metric system and then converted into lane-block position based on a secondary reference point for data analysis.

In addition to this, the original data from the VBOX DGPS unit was recorded at 20 Hz frequency (containing twenty updates per second), which was sampled to a 1 Hz frequency (containing one update per second) for data analysis purposes. The steps shown in Appendix D were followed to convert the data and organize it into a Microsoft® Office Excel spreadsheet for further analysis.

Each lane is about 2.5 meters wide and a block is 4.5 meters wide (equivalent to the average length of a car). Two starting locations, namely SL1 and SL2, are designated 15 blocks apart on the test track. The point after which the drivers must slow down and safely come to a complete stop is called *End of Exit Lane* (EEL). The exit lane spans a total length of 50 blocks from Data Collection Line (DCL) to EEL and the entire track spans a length of 80 blocks from SL2 to EEL. There are two-stop lines ST1 and ST2 that provide safe stopping locations for both drivers. As a safety measure, the driver who exits

the lane first was instructed to slow down immediately after EEL and stop at ST2 location, and the driver who exits the lane second was instructed to stop at ST1 location. In case of an emergency, the drivers were instructed to move to the shoulder closest to their current lane and come to a complete stop. These precautionary measures ensured the safety of drivers while maneuvering on the test track.

5.3 Experimentation Protocol

The steps involved in the experimentation protocol are shown in figure 5-3. Initially, the expertise level of the drivers and their demographics are captured via a pre-study survey without any personal identifiers. The drivers were then briefed about the overall goals, objectives and risks involved in the experiment. They were later required to provide their consent for participating in the experiment by signing an informed consent form (shown in Appendix E) that explains their rights as a participant. The drivers were randomly assigned to a specific role (either CD or SD) after they provided their consent for the experiment. During this stage, the drivers were provided with a briefing on the safety protocol, including the precautionary measures, which must be followed in case of an emergency. The drivers then participated in four practice trial sessions (practice trial #: 1–4) as observers and received specific training instructions from the experimenter about performing a successful lane change maneuver on the test track, while maintaining a specified target velocity. Then, each driver was allowed to participate in two additional practice trial sessions (CD → practice trials 5–6 and SD → practice trials 7–8) as an

actual driver, which enabled them to familiarize themselves with the test vehicle and its capabilities.

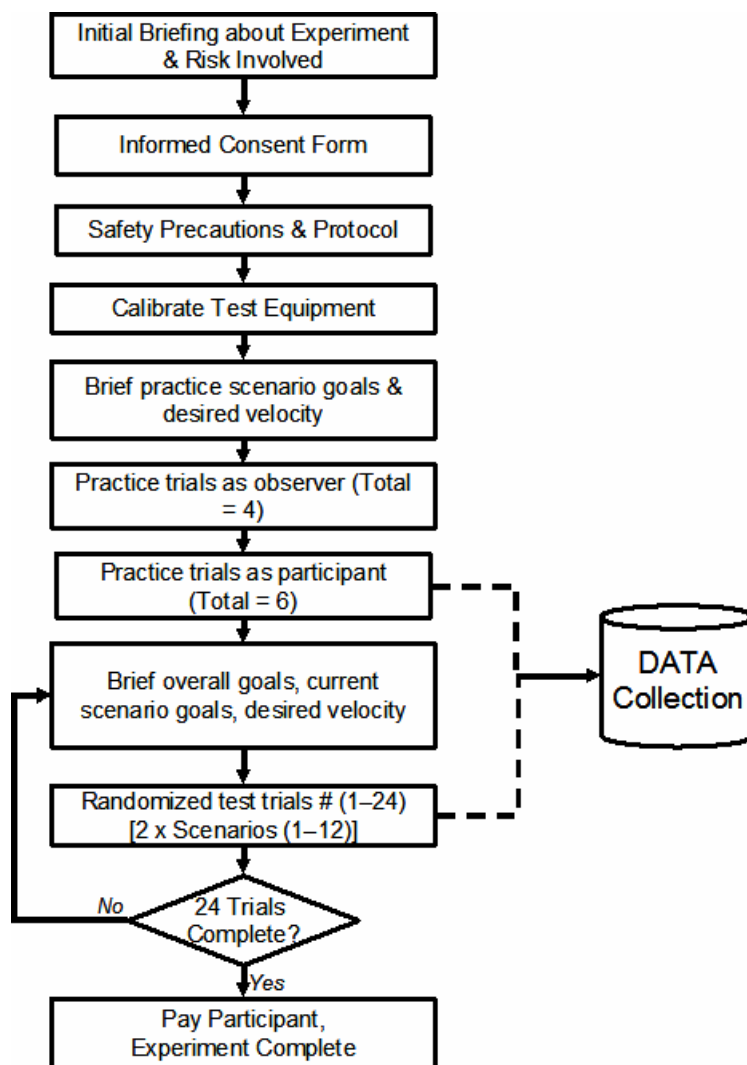


Figure 5-3: Experimentation Protocol

Then, both drivers participated as concurrent drivers in two practice trials to acquaint themselves with the test track and lane change maneuvers, while maintaining a pre-specified target velocity. The drivers were also instructed to attain and maintain their respective target velocity as quickly as possible after the start of the current scenario.

They were also encouraged to clarify any questions regarding the experiment at the end of each practice trial. The initial briefing, training and practice trial sessions took approximately 30 minutes to complete.

After the drivers completed their practice trials, they were randomly assigned to 24 trial sessions comprising of the 12 test scenarios, which were repeated two times each. Prior to beginning of each trial, both drivers received specific instruction about their starting location (initial lane-block position) and the target velocity that they had to maintain for that trial scenario. The overall goals for each driver (i.e., exit the highway, maintain current speed) was also refreshed prior to the beginning each trial. The drivers were compensated for their participation after completing all of their 24 actual trials. The instruction that both drivers received for each scenario is summarized in Appendix C.

In addition, an informal post-study survey (as described in Appendix F) was used to elicit the experience of each participant driver during the driving task. The driver related performance metrics were collected from the DGPS units and used in further data analysis. The data analysis for each trial scenario was then used to verify the precision of the CPN model.

5.4 Independent Variables

Two independent variables, *relative position* (both lane and block) and *relative velocity* were used to control the settings of each test scenario. Table **5-1** shows the list of the independent variables and their different level settings used for the experiment. There are two levels for the starting lane position of each driver – *Lane 3* or *Lane 2*, and two

levels for the starting block position for each diver – *Starting Location 1 (SL1: Block 15)* or *Starting Location 2 (SL2: Block 1)*. These two variables collectively yield twenty-four possible levels for relative position with respect to both drivers (SD and CD) in the HLDS system. However, only a subset of these relative position levels (eight relative position levels, including two at single level and three at both levels of relative velocity) was used in the actual experiment.

Table 5-1: Independent Variables and their Different Levels

Different Levels for each Individual Independent Variable		
Starting Lane Position	Starting Block Position	Relative Velocity
Lane 3 (L ₃)	Starting Location 1 (SL ₁ : Block 15)	$V_{SD} (= 40 \text{ mph}) > V_{CD} (= 20 \text{ mph})$
Lane 2 (L ₂)	Starting Location 2 (SL ₂ : Block 1)	$V_{SD} = V_{CD} (= 20 \text{ mph})$
		$V_{SD} (= 20 \text{ mph}) < V_{CD} (= 40 \text{ mph})$
Actual Levels used for the Independent Variables		
Relative Position: SD Position, CD Position		Relative Velocity
(Lane 2, Starting Location 2), (Lane 2, Starting Location 1)		$V_{SD} > V_{CD}$
(Lane 2, Starting Location 2), (Lane 3, Starting Location 1)		$V_{SD} > V_{CD}$
(Lane 2, Starting Location 1), (Lane 3, Starting Location 1)		$V_{SD} > V_{CD}$
(Lane 3, Starting Location 2), (Lane 2, Starting Location 1)		$V_{SD} > V_{CD}$
(Lane 3, Starting Location 2), (Lane 3, Starting Location 1)		$V_{SD} > V_{CD}$
(Lane 3, Starting Location 1), (Lane 2, Starting Location 1)		$V_{SD} > V_{CD}$
(Lane 2, Starting Location 2), (Lane 2, Starting Location 1)		$V_{SD} = V_{CD}$
(Lane 2, Starting Location 2), (Lane 3, Starting Location 2)		$V_{SD} = V_{CD}$
(Lane 2, Starting Location 2), (Lane 3, Starting Location 1)		$V_{SD} = V_{CD}$
(Lane 3, Starting Location 2), (Lane 2, Starting Location 2)		$V_{SD} = V_{CD}$
(Lane 3, Starting Location 2), (Lane 2, Starting Location 1)		$V_{SD} = V_{CD}$
(Lane 3, Starting Location 2), (Lane 3, Starting Location 1)		$V_{SD} = V_{CD}$

The second independent variable depicts the relative velocity between the drivers and yields three levels. However, only two out of these three possible levels of relative velocity ($V_{SD} > V_{CD}$ or $V_{SD} = V_{CD}$) were used in the experiment. Therefore, a combination of these relative positions and relative velocity results in the twelve experimental test scenarios as described in the next section.

5.5 Description of Test Scenarios

Twelve test scenarios were developed based on the independent variables described in Table 5-2. This table also indicates whether the scenario includes concurrency, stochasticity and spatio-temporality.

Table 5-2: Test Scenarios

Scenario #	Starting Position of Both Drivers				Relative Velocity (Reaction between V_{SD} & V_{CD})	CD starts vertically closer to Exit Lane ¹	CD starts horizontally closer to Exit Lane ²	SD drives faster than CD ³	Is Concurrency included ?	Is Stochasticity included?	Is Spatio-Temporality included?
	Subject Driver		Confederate Driver								
	Lane Position (LP_{SD})	Block Position (BP_{SD})	Lane Position (LP_{CD})	Block Position (BP_{CD})							
1	Lane 2	Block 1	Lane 2	Block 15	$V_{SD} > V_{CD}$	No	Yes	Yes	No	Yes	Yes
2	Lane 2	Block 1	Lane 3	Block 15	$V_{SD} > V_{CD}$	No	Yes	Yes	No	Yes	Yes
3	Lane 2	Block 15	Lane 3	Block 15	$V_{SD} > V_{CD}$	No	No	Yes	No	Yes	Yes
4	Lane 3	Block 1	Lane 2	Block 15	$V_{SD} > V_{CD}$	Yes	Yes	Yes	No	Yes	Yes
5	Lane 3	Block 1	Lane 3	Block 15	$V_{SD} > V_{CD}$	No	Yes	Yes	No	Yes	Yes
6	Lane 3	Block 15	Lane 2	Block 15	$V_{SD} > V_{CD}$	Yes	No	Yes	No	Yes	Yes
7	Lane 2	Block 1	Lane 2	Block 15	$V_{SD} = V_{CD}$	No	Yes	No	No	Yes	Yes
8	Lane 2	Block 1	Lane 3	Block 1	$V_{SD} = V_{CD}$	No	No	No	Yes	Yes	Yes
9	Lane 2	Block 1	Lane 3	Block 15	$V_{SD} = V_{CD}$	No	Yes	No	No	Yes	Yes
10	Lane 3	Block 1	Lane 2	Block 1	$V_{SD} = V_{CD}$	Yes	No	No	Yes	Yes	Yes
11	Lane 3	Block 1	Lane 2	Block 15	$V_{SD} = V_{CD}$	Yes	Yes	No	No	Yes	Yes
12	Lane 3	Block 1	Lane 3	Block 15	$V_{SD} = V_{CD}$	No	Yes	No	No	Yes	Yes

1: CD starts VERTICALLY further away (Lane 3) or closer (Lane 2) to the exit lane
2: CD starts HORIZONTALLY further away (Block 1) or closer (Block 15) to the exit lane
3: SD drives faster than [$V_{SD} > V_{CD}$] or at the same velocity [$V_{SD} = V_{CD}$] as CD

During the actual test scenario, the CD was instructed to follow a scripted path as specified for each scenario. This scripted path requires the CD to move toward the exit lane right after the exit lane begins. This method of using a scripted path for CD allows us to elicit various driving behaviors from SD.

5.6 Dependent Variables

Four dependent variables (output metrics) were derived from the driver related performance data recorded by the test equipment located in the vehicles driven by both

drivers. The dependent variables are ΔLP , ΔTD , ΔTTE and ΔUD . A description of these dependent variables is provided in Table 5-3.

Table 5-3: Description of the Dependent Variables

Output Metrics	Description
ΔLP	Root mean square deviation in the lane position (path) traversed by the human driver and the model at every time update during the scenario.
ΔTD	Root mean square deviation in the turn direction exhibited the human driver and the model at every time update during the scenario.
ΔTTE	Absolute deviation in time to exit (by moving into the exit lane) for the human driver and the model during the scenario.
ΔU	Absolute deviation in the utilization of the exit lane for the human driver and the model during the scenario.

The formula for calculating these dependent variables are given below:

- The formula for calculating ΔLP , the root mean square deviation in lane position or path traversed by the human driver and the model, is given by Eq. 5.1.

$$\Delta LP = \frac{\sqrt{\sum_{i=1}^T (LP_i^{\text{human}} - LP_i^{\text{model}})^2}}{T},$$

$$T = \max(T^{\text{human}}, T^{\text{model}}), \text{ where}$$

$$LP_i^{\text{human}} = \text{Lane position or path for human subject driver at time } i,$$

$$LP_i^{\text{model}} = \text{Lane position or path for model subject driver at time } i,$$

$$T^{\text{human}} = \text{Total scenario duration time for human subject driver, and}$$

$$T^{\text{model}} = \text{Total scenario duration time for model subject driver.}$$

5.1

If the value of ΔLP was found to be significant, then this would imply that the model is not accurate in predicting the lane position occupied by the human driver.

- The formula for calculating ΔTD , the root mean square deviation in turn direction between the human driver and the model, is given by Eq. 5.2.

$$\Delta TD = \frac{\sqrt{\sum_{i=1}^T (TD_i^{\text{human}} - TD_i^{\text{model}})^2}}{T},$$

$$T = \max(T^{\text{human}}, T^{\text{model}}), \text{ where}$$

$$TD_i^{\text{human}} = \text{Turn direction for human subject driver at time } i,$$

$$TD_i^{\text{model}} = \text{Turn direction for model subject driver at time } i,$$

$$T^{\text{human}} = \text{Total scenario duration time for human subject driver, and}$$

$$T^{\text{model}} = \text{Total scenario duration time for model subject driver.}$$

5.2

If the value of ΔTD was found to be significant, then this would imply that the model is not accurate in predicting the turn direction pursued by the human driver.

- The formula for calculating ΔTTE , the absolute deviation in time to exit the highway lane system for the human driver and the model, is given by Eq. 5.3.

$$\Delta TTE = |TTE^{\text{human}} - TTE^{\text{model}}|, \text{ where}$$

$$TTE^{\text{human}} = \text{Time to exit for human subject driver, and}$$

$$TTE^{\text{model}} = \text{Time to exit for model subject driver.}$$

5.3

If the value of ΔTTE was found to be significant, then this would imply that the model is not accurate in predicting the time taken by the human driver to move into the exit lane.

- The formula for calculating ΔU , the absolute deviation in utilization of the exit lane by both human driver and the model, is given by Eq. 5.4.

$$\Delta U = \frac{|TTE^{\text{human}} - TTE^{\text{model}}|}{T},$$

$$T = \max(T^{\text{human}}, T^{\text{model}}), \text{ where}$$

$$TTE^{\text{human}} = \text{Time to exit for human subject driver}, \quad \mathbf{5.4}$$

$$TTE^{\text{model}} = \text{Time to exit for model subject driver},$$

$$T^{\text{human}} = \text{Total scenario time for human subject driver, and}$$

$$T^{\text{model}} = \text{Total scenario time for model subject driver.}$$

If the value of ΔU was found to be significant, then this would imply that the model is not accurate in predicting the utilization of the exit lane or the amount of time spent by the human driver in the exit lane.

5.7 Chapter Summary

In this chapter, the methodology, description of the participants, tools and equipment used to conduct the empirical study is described. In addition to this, a detailed explanation of the independent variables is provided along with the summary of the experimentation protocol. The test scenarios used in the experiment are also described.

Finally, the dependent variables or output metrics used for analysis are listed along with their formulation.

Chapter 6

RESULTS AND ANALYSIS

This chapter provides an explanation of the results and analysis for the performance data obtained from the empirical study and CPN model using the dependent variables identified in the previous chapter. The data analysis procedure is explained in section **6.1**. Sections **6.2** and **6.3** describe the results related to the deviations in lane position and turn direction, between the empirical and model predicted values. The results associated with deviation in the time taken for SD to move from the starting lane to the exit lane, based on empirical and model predicted values, are explained in section **6.4**. Section **6.5** presents the results for deviation in the utilization of the exit lane by SD based upon empirical and model predicted values. A comparison of the results obtained from an affordance-based CPN model and a random model is presented in section **6.6**.

6.1 Data Analysis Procedure

The data analysis procedure shown in Figure **6-1** will be consistently used to analyze all four dependent variables (ΔLP , ΔTD , ΔTTE and ΔU) throughout the rest of this chapter. The goal of this data analysis is to verify how well the affordance-based CPN model fits human performance data (i.e. actualized actions) and identify any variables that impact this fit systematically, which would suggest possible improvements to the model.

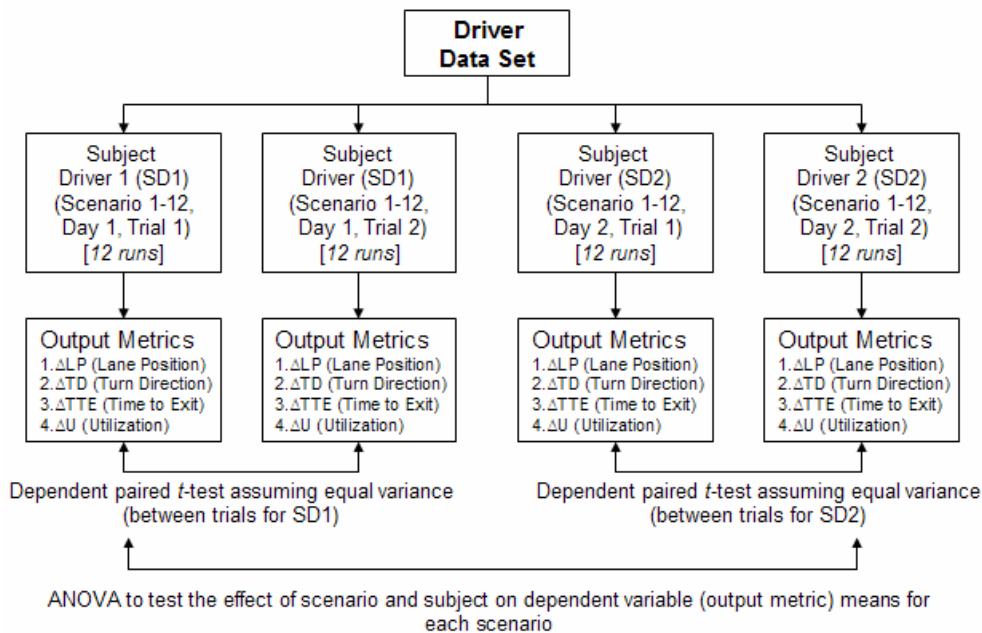


Figure 6-1: Data Analysis Procedure

The first possible variable that might affect the model's ability to fit human performance data is "trial" – or the human's amount of exposure to a scenario. Each subject performed a specific scenario twice during the experiment. A dependent *t*-test will determine whether the fit of the model was significantly different across these two trials. If the dependent variable is not significant (using $\alpha = 0.05$), then data across trials can be aggregated for further analyses.

The next possible variables are "scenario" and "subject" – that is, the two subjects who played the role of subject driver within the experiment and the nature of the scenario. An ANOVA based analysis will be used to determine whether the model fit human performance data significantly better on some scenarios than on others. If the *F*-statistic for scenario effects (Keppel, 1991) is found to be significant (using $\alpha = 0.05$), then this would indicate that the model does not appear to fit the empirical data of the

subject driver for that dependent variable on at least one scenario. If the F-statistic for the subject effects is found to be significant (using $\alpha = 0.05$), then it would mean that there was a significant effect due to subjects on the model predicted value for that dependent variable. This justifies a further need for investigation on that particular dependent variable. Then, further post-hoc analyses using pivot tables would be conducted to determine exactly which scenarios led to particularly good or bad predictions by the model and identify any emerging patterns.

The twelve original scenarios were classified based on *starting lane position* (whether CD was vertically closer to exit lane), *starting block position* (whether CD was horizontally closer to exit lane) and *relative velocity* (whether SD was driving faster than CD) as shown in Table **6-1**.

Table **6-1**: Scenario Classifications

Scenario #	CD vertically closer to exit lane ?	CD horizontally closer to exit Lane ?	SD faster than CD?
1	No	Yes	Yes
2	No	Yes	Yes
3	No	No	Yes
4	Yes	Yes	Yes
5	No	Yes	Yes
6	Yes	No	Yes
7	No	Yes	No
8	No	No	No
9	No	Yes	No
10	Yes	No	No
11	Yes	Yes	No
12	No	Yes	No

The scenarios were then grouped using a pivot table, as shown in Table 6-2 based on the earlier scenario classifications. Following that, logical analyses of the characteristics of those scenarios were conducted to produce recommendations for an improved model.

Table 6-2: Scenario Grouping Using the Pivot Table

SD drives faster than CD?	no	
	CD horizontally closer to exit lane ?	
CD vertically closer to exit lane ?	no	yes
no	Scenario-8 <i>(includes concurrency)</i>	Scenario-7 Scenario-9 Scenario-12
yes	Scenario-10 <i>(includes cocurrency)</i>	Scenario-11
SD drives faster than CD?	yes	
	CD horizontally closer to exit lane ?	
CD vertically closer to exit lane ?	no	yes
no	Scenario-3	Scenario-1 Scenario-2 Scenario-5
yes	Scenario-6	Scenario-4

The details of the results for all four dependent variables are discussed in the subsequent sections.

6.2 Deviation in Lane Position (ΔLP)

In this section, the data related to the root mean square deviation in the lane position occupied by the human subject driver and model predictions were analyzed. The deviation in lane position (ΔLP) for both subject drivers on trials across all scenarios is shown in Table 6-3. The possible range for ΔLP is 0.0 to 1.0. The mean and standard deviation values for ΔLP on both trials for SD1 (Trial 1: Mean = 0.197, Std. Dev = 0.163; Trial 2: Mean = 0.153, Std. Dev = 0.111) is lesser than SD2 (Trial 1: Mean = 0.287, Std. Dev = 0.189; Trial 2: Mean = 0.287, Std. Dev = 0.187).

Table 6-3: Descriptive Statistics for ΔLP

Scenario #	Deviation in Lane Position (ΔLP)			
	Subject Driver 1 (SD1)		Subject Driver 2 (SD2)	
	Day 1 (Trial 1)	Day 1 (Trial 2)	Day 2 (Trial 1)	Day 2 (Trial 2)
1	0.087	0.000	0.565	0.667
2	0.043	0.083	0.000	0.042
3	0.200	0.200	0.200	0.150
4	0.043	0.083	0.250	0.292
5	0.125	0.087	0.174	0.125
6	0.350	0.368	0.550	0.500
7	0.167	0.130	0.167	0.167
8	0.292	0.174	0.250	0.167
9	0.083	0.130	0.250	0.250
10	0.043	0.043	0.083	0.208
11	0.391	0.208	0.417	0.500
12	0.542	0.333	0.542	0.375
<i>Minimum</i>	0.043	0.000	0.000	0.042
<i>Maximum</i>	0.542	0.368	0.565	0.667
<i>Mean</i>	0.197	0.153	0.287	0.287
<i>Std. Dev</i>	0.163	0.111	0.189	0.187

First, two individual paired t-tests were conducted on ΔLP values to test whether the values of ΔLP were significantly different between trials for both drivers. The paired t-tests for SD1 (t-statistic = 1.736, p-value = 0.110) and SD2 (t-statistic = 0.019, p-value

= 0.984) indicated that there appears to be no significant effect on ΔLP due to trial for both subjects. The complete details of these t-tests are shown in Appendix G. Therefore, the ΔLP values between trials for each subject were aggregated. The descriptive statistics after aggregating by trials is shown in Table 6-4.

Table 6-4: Descriptive Statistics for ΔLP After Aggregating by Trials

Scenario #	Deviation in Lane Position (ΔLP) after aggregating by Trials	
	Subject Driver 1 (SD1)	Subject Driver 2 (SD2)
	Day 1	Day 2
1	0.043	0.616
2	0.063	0.021
3	0.200	0.175
4	0.063	0.271
5	0.106	0.149
6	0.359	0.525
7	0.149	0.167
8	0.233	0.208
9	0.107	0.250
10	0.043	0.146
11	0.300	0.458
12	0.438	0.458
<i>Minimum</i>	0.043	0.021
<i>Maximum</i>	0.438	0.616
<i>Mean</i>	0.175	0.287
<i>Std. Dev</i>	0.132	0.183

Figure 6-2 provides a graphical representation of ΔLP for both subject drivers on all scenarios.

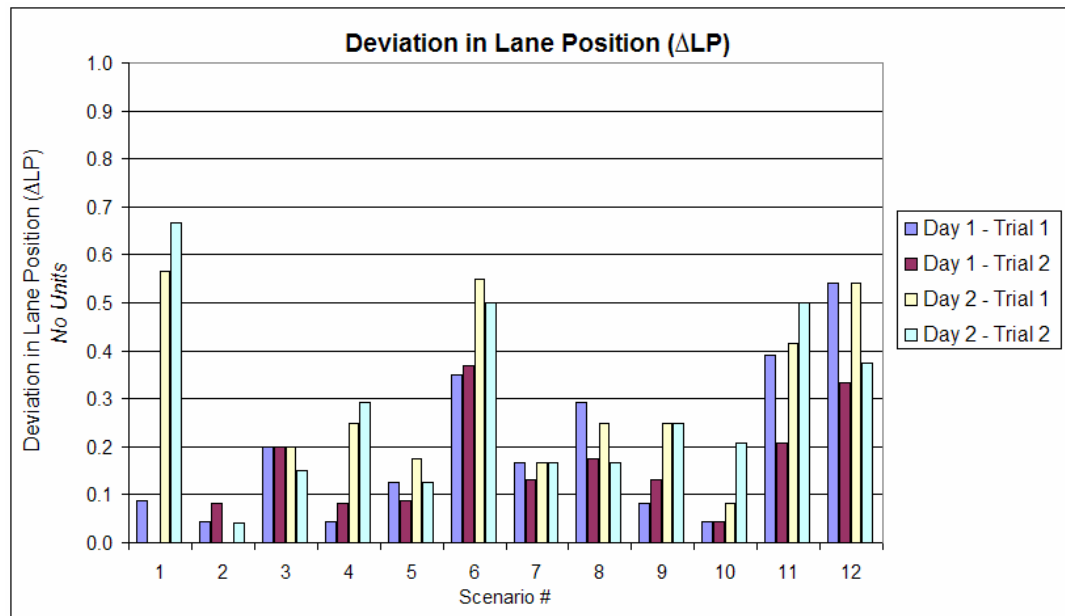


Figure 6-2: Graphical Representation of Deviation in Lane Position

SD2 exhibited a peak deviation value for lane position on scenario 1 for both trials (0.565, 0.667). The smaller values for ΔLP indicate that the model appears to be consistent in predicting the lane position occupied by the human driver. During scenarios 1, 6, 11 and 12, the drivers accounted for ΔLP values greater than 0.3. On all the other scenarios, the ΔLP value was lesser than 0.3 on both trials. Therefore, further data analysis was conducted to confirm whether the values of ΔLP are significantly different across scenarios.

An ANOVA based analysis was conducted to test the effects of scenario and subject on deviation in lane position. The computed F-Statistic was used to analyze the effects due to each scenario and subjects on ΔLP . The results of the F-test are summarized in Table 6-5.

Table 6-5: Test for the Effect of Scenario and Subject on ΔLP

Source	df	SS	MS	F _{Computed}	F _{Critical}	Significant?
A (scenario)	11	0.404903	0.036809	2.609305	2.82	No
S (subject)	1	0.074824	0.074824	5.304044	4.84	Yes
Error	11	0.155176	0.014107			
Total	23	0.634903				

The results confirm that there appears to be no significant due to scenario ($F_{\text{Computed}} = 2.609 < F_{\text{Critical}} = 2.82$), but there seems to be a significant effect ($F_{\text{Computed}} = 5.304 > F_{\text{Critical}} = 4.84$) on lane position due to the subject. This implies that the model appears to be consistent in predicting the lane position between subject drivers on all scenarios. The estimated marginal mean for ΔLP , standard error and 95% confidence interval (for this mean) on all scenarios are shown in Table 6-6.

Table 6-6: Estimated Marginal Means for Deviation in Lane Position

Estimated Marginal Means for Deviation in Lane Position (ΔLP)				
ΔLP on Scenario #	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	0.24	0.197	-2.263	2.744
2	0.34	0.276	-3.171	3.85
3	0.11	0.09	-1.028	1.249
4	0.167	0.104	-1.151	1.485
5	0.128	0.022	-0.149	0.404
6	0.442	0.083	-0.611	1.495
7	0.158	0.009	0.043	0.273
8	0.221	0.012	0.065	0.376
9	0.178	0.072	-0.731	1.088
10	0.095	0.051	-0.556	0.745
11	0.379	0.079	-0.628	1.386
12	0.448	0.01	0.316	0.58

A pivot table was constructed to identify the scenarios where there was a mismatch between empirical and model predicted performance data for lane position

(ΔLP), as shown in Table 6-7. These scenario groupings are based on the criteria described in Table 6-2. This pivot table allows us to investigate the effect of the independent variables (starting lane and block position, relative velocity) on the dependent variable, ΔLP , and identify any emerging patterns. The details of the pivot table would be analyzed in the next chapter.

Table 6-7: Pivot Table for ΔLP

SD drives faster than CD?				
no		CD horizontally closer to exit lane ?		
CD vertically closer to exit lane ?	Data	no	yes	Grand Total
no	Average of ΔLP	0.221	0.261	0.251
	StdDev of ΔLP	0.017	0.152	0.130
	Count of ΔLP	2	6	8
yes	Average of ΔLP	0.095	0.379	0.237
	StdDev of ΔLP	0.072	0.112	0.181
	Count of ΔLP	2	2	4
Total Average of ΔLP		0.158	0.291	0.246
Total StdDev of ΔLP		0.084	0.146	0.141
Total Count of ΔLP		4	8	12

SD drives faster than CD?				
yes		CD horizontally closer to exit lane ?		
CD vertically closer to exit lane ?	Data	no	yes	Grand Total
no	Average of ΔLP	0.188	0.167	0.172
	StdDev of ΔLP	0.018	0.225	0.190
	Count of ΔLP	2	6	8
yes	Average of ΔLP	0.442	0.167	0.305
	StdDev of ΔLP	0.117	0.147	0.192
	Count of ΔLP	2	2	4
Total Average of ΔLP		0.315	0.167	0.216
Total StdDev of ΔLP		0.162	0.198	0.193
Total Count of ΔLP		4	8	12

6.3 Deviation in Turn Direction (Δ TD)

In this section, the results related to root mean square deviation in turn direction (Δ TD) of the subject driver's steering wheel is analyzed. Table 6-8 shows the descriptive statistics for Δ TD for both subject drivers on all trials. The values for Δ TD range from 0.0 to 1.0.

Table 6-8: Descriptive Statistics for Δ TD

Scenario #	Deviation in Turn Direction (Δ TD)			
	Subject Driver 1 (SD1)		Subject Driver 2 (SD2)	
	Day 1 (Trial 1)	Day 1 (Trial 2)	Day 2 (Trial 1)	Day 2 (Trial 2)
1	0.087	0.000	0.174	0.167
2	0.087	0.083	0.000	0.083
3	0.025	0.025	0.025	0.025
4	0.087	0.083	0.167	0.167
5	0.167	0.174	0.174	0.167
6	0.048	0.211	0.051	0.049
7	0.083	0.087	0.083	0.083
8	0.083	0.087	0.083	0.083
9	0.083	0.087	0.083	0.083
10	0.087	0.087	0.083	0.042
11	0.174	0.167	0.167	0.167
12	0.167	0.167	0.167	0.167
<i>Minimum</i>	0.025	0.000	0.000	0.025
<i>Maximum</i>	0.174	0.211	0.174	0.167
<i>Mean</i>	0.098	0.105	0.105	0.107
<i>Std. Dev</i>	0.047	0.063	0.063	0.056

These deviation values appear to be generally smaller than deviations in lane position as the driver's turn left or right only while changing lanes and otherwise continue driving straight ahead (which is more frequent). The mean and standard deviation values for Δ TD appear to be similar for SD1 (Trial 1: Mean = 0.098, Std. Dev = 0.047; Trial 2: Mean = 0.105, Std. Dev = 0.063) and SD2 (Trial 1: Mean = 0.105, Std. Dev = 0.063; Trial 2: Mean = 0.107, Std. Dev = 0.056).

As before, two individual paired t-tests were conducted to test whether the values of ΔTD were significantly different between trials for both drivers. The paired t-tests for SD1 (t-statistic = -0.411, p-value = 0.688) and SD2 (t-statistic = -0.268, p-value = 0.793) appears to indicate that there was no significant effect on ΔTD due to trials for both subjects. The complete details of these t-tests are shown in Appendix G. Therefore, the values of ΔTD between trials for each subject were aggregated. The descriptive statistics after aggregating by trials is shown in Table 6-9.

Table 6-9: Descriptive Statistics for ΔTD After Aggregating by Trials

Scenario #	Deviation in Turn Direction (ΔTD) after aggregating by Trials	
	Subject Driver 1 (SD1)	Subject Driver 2 (SD2)
	Day 1	Day 2
1	0.043	0.170
2	0.085	0.042
3	0.025	0.025
4	0.085	0.167
5	0.170	0.170
6	0.129	0.050
7	0.085	0.083
8	0.085	0.083
9	0.085	0.083
10	0.087	0.063
11	0.170	0.167
12	0.167	0.167
<i>Minimum</i>	0.025	0.025
<i>Maximum</i>	0.170	0.170
<i>Mean</i>	0.101	0.106
<i>Std. Dev</i>	0.048	0.058

A graphical representation of the ΔLP for both subject drivers on all scenarios is shown in Figure 6-3.

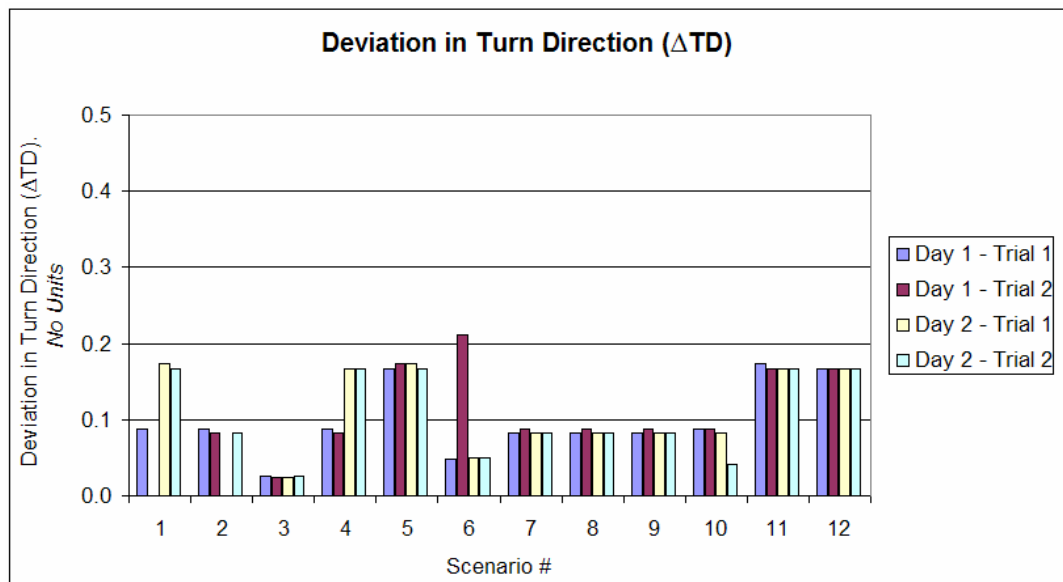


Figure 6-3: Graphical Representation for Deviation in Turn Direction

A peak deviation value of 0.211 was recorded for SD1 on scenario-6. The overall average for ΔTD across all trials for both subjects was found to be 0.104. Both drivers accounted for high ΔTD values on scenarios 5, 11 and 12. In addition to these scenarios, SD2 showed a high value for ΔTD on scenario 1 and 4. On all the other scenarios, the ΔTD value was lesser than 0.1 on both trials.

An ANOVA based analysis was conducted to test the effects of scenario and subject on deviation in turn direction. The computed F-Statistic was used to analyze the effects due to each scenario and subjects on ΔTD . The results of the F-test are summarized in Table 6-10.

Table 6-10: Test for the Effects of Scenario and Subject on ΔTD

Source	df	SS	MS	F _{Computed}	F _{Critical}	Significant?
A (scenario)	11	0.046224	0.004202	2.952682	2.82	Yes
S (subject)	1	0.000113	0.000113	0.079132	4.84	No
Error	11	0.015655	0.001423			
Total	23	0.061992				

The results indicate that there appears to be a significant effect due to scenario ($F_{\text{Computed}} = 2.953 > F_{\text{Critical}} = 2.82$), but there seems to be no significant effect due to subject ($F_{\text{Computed}} = 0.079 < F_{\text{Critical}} = 4.84$) on ΔTD . This result is expected because the model is not expected to make a turn at the exact same time as a human driver during any given scenario. In addition to this, both drivers turned the car and moved into an adjacent lane only while making a lane change, which makes this output measure more sensitive. However, the overall lane position occupied by both drivers was closely predicted by the model. The estimated marginal mean for ΔTD , standard error and 95% confidence interval (for this mean) on all scenarios is shown in Table 6-11.

Table 6-11: Estimated Marginal Means for Deviation in Turn Direction

Estimated Marginal Means for Deviation in Turn Direction (Δ TD)				
Δ TD on Scenario #	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	0.107	0.063	-0.699	0.913
2	0.063	0.022	-0.213	0.34
3	0.025	0	0.025	0.025
4	0.126	0.041	-0.392	0.644
5	0.17	0	0.17	0.17
6	0.09	0.04	-0.414	0.594
7	0.084	0.001	0.073	0.096
8	0.084	0.001	0.073	0.096
9	0.084	0.001	0.073	0.096
10	0.075	0.012	-0.081	0.23
11	0.168	0.002	0.145	0.191
12	0.167	0	0.167	0.167

As before, a pivot table based analysis was conducted to get insights into the scenarios where there was a mismatch between empirical and model predicted performance data for Δ TD. The scenarios were again classified using the same criteria described in Table 6-2. A summary of the results of the pivot table analysis for Δ TD are provided in Table 6-12. This pivot table allows us to scrutinize the effect of the independent variables (starting lane and block position, relative velocity) on the dependent variable, Δ TD, and identify any emerging patterns.

Table 6-12: Pivot Table for ΔTD

SD drives faster than CD?				
no				
		CD horizontally closer to exit lane ?		
CD vertically closer to exit lane ?	Data	no	yes	Grand Total
no	Average of ΔTD	0.084	0.112	0.105
	StdDev of ΔTD	0.001	0.043	0.038
	Count of ΔTD	2	6	8
yes	Average of ΔTD	0.075	0.168	0.122
	StdDev of ΔTD	0.017	0.003	0.055
	Count of ΔTD	2	2	4
Total Average of ΔTD		0.079	0.126	0.110
Total StdDev of ΔTD		0.011	0.045	0.043
Total Count of ΔTD		4	8	12

SD drives faster than CD?				
yes				
		CD horizontally closer to exit lane ?		
CD vertically closer to exit lane ?	Data	no	yes	Grand Total
no	Average of ΔTD	0.025	0.114	0.091
	StdDev of ΔTD	0.000	0.064	0.068
	Count of ΔTD	2	6	8
yes	Average of ΔTD	0.090	0.126	0.108
	StdDev of ΔTD	0.056	0.058	0.051
	Count of ΔTD	2	2	4
Total Average of ΔTD		0.057	0.117	0.097
Total StdDev of ΔTD		0.050	0.059	0.061
Total Count of ΔTD		4	8	12

The details of the pivot table would be discussed in the next chapter.

6.4 Deviation in Time to Exit (ΔTTE)

In this section, the results related to the absolute difference in the time taken for SD to move into the exit lane are analyzed. Table 6-13 shows the absolute deviation in time to exit (ΔTTE) for both subject drivers on all trials. The values for ΔTTE range between zero and maximum duration of the scenario. The mean and standard deviation values of ΔTTE appears to be similar for SD1 (Trial 1: Mean = 3.167, Std. Dev = 2.368; Trial 2: Mean = 2.417, Std. Dev = 1.564) and SD2 (Trial 1: Mean = 4.083, Std. Dev = 2.466; Trial 2: Mean = 3.667, Std. Dev = 2.103).

Table 6-13: Deviation in Time to Exit (ΔTTE)

Scenario #	Deviation in Time to Exit (ΔTTE)			
	Subject Driver 1 (SD1)		Subject Driver 2 (SD2)	
	Day 1 (Trial 1)	Day 1 (Trial 2)	Day 2 (Trial 1)	Day 2 (Trial 2)
1	1	0	6	7
2	1	2	0	1
3	4	4	4	3
4	1	1	4	4
5	2	1	1	1
6	4	4	6	5
7	4	3	4	4
8	7	4	6	4
9	2	3	6	6
10	0	0	0	0
11	5	3	5	4
12	7	4	7	5
<i>Minimum</i>	0	0	0	0
<i>Maximum</i>	7	4	7	7
<i>Mean</i>	3.167	2.417	4.083	3.667
<i>Std. Dev</i>	2.368	1.564	2.466	2.103

As in the previous section, two individual paired t-tests were conducted on ΔTTE values between trials for both drivers to test whether the values of ΔTTE were significantly different between trials. The paired t-tests for SD1 (t-statistic = 1.914, p-

value = 0.081) and SD2 (t-statistic = 1.448, p-value = 0.175) appears to indicate that there was no significant effect on Δ TTE due to trial for both subjects. The details of these paired t-tests are shown in Appendix G. The Δ TTE values between trials for each subject were aggregated. The descriptive statistics after aggregating by trials is shown in Table 6-14.

Table 6-14: Descriptive Statistics for Δ TTE After Aggregating by Trials

Scenario #	Deviation in Time to Exit (Δ TTE) after aggregating by Trials	
	Subject Driver 1 (SD1)	Subject Driver 2 (SD2)
	Day 1	Day 2
1	0.5	6.5
2	1.5	0.5
3	4	3.5
4	1	4
5	1.5	1
6	4	5.5
7	3.5	4
8	5.5	5
9	2.5	6
10	0	0
11	4	4.5
12	5.5	6
<i>Minimum</i>	0	0
<i>Maximum</i>	5.5	6.5
<i>Mean</i>	2.792	3.875
<i>Std. Dev</i>	1.888	2.237

A graphical representation of the Δ TTE for both subject drivers on all scenarios is shown in Figure 6-4. The overall minimum and maximum Δ TTE for both drivers on all trials was 0 and 7 seconds, respectively. Each scenario lasted about 25 seconds for a subject driver traveling at 40 mph. The smaller values for Δ TTE appear to indicate that the model was consistent in predicting the time taken to exit the highway lane by the human driver. The overall average Δ TTE value was calculated as 3.33 seconds.

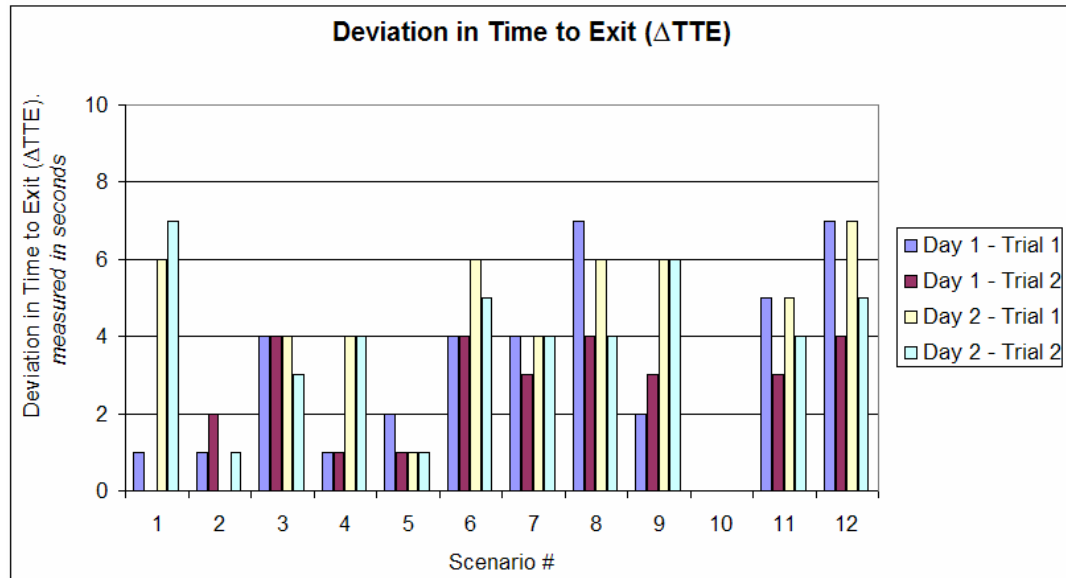


Figure 6-4: Graphical Representation for Deviation in Time to Exit

An ANOVA based analysis was conducted to test the effects of scenario and subject on deviation in time to exit the highway lane system. The computed F-Statistic was used to analyze the effects due to each scenario and subjects on ΔTTE . The results of the F-test for ΔTTE are summarized in Table 6-15.

Table 6-15: Test for the Effects of Scenario and Subject on ΔTTE

Source	df	SS	MS	F_{Computed}	F_{Critical}	Significant?
A (scenario)	11	70.33333	6.393939	2.935652	2.82	Yes
S (subject)	1	7.041667	7.041667	3.233043	4.84	No
Error	11	23.95833	2.17803			
Total	23	101.3333				

The results indicate that there appears to be a significant effect due to scenario ($F_{\text{Computed}} = 2.936 > F_{\text{Critical}} = 2.82$) but there seems to be no significant effect due to subject ($F_{\text{Computed}} = 3.233 < F_{\text{Critical}} = 4.84$) on ΔTTE . This implies that the model appears to be inconsistent in predicting the values of ΔTTE within-subjects on one or more

scenarios. However, the model appears to be consistent in predicting the values of ΔTTE between-subjects (both drivers) on all scenarios. The significance in scenario effect on ΔTTE is attributed to the errors of commission and omission (Park 1997; Reason 1990) performed by a subject driver during a test scenario. For instance, a SD may incorrectly perceive that an exit lane is inherent blocked by CD (error of commission) or completely fail to pursue a lane change maneuver (error of omission) during a close-call situation thereby adding to ΔTTE . In such a situation, the model pursues a riskier path, and is capable of judging precisely whether an affordance is available to be actualized into an action. This minimizes the deviation in ΔTTE . The overall average ΔTTE for both drivers is 3.33 seconds, which is less than 17% of the total scenario duration of 25 seconds (when SD drives at 40 mph). The estimated marginal mean for ΔTTE , standard error and 95% confidence interval (for this mean) on all scenarios is shown in Table 6-16.

Table 6-16: Estimated Marginal Means for Deviation in Time to Exit

Estimated Marginal Means for Deviation in Time to Exit (ΔTTE)				
ΔTTE on Scenario #	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	3.5	3	-34.619	41.619
2	1	0.5	-5.353	7.353
3	3.75	0.25	0.573	6.927
4	2.5	1.5	-16.559	21.559
5	1.25	0.25	-1.927	4.427
6	4.75	0.75	-4.78	14.28
7	3.75	0.25	0.573	6.927
8	5.25	0.25	2.073	8.427
9	4.25	1.75	-17.986	26.486
10	0	0	0	0
11	4.25	0.25	1.073	7.427
12	5.75	0.25	2.573	8.927

As before, a pivot table based analysis was conducted to get insights on the scenarios where there was a mismatch between empirical and model predicted time to exit data for the subject driver. The scenario classifications from Table 6-2 were again used for this purpose. The results of the pivot table are summarized in Table 6-17. This pivot table allows us to associate the effect of the independent variables (starting lane and block position, relative velocity) on the dependent variable, Δ TTE, and identify any emerging patterns.

Table 6-17: Pivot Table for Δ TTE

SD drives faster than CD?		CD horizontally closer to exit lane ?		
no		CD horizontally closer to exit lane ?		
CD vertically closer to exit lane ?	Data	no	yes	Grand Total
no	Average of Δ TTE	5.250	4.583	4.750
	StdDev of Δ TTE	0.354	1.463	1.282
	Count of Δ TTE	2	6	8
yes	Average of Δ TTE	0.000	4.250	2.125
	StdDev of Δ TTE	0.000	0.354	2.462
	Count of Δ TTE	2	2	4
Total Average of Δ TTE		2.625	4.500	3.875
Total StdDev of Δ TTE		3.038	1.254	2.090
Total Count of Δ TTE		4	8	12

SD drives faster than CD?		CD horizontally closer to exit lane ?		
yes		CD horizontally closer to exit lane ?		
CD vertically closer to exit lane ?	Data	no	yes	Grand Total
no	Average of Δ TTE	3.750	1.917	2.375
	StdDev of Δ TTE	0.354	2.289	2.117
	Count of Δ TTE	2	6	8
yes	Average of Δ TTE	4.750	2.500	3.625
	StdDev of Δ TTE	1.061	2.121	1.887
	Count of Δ TTE	2	2	4
Total Average of Δ TTE		4.250	2.063	2.792
Total StdDev of Δ TTE		0.866	2.112	2.050
Total Count of Δ TTE		4	8	12

The details of this pivot table would be analyzed in the next chapter.

6.5 Deviation in Utilization of the Exit Lane (ΔU)

In this section, the results related to the absolute difference in the utilization of the exit lane for SD are analyzed. Table 6-18 shows the absolute deviation in utilization of the exit lane (ΔU) for both subject drivers on all trials. The possible range for ΔU is 0.0 to 1.0. The mean and standard deviation values for ΔU appear to be similar for SD1 (Trial 1: Mean = 0.139, Std. Dev = 0.102; Trial 2: Mean = 0.109, Std. Dev = 0.074) and SD2 (Trial 1: Mean = 0.178, Std. Dev = 0.108; Trial 2: Mean = 0.158, Std. Dev = 0.09).

Table 6-18: Deviation in Utilization of Exit Lane (ΔU)

Scenario #	Deviation in Utilization of Exit Lane (ΔU)			
	Subject Driver 1 (SD1)		Subject Driver 2 (SD2)	
	Day 1 (Trial 1)	Day 1 (Trial 2)	Day 2 (Trial 1)	Day 2 (Trial 2)
1	0.043	0.000	0.261	0.292
2	0.043	0.083	0.000	0.042
3	0.200	0.200	0.200	0.150
4	0.043	0.042	0.167	0.167
5	0.083	0.043	0.043	0.042
6	0.200	0.211	0.300	0.250
7	0.167	0.130	0.167	0.167
8	0.292	0.174	0.250	0.167
9	0.083	0.130	0.250	0.250
10	0.000	0.000	0.000	0.000
11	0.217	0.125	0.208	0.167
12	0.292	0.167	0.292	0.208
<i>Minimum</i>	0	0	0	0
<i>Maximum</i>	0.292	0.211	0.3	0.292
<i>Mean</i>	0.139	0.109	0.178	0.158
<i>Std. Dev</i>	0.102	0.074	0.108	0.09

At first, two individual paired t-tests were conducted on ΔU values between trials for both drivers to test whether the mean values of ΔU were significantly different. The paired t-tests for SD1 (t-statistic = 1.811, p-value = 0.097) and SD2 (t-statistic = -1.668, p-value = 0.123) appears to indicate that there was no significant effect on ΔU due to

trial on both subjects. The details of these paired t-tests are shown in Appendix G. The model appears to be consistent in predicting the values of ΔU for both subject drivers between trials. Therefore, the ΔU values between trials for each driver were aggregated. The descriptive statistics for ΔU after aggregating by trials is shown Table 6-19.

Table 6-19: Descriptive Statistics for ΔU After Aggregating by Trials

Scenario #	Deviation in Utilization of Exit Lane (ΔU) after aggregating by Trials	
	Subject Driver 1 (SD1)	Subject Driver 2 (SD2)
	Day 1 (Trial 1)	Day 2 (Trial 1)
1	0.022	0.276
2	0.063	0.021
3	0.200	0.175
4	0.043	0.167
5	0.063	0.043
6	0.205	0.275
7	0.149	0.167
8	0.233	0.208
9	0.107	0.250
10	0.000	0.000
11	0.171	0.188
12	0.229	0.250
<i>Minimum</i>	0	0
<i>Maximum</i>	0.233	0.276
<i>Mean</i>	0.124	0.168
<i>Std. Dev</i>	0.084	0.097

A graphical representation of the ΔU for both subject drivers on all scenarios is shown in Figure 6-5.

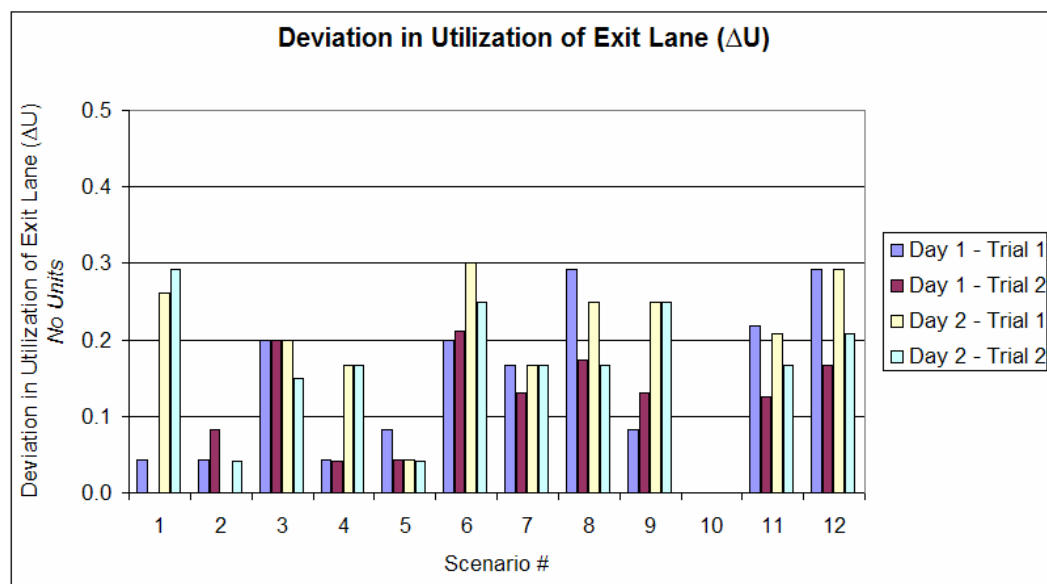


Figure 6-5: Graphical Representation for Deviation in Utilization of Exit Lane

The overall minimum and maximum ΔU for both drivers on all trials was 0.0 (0%) and 0.3 (30%), respectively. The average utilization on all scenarios was calculated as 0.146 (14.6%).

An ANOVA based analysis was conducted to test the effects of scenario and subject on deviation in utilization (ΔU) of the exit lane in the highway lane system. The computed F-Statistic was used to analyze the effects due to each scenario and subjects on ΔU . The results of the F-test for ΔU are summarized in Table 6-20.

Table 6-20: Test for the Effects of Scenario and Subject on ΔU

Source	df	SS	MS	F _{Computed}	F _{Critical}	Significant?
A (scenario)	11	0.139358	0.012669	3.230515	2.82	Yes
S (subject)	1	0.011876	0.011876	3.028217	4.84	No
Error	11	0.043138	0.003922			
Total	23	0.194372				

The results confirm that there appears to be a significant effect due to scenario ($F_{\text{Computed}} = 3.231 > F_{\text{Critical}} = 2.82$) but there seems to be no significant effect due to subject ($F_{\text{Computed}} = 3.028 < F_{\text{Critical}} = 4.84$) on utilization of exit lane (ΔU). This implies that the model appears to be inconsistent in predicting the values of ΔU within-subjects on one or more scenarios. However, the model appears to be consistent in predicting the values of ΔU between-subjects (both subject drivers) on all scenarios.

The significance in scenario effect for ΔU can be explained based on the errors of commission and omission (Park 1997; Reason 1990) committed by a subject driver, since the deviation in utilization of the exit lane (ΔU) is directly proportional to the time taken to exit the highway (ΔTTE). A SD may incorrectly perceive that an exit lane is inherent blocked by CD (error of commission) or completely fail to pursue a lane change maneuver (error of omission) during a close-call situation thus adding to the deviation in utilization of the exit lane. However, the model pursues a risky path, and is capable of precisely judging whether an affordance is available to be actualized into an action during a close-call situation. The overall average deviation in utilization of the exit lane is 0.146 or 14.6%. The estimated marginal mean for deviation in turn direction, standard error and 95% confidence interval (for this mean) on all scenarios is shown in Table **6-21**.

Table 6-21: Estimated Marginal Means for Deviation in Utilization of Exit Lane

Estimated Marginal Means for Deviation in Utilization of Exit Lane (ΔU)				
ΔU on Scenario #	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	0.149	0.127	-1.468	1.766
2	0.042	0.021	-0.228	0.313
3	0.188	0.013	0.029	0.346
4	0.105	0.062	-0.684	0.893
5	0.053	0.01	-0.079	0.185
6	0.24	0.035	-0.203	0.683
7	0.158	0.009	0.043	0.273
8	0.221	0.012	0.065	0.376
9	0.178	0.072	-0.731	1.088
10	0	0	0	0
11	0.179	0.008	0.076	0.283
12	0.24	0.01	0.107	0.372

As before, a pivot table based analysis was conducted to get insights on the scenarios where there was a mismatch between empirical and model predicted utilization of exit lane for the subject driver. The scenario groupings described in Table 6-2 was again used for this purpose. A summary of the pivot table results for ΔU is provided in Table 6-22. This pivot table allows us to investigate the effect of the independent variables (starting lane and block position, relative velocity) on the dependent variable, ΔU , and identify any emerging patterns.

Table 6-22: Pivot Table for ΔU

SD drives faster than CD?				
		CD horizontally closer to exit lane ?		
CD vertically closer to exit lane ?	Data	no	yes	Grand Total
no	Average of ΔU	0.221	0.192	0.199
	StdDev of ΔU	0.017	0.060	0.053
	Count of ΔU	2	6	8
yes	Average of ΔU	0.000	0.179	0.090
	StdDev of ΔU	0.000	0.012	0.104
	Count of ΔU	2	2	4
Total Average of ΔU		0.110	0.189	0.163
Total StdDev of ΔU		0.128	0.051	0.087
Total Count of ΔU		4	8	12

SD drives faster than CD?				
		CD horizontally closer to exit lane ?		
CD vertically closer to exit lane ?	Data	no	yes	Grand Total
no	Average of ΔU	0.188	0.081	0.108
	StdDev of ΔU	0.018	0.097	0.096
	Count of ΔU	2	6	8
yes	Average of ΔU	0.240	0.105	0.172
	StdDev of ΔU	0.049	0.088	0.097
	Count of ΔU	2	2	4
Total Average of ΔU		0.214	0.087	0.129
Total StdDev of ΔU		0.043	0.089	0.097
Total Count of ΔU		4	8	12

The details of the pivot table would be discussed in the next chapter.

6.6 Hypothesis Testing and Model Comparison

In order to test the fundamental hypothesis and estimate the precision of the affordance-based CPN model in representing driver (animal) behavior within the HLDS (animal-environment) system, a comparison was done between the driver-related performance metrics generated by the affordance-based and random CPN models. The random CPN model described in the model development section was used for this purpose. The comparison statistics between these two models is shown Table 6-23.

Table 6-23: Comparison Between CPN Model and Random Model

Scenario	CPN Model Deviations [I] (2 SD, 2 trials each SD)				Random Model Deviations [J] (2 SD, 250 Trials for each SD)					Difference in Deviation [J - I]			
	ΔLP	ΔTD	ΔTTE	ΔU	ΔLP	ΔTD	ΔTTE	ΔU	% Goal State Reached (%GSR)	ΔLP	ΔTD	ΔTTE	ΔU
1	0.330	0.107	3.500	0.149	0.442	0.572	9.966	0.364	7.47%	0.112	0.466	6.466	0.215
2	0.042	0.063	1.000	0.042	0.639	0.374	6.996	0.339	9.42%	0.597	0.311	5.996	0.297
3	0.188	0.025	3.750	0.188	0.645	0.497	6.306	0.218	3.68%	0.457	0.473	2.556	0.031
4	0.167	0.126	2.500	0.105	0.581	0.698	6.619	0.361	8.72%	0.414	0.572	4.119	0.257
5	0.128	0.170	1.250	0.053	0.588	0.423	13.825	0.395	0.07%	0.460	0.252	12.575	0.342
6	0.442	0.090	4.750	0.240	0.540	0.530	7.852	0.272	2.86%	0.098	0.440	3.102	0.032
7	0.158	0.084	3.750	0.158	0.483	0.467	12.307	0.354	5.85%	0.325	0.382	8.557	0.196
8	0.221	0.084	5.250	0.221	0.402	0.490	7.530	0.247	9.26%	0.181	0.406	2.280	0.026
9	0.178	0.084	4.250	0.178	0.553	0.598	12.363	0.239	6.20%	0.375	0.514	8.113	0.060
10	0.095	0.075	0.000	0.000	0.527	0.357	11.182	0.324	8.35%	0.433	0.282	11.182	0.324
11	0.379	0.168	4.250	0.179	0.592	0.547	9.342	0.312	4.24%	0.213	0.379	5.092	0.133
12	0.448	0.167	5.750	0.240	0.588	0.434	12.006	0.398	7.68%	0.140	0.268	6.256	0.158
<i>Minimum</i>	0.042	0.025	0.000	0.000	0.402	0.357	6.306	0.218	0.001	0.098	0.252	2.280	0.026
<i>Maximum</i>	0.448	0.170	5.750	0.240	0.645	0.698	13.825	0.398	0.094	0.597	0.572	12.575	0.342
<i>Average</i>	0.231	0.104	3.333	0.146	0.548	0.499	9.691	0.318	0.062	0.317	0.395	6.358	0.172
<i>Std. Dev</i>	0.136	0.046	1.788	0.080	0.075	0.098	2.612	0.061	0.029	0.164	0.102	3.279	0.118

The random model does not always lead to the goal state and the percentage of goal state reached appears to indicate the percentage of trials (out of 500 trials per scenario = 2 x 250 per SD) that lead to the goal state for the random model on each scenario. The table shows the values of four output metrics predicted by the random model on only those scenarios where the goal state was reached (i.e. SD was able to exit

the highway). It also appears to indicate that the difference between the output metrics generated by the random model and the affordance-based CPN model is positive for all metrics, which means that the deviation between the affordance-based CPN model and human driver is smaller than the deviation between the random model and human driver.

Four dependent paired t-test was conducted to test whether the mean and standard deviation values for each of the output metrics were significantly different on all scenarios. The dependent paired t-Test statistics for comparing means of affordance-based and random CPN models is shown in Table 6-24.

Table 6-24: Dependent Paired t-Test Statistics for Comparing Means of Affordance-based and Random CPN Models

Dependent Two Sample Paired t-test for Comparing Means of Affordance-Based and Random CPN Model on all Scenarios		
Output Metric	<i>t-statistic</i>	<i>p-value</i>
ΔLP	-6.701	0.000
ΔTD	-13.370	0.000
ΔTTE	-6.716	0.000
ΔU	-5.081	0.000

The t-statistic for the four output metrics appear to indicate that the means and standard deviations of the metrics are significantly different between the affordance based model and the random CPN model [ΔLP (t-statistic = -6.701, p-value = 0.000), ΔTD (t-statistic = -13.370, p-value = 0.000), ΔTTE (t-statistic = -6.716, p-value = 0.000), ΔU (t-statistic = -5.081, p-value = 0.000)]. The mean value for all output metrics of the random CPN model is higher than that of the affordance-based CPN model, which leads us to infer that the affordance-based CPN model fits the human performance data better than the random

model. This supports the fundamental hypothesis that affordance-based model is a good fit for representing affordances, effectivities and actualized actions.

6.7 Chapter Summary

In this chapter, the data analysis procedure was initially explained. Then, the results of the affordance-based CPN model for the subject driver was presented for the four output metrics described in the methodology. Each output metric was individually analyzed using the data analysis procedure explained earlier. Then, the consistency of the model was verified by comparing predictions the driver related performance data generated by the affordance-based CPN model and random model. The affordance-based CPN model exhibited smaller deviations than the random model for all output metrics.

Chapter 7

DISCUSSION AND CONCLUSION

7.1 Pivot Table Analysis

In general, the following patterns seem to emerge based on the pivot table analysis of all scenarios.

1. ΔTD was different from the other the dependent variables (ΔLP , ΔTTE and ΔU).
2. While considering ΔLP , when CD is closer to the exit lane vertically, but not horizontally, the fit of the model's predictions to the human data appears to depend on the relative speeds of both drivers.
 - a. If the SD and CD drive at the same velocity, the model does not fit well at all (t-statistic = 2.755, p-value = 0.035).
 - b. If the SD is going the faster than the CD, then the model fits very well (t-statistic = -2.722, p-value = 0.056).
3. While considering ΔTD , only one variable seemed to have an impact – the location of the CD relative to the SD and the exit lane in the horizontal direction. An independent two sample t-test (t-statistic = -2.977, p-value = 0.004) appears to indicate that values of ΔTD is significantly different when the CD is horizontally further away from the exit lane than when the CD is horizontally closer to the exit

- lane. The model fits human performance data more closely when the CD is horizontally further away from the exit lane.
4. While considering ΔTTE , when CD is closer to the exit lane vertically, but not horizontally, the fit of the model's predictions to the human data appears to depend on the relative speeds of both drivers.
 - a. If the SD and CD drive at the same velocity, the model does not fit well at all (t-statistic = 12.721, p-value = 0.000).
 - b. If the SD is going the faster than the CD, then the model fits, appear to be closer to borderline significance (t-statistic = -2.396, p-value = 0.035).
 5. While considering ΔU , when CD is closer to the exit lane vertically, but not horizontally, the fit of the model's predictions to the human data appears to depend on the relative speeds of both drivers.
 - a. If the SD and CD drive at the same velocity, the model does not fit well at all (t-statistic = 13.033, p-value = 0.000).
 - b. If the SD is going the faster than the CD, then the model fits, appear to be closer borderline significance (t-statistic = -2.957, p-value = 0.030).

Some insights gained from the above analyses for improving the precision of the affordance-based CPN model, while predicting the actualized actions, are stated below.

1. The current turn probabilities are appear to consistently lead to the goal state for scenarios where CD starts vertically and horizontally away from the exit lane, regardless of the relative velocity.

2. When CD is horizontally closer to the exit lane, the relative velocity of the SD with respect to CD plays a very important role in turn probabilities. The turn probabilities should be estimated appropriately for both same and higher velocity cases.

7.2 Formative Analysis

In this section, the affordance values calculated for SD2 during a test scenario (scenario 4, trial 2) is presented through the formative analysis overlay described in Table 7-1.

Table 7-1: Sample Formative Analysis for SD2 Data (on Scenario 4, Trial 2)

Scenario Time	Affordance Values for the Niche (Set of lane affordances) available to the SD during Scenario 4			Comments
	Lane 1	Lane 2	Lane 3	
0	0	0	0.1089	
1	0	0	0.1089	
2	0	0	0.1089	
3	0	0	0.1089	<i>Speed up point</i>
4	0	0	0.1089	
5	0	0	0.1089	
6	0	0	0.1089	
7	0	0	0.1089	
8	0	0	0.1089	
9	0	0	0.1089	
10	0	0	0.1089	<i>Exit Lane Begins</i>
11	0	0	0.132	
12	0	0	0.132	
13	0	0	0.132	
14	0	0.2211	0	
15	0.1938	0	0.462	<i>SD moved into exit lane</i>
16	0.2278	0.2211	0	
17	0.2278	0.2211	0	
18	0.2278	0.2211	0	
19	0.2278	0.2211	0	
20	0.2278	0.2211	0	
21	0.2278	0.2211	0	
22	0.2278	0.2211	0	
23	0.2278	0.2211	0	
24	0.2278	0.2211	0	<i>Highway Lane Ends</i>
Cells filled with BLACK color provide no affordance to SD				
Cells filled with WHITE color or shades of GRAY provide valid affordance to SD				

The affordance value of each lane shown in this table corresponds to the propensity (or strength) of the lane affordance to be actualized into an action during the next update interval. The non-zero affordance (shown by cells filled with white or shades of gray) value for a particular lane indicates that the driver has an available affordance to move into that lane. An affordance with a high value (closer to white color or lighter shades of gray) indicates a stronger propensity to be actualized during the next update cycle than an affordance with a low value. A zero affordance value (cell filled with black color) indicates that the driver has no available affordance to move into that lane. The color-coding indicates the contiguous set of available and unavailable affordances (including the strength) that exist for the driver to achieve the goal of exiting the highway lane system.

During scenario 4, SD starts in lane 3 (SL2) and drives straight ahead on lane 3 for 6 seconds to reach target velocity. However, on driving further, SD realizes that the safety margin is violated because CD is straight ahead. Therefore, SD passes CD by moving to lane 2 (at 14 seconds) and then to lane 1 (at 15 seconds), and eventually exits the highway lane system. The niche of lanes affordances that become available to the SD are shown in the table along with a specification of critical events that occur during the course of scenario.

7.3 Research Limitations

Although the results of the analysis support the fundamental hypothesis presented earlier, caution should be emphasized while interpreting the results. The model is currently

verified using a small sample size. A larger sample size is required to verify the precision of the affordance-based CPN model in the future. The results are verified within the realm of HEPS domain, which may not generalize to other domains. The sample of participants (SD and CD) used within this model was expert drivers and the results may not apply to the general population that includes novice drivers. Therefore, additional testing must be done to evaluate the applicability of the model for the general population. The safety factor is also currently held constant for both leading and lagging gaps, and may not be applicable to all drivers due to their differences in age, gender, experience level, training and learning.

7.4 Future Research

The following elements are would address as part of future research and development efforts for this line of work.

- A larger sample size will be used to test and validate the robustness of the results obtained from the affordance-based CPN model for the HEPS domain. In the current research, only one SD and one CD were used. However, in actuality there may be more than one CD and SD on the highway lane system.
- The turn probabilities initialized within the affordance-based CPN model are not based on the actual estimates of derived from the subject drivers. Therefore, these turn probabilities will be based upon best estimates of turn probabilities derived from empirical data.

- Although, the model is theoretically scalable (by including more drivers and lanes within the model), the practical characteristic issues such as concurrency, stochasticity and spatio-temporality associated with the scalability of the model must be addressed.
- The mathematical model developed within this research excluded blind spots and rear view perception to reduce the complexity within the model. However, in realistic driving environments driver perceive both of these elements. Therefore, future mathematical models must incorporate the visual perception of blind spots and rear view mirror within the modeling approach.
- The safety factor assumed within the affordance-based model must be estimated based on the liberal (risk seeking) or conservative (risk averse) behaviors of the subject driver, in order to be an accurate indicator of the true safe distance.
- The safety factor is also currently held constant for both leading gap (when the confederate driver is directly ahead) and lagging gap (when the confederate driver is directly behind). However, empirical research suggests that the safety factor margin observed by drivers is not constant for both leading and lagging gaps. Therefore, these safety margins must be estimated based on empirical data.
- This affordance-based CPN model was compared with another CPN model that includes dynamically generated random turn probabilities. There other intelligent models, such as Artificial Intelligence-based models, Genetic Algorithm-based models, that may perform superiorly to the random model. These models must be used for benchmarking the precision and efficiency of the affordance-based CPN

model. Extreme caution must also be emphasized while trying to interpret the results with respect to these other models.

- An initial attempt toward providing a generalized model was made through the mathematical and CPN models presented in this research. However, this model of affordances must be applied to and verified in other domains that include characteristics such as concurrency, stochasticity and spatio-temporality in order to be generalized.

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Appendix A

CPN BASICS

Table A-1 shows the basic elements of a CPN representation.

Table A-1: Basic Elements of CPN Representation

Graphical Notation	Type of Graphical Notation	Explanation of the Graphical Notation
	Place	Represents a place within a CPN. They are connected to transitions within the CPN and have a maximum capacity.
	Transition	Represents a transition within a CPN. When fired, tokens are consumed from the input places and new tokens are created in the output places.
	Token	Represents colored tokens within the CPN. The primary difference between a regular Petri Net and CPN is that each token is a member of a certain color set which have different values or types.
	Arc	Represents arcs within the CPN. The arcs have arc expressions that constrain the number of tokens that pass through them.
Case x of $P \Rightarrow 2r$	Arc Expression	Represents the conditions that are required to be met before the token transition occurs.
$[x = y]$	Guard	Represents a restriction that is imposed on the place.

Appendix B

CPN MODEL DECLARATIONS AND FUNCTIONS

DECLARATIONS:

Constants:

```
val MAX_DRIVERS = 2;          (* 1 = Confederate Driver; 2 = Subject Driver *)
val MAX_TURNS = 3;           (* 1 = Right Turn; 2=Head Straight; 3 = Left Turn*)
val MAX_LANES= 3;            (* 1 = Lane1/Exit Lane; 2 = Lane2; 3 = Lane3 *)
val MAX_BLOCKS= 160;         (* Only 80 blocks are used for data collection *)
val MAX_VELOCITY = 10;       (* Only 4 blocks/sec used for maximum velocity *)
val MAX_ACCELERATION = 10;   (* Only 4 blocks/sec^2 used for maximum
acceleration *)
val SAFE = 3;                (* Safety Factor, minimum distance maintained by a driver *)
val EXIT_LANE = 1;           (* 1 = Lane1/Exit Lane *)
val EXIT_START_BLOCK = 30;   (* Starting Block for Exit Lane = 30 *)
val EXIT_END_BLOCK = 80;     (* Ending Block for Exit Lane = 80 *)
```

Color Sets:

```
colset E = with e;
colset INT = int;
colset INT2 = int with 0..1;
colset INT100 = int with 0..100;
colset LN = int with 1..MAX_LANES;      (* Color set for Lanes *)
colset BL = int with 1..MAX_BLOCKS;     (* Color set for Blocks *)
colset DR = int with 1..MAX_DRIVERS;    (* Color set for Drivers *)
colset TN = int with 1..MAX_TURNS;      (* Color set for Turn Direction *)
colset VL = int with 0..MAX_VELOCITY;   (* Color set for Velocity *)
colset AC = int with 0..MAX_ACCELERATION; (* Color set for Acceleration *)

colset I2xI2 = product INT2 * INT2;
colset LNxBL = product LN * BL;

colset DRxLNxBL = product DR * LN * BL; (* Color set for Affordance-type Token *)
colset DRIVER = product INT*DR*LN*BL*VL*AC*TN
    declare output_col, input_ms; (* Color Set for Effectivity-type Token *)
colset TURNPROB = product INT100 * INT100 * INT100 *
    INT100 * INT100 * INT100 *
    INT100 * INT100 * INT100;
    (* Color set for Fixed/Random Turn Probabilities *)
```

Local Variables:

```

var n, i: INT; (* n = simulation time *)
var af1, af2, af3: INT; (* affordance variables *)
var d1, d2, d3: DR; (* Driver indices variables *)
var l1, l2, l3, destlane: LN; (* Lane variables *)
var b1, b2, b3: BL; (* Block variables *)
var t1, t2, t3 : TN; (* Turn Direction variables *)
var v1, v2, v3: VL; (* Velocity variables *)
var a1, a2, a3: AC; (* Acceleration variables *)
var dt: INT;
var l1wt, l2wt, l3wt: INT100; (* Lane weights *)
var p1, p2, p3,p4, p5, p6,p7, p8, p9:INT100; (* Turn Probabilities *)
var plc, plk: INT; (* Probability of Lane keeping/Changing *)
var tp1: TURNPROB;

```

Global Variables:

```

globref driverinputs = empty :DRIVER ms; (* Driver input file handle *)
globref tpinputs = empty :TURNPROB ms; (* Turn Probability Inputs *)
globref outfile1 = TextIO.stdOut; (* Driver 1 output file handle *)
globref outfile2 = TextIO.stdOut; (* Driver 2 output file handle *)

```

Functions and other color sets:

```

(* Function to get driver inputs *)
fun getDriverInputs() = (!driverinputs);

(* Function to get turn probability inputs *)
fun getTurnInputs() = (!tpinputs);

(* Function to check if driver is occupying Lane1 *)
fun LANE1 (x,y) = (x=1);

(* Function to check if driver is occupying Lane2 *)
fun LANE2 (x,y) = (x=2);

(* Function to check if driver is occupying Lane3 *)
fun LANE3 (x,y) = (x=3);

(* Function to find maximum of three values *)
fun FindMax3 (a,b,c) =
  (if ((a>b) andalso (a>c))
   then a
   else if
    ((b>a) andalso (b>c))
    then b
   else c );

```

(* Function to find maximum of three lanes *)

```
fun FindMax3Lanes (a,b,c) =
  1^(if ((a>b) andalso (a>c))
    then 1
    else if
      ((b>a) andalso (b>c))
    then 2
    else 3 );
```

(* Function to gradually ramp up the
subject driver velocity from 0 to 4 Blocks/sec
during the first 6 seconds *)

```
fun RampUpVel4(n:int) =
  1^(
    if (n=0) then 1
    else if (n=1) then 1
    else if (n=2) then 1
    else if (n=3) then 2
    else if (n=4) then 2
    else if (n=5) then 3
    else 4 );
```

(* Function to calculate the absolute difference between two values *)

```
fun diff(x,y) = (if (x>y) then (x-y) else (y-x));
```

(* Function to calculate the new driver position (effectivity token)
based on driver attributes *)

```
fun CalcNewPOS(n:INT, d: DR, l1: LN, b1: BL, v1: VL, a1: AC, t1: TN)
= 1^(n,
  d,
  if ((t1 = 3) andalso LANE1(l1,b1))
  then 1^2
  else if ((t1 = 3) andalso LANE2(l1,b1))
  then 1^3
  else if ((t1 = 1) andalso LANE3(l1,b1))
  then 1^2
  else if ((t1 = 1) andalso LANE2(l1,b1))
  then 1^1
  else 1^l1,
  b1+v1+a1,
  v1,
  a1,
  t1);
```

```
(* Function to decide if subject driver must change from the current lane *)
fun PLC (l1:LN,b1:BL,l2:LN,b2:BL) =
  1^(
    if ((diff(l1,l2)=1) andalso (diff(b1,b2)<=SAFE))
    then 0 (* Both Drivers are parallel to each other *)
    else if ((b2 > EXIT_START_BLOCK) andalso (l2 <> EXIT_LANE))
    then 1 (* Not in Exit Lane *)
    else if ((diff(l1,l2)=0) andalso (diff(b1,b2)<=SAFE))
    then 1 (* One driver is behind another and closing in very quickly *)
    else 0 (* default *)
  );
```

```
(* Function to decide if subject driver must keep the current lane *)
fun PLK (l1:LN,b1:BL,l2:LN,b2:BL) =
  1^(
    if ((diff(l1,l2)=1) andalso (diff(b1,b2)<=SAFE))
    then 1 (* Both Drivers are parallel to each other *)
    else if ((b2 > EXIT_START_BLOCK) andalso (l2 <> EXIT_LANE))
    then 0 (* Not in Exit Lane *)
    else if ((diff(l1,l2)=0) andalso (diff(b1,b2)<=SAFE))
    then 0 (* One driver is behind another and closing in very quickly *)
    else 1 (* default *)
  );
```

```
(* Function to decide Lane1 turn probability value *)
fun L1AFF(l2:LN, b2:BL, p1:int, p4:int, p7:int) =
  1^(
    if LANE1(l2,b2)
    then p1
    else if LANE3(l2,b2)
    then p7
    else p4
  );
```

```
(* Function to decide Lane2 turn probability value *)
fun L2AFF(l2:LN, b2:BL, p2:int, p5:int, p8:int)
= 1^(
  if LANE1(l2,b2)
  then p2
  else if LANE2(l2,b2)
  then p5
  else p8
);
```



```
(* Function to decide Lane3 turn probability value *)
fun L3AFF(l2:LN, b2:BL, p3:int, p6:int, p9:int) =
  1`
    if LANE1(l2,b2)
    then p3
    else if LANE2(l2,b2)
        then p6
        else p9
);
```

```
(* Function to find next lane position for the driver)
fun FindNextLanePosition(destlane:LN, n:INT, d3:DR, l3:LN, b3:BL, v3:VL, a3:AC,
t3:TN) =
  1`
    n,d3,destlane,b3+v3+a3,v3,a3,
    if ((destlane = l3) andalso (LANE1(destlane,b3)))
    then 2
    else if ((destlane>l3) andalso (LANE2(destlane,b3)))
    then 3
    else if ((destlane<l3) andalso (LANE1(destlane,b3)))
    then 1
    else if ((destlane=l3) andalso (LANE2(destlane,b3)))
    then 2
    else if ((destlane>l3) andalso (LANE3(destlane,b3)))
    then 3
    else if ((destlane<l3) andalso (LANE2(destlane,b3)))
    then 1
    else if ((destlane=l3) andalso (LANE3(destlane,b3)))
    then 2
    else 2
);
```

```
(* Color set for Lane1 without driver information*)
colset LN1 = subset LNxBL by LANE1;
```

```
(* Color set for Lane2 without driver information*)
colset LN2 = subset LNxBL by LANE2;
```

```
(* Color set for Lane3 without driver information*)
colset LN3 = subset LNxBL by LANE3;
```

Appendix C

GPS CONVERSIONS

C.1 WGS84 Conversions

The World Geodetic System (WGS84, 2007) was used to convert the latitude, longitude and altitude data of both vehicles into a Cartesian (x-y planar) coordinate with respect to a primary reference point (DGPS base station location). These x-y values were then transformed using rotation and translation based on a secondary reference point (located between lane 3 and lane 2 at block 1).

DGPS Base Station Parameters:

$$lat_0 (\text{latitude}) = 40.86313783175$$

$$lon_0 (\text{longitude}) = -77.83490273560$$

$$alt_0 (\text{altitude}) = 367.353$$

Other Parameters Initialization:

$$a = 6378137$$

$$e = 8.1819190842622e^{-2}$$

$$N_{\text{latitude}} = \frac{a}{\sqrt{1 - e^2 \times \sin^2 \left((lat_i - lat_0) \times \frac{\mathbf{P}}{180} \right)}}, \text{ where}$$

lat_i = latitude of vehicle at time i

$$N_{\text{longitude}} = N_{\text{latitude}} \times \cos \left(lat_0 \times \frac{\mathbf{P}}{180} \right), \text{ where}$$

lat_0 = Base station latitude

X-Y Coordinates:

$$X = (lat_i - lat_0) \times (N_{latitude} + alt_i) \times \frac{P}{180}, \text{ where}$$

lat_i = Latitude of the vehicle at time i ,

lat_0 = Base station latitude, and

alt_i = Altitude of the vehicle at time i .

$$Y = (lon_i - lon_0) \times (N_{longitude} + alt_i) \times \frac{P}{180}, \text{ where}$$

lon_i = Longitude of the vehicle at time i ,

lon_0 = Base station longitude, and

alt_i = Altitude of the vehicle at time i .

C.2 Transformation with respect to the Secondary Reference Point

In order to transform the x-y coordinates with respect to the secondary reference point, the following transformation equations were used on both SD and CD data.

1. Initial Translation:

$$X_{translated} = X_i - 7.833 \text{ meters},$$

$$X_{translated} = Y_i + 95.264 \text{ meters}, \text{ where}$$

X_i = X coordinate of the vehicle at time i , and

Y_i = Y coordinate of the vehicle at time i .

2. Rotation:

$$X_{rotated} = X_{translated} \times \cos\left(-37.5 \times \frac{\mathbf{p}}{180}\right) - Y_{translated} \times \sin\left(-37.5 \times \frac{\mathbf{p}}{180}\right), \text{ and}$$
$$Y_{rotated} = Y_{translated} \times \cos\left(-37.5 \times \frac{\mathbf{p}}{180}\right) + X_{translated} \times \sin\left(-37.5 \times \frac{\mathbf{p}}{180}\right).$$

3. Final Translation:

$$X_i^{final} = X_{rotated} - 60 \text{ meters, where}$$

X_i^{final} = X coordinate of the vehicle at time i with respect to the secondary reference point.

$$Y_i^{final} = Y_{rotated} + 23.5 \text{ meters, where}$$

Y_i^{final} = Y coordinate of the vehicle at time i with respect to the secondary reference point.

Appendix D

VBOX DATA SUBSAMPLING METHOD

The original data from the VBOX unit was recorded at 20 Hz frequency (provides twenty updates per second), which was sampled to 1 Hz (provides one update per second) for data analysis purposes. The following steps were followed to convert the data and organize it into an excel spreadsheet for further analysis.

Steps to convert VBOX DGPS data log file (VBox-00x.vbo) into a corresponding one second update MS Excel spreadsheet file

Support Tools Needed:

1. Sub-sampler Software (Subsample.exe)
2. VBOX Tools Software
3. Data_Analysis_Template.xls

Step 1: Sampling the current data log file for 1-second update interval

1. Identify the start UTC time and end UTC time of the current run.
2. Open the VBOX DGPS Data Log File (Vbox-00x.vbo) using the Sub-sampler software.
3. If data is logged originally using 20 Hz frequencies then enter 20 (for 1sec update) in the “Divide by Samples” field.
4. Load the current VBOX DGPS Data Log File (VBox-00x.vbo) using the “Load File” button.
5. Save the sub-sampled file using the “Save File” button and save the new file as “VBox-00x_1sec_resample.vbo”.
6. Open the sub-sampled file (VBox-00x_1sec_resample.vbo) using notepad
7. Delete the first two rows after “[data]” as these rows correspond to 20 Hz frequency
8. Replace the original file by resave this modified file.

Step 2a: Saving the fields (longitude & latitude) necessary for calculating the X-Y position

1. Open the VBOX Tools Software.
2. Load the sub-sampled VBOX DGPS data log file (VBox-00x_1sec_resample.vbo) using the “Load All” button.
3. Select the “Tools > Export Data > To Mapping Software” option from the button menu.
4. Select “Every Trigger Event” option in the dialog box to record all trigger events from the sub-sampled file.
5. Save the data as a text file with the name “VBox-00x_1sec.txt”.

CAUTION: Do not close the VBOX Tools Software.

Step 2b: Saving the altitude (height) field necessary for calculating the X-Y position

1. Select “Save > Save Button” to save selected fields necessary for calculating height
2. Select “GPS UTC Time & Height” checkboxes under the “Measured” tab.
3. Ensure that all other checkboxes in this tab and other tabs are deselected.
4. Click on “Save Button” in this dialog box.
5. When prompted save the data as a comma separated values (CSV) file using the name “VBox-00x_1sec_resample.csv”.

Step 3: Creating the VBOX data log file for 1-second update interval

1. Open a Microsoft Excel window.
2. Open “VBox-00x_1sec_resample.csv” using this window.
3. Open another Microsoft Excel window.
4. Select “File > Open” from the main menu.
5. Browse to the directory that contains “VBox-00x_1sec.txt” from step 2a.
6. In the “Open” dialog box, select “all files” from the “Files of Type” field.
7. Now select “VBox-00x_1sec.txt” file and click on the “Open” button, which opens a “Text Import Wizard”.
 - a. In step 1 of “Text Import Wizard”:
 - i. Choose “Delimited” radio button,
 - ii. Enter “start import at row” as 1
 - iii. File Origin “Windows (ANSI)”
 - b. In step 2 of “Text Import Wizard”:
 - i. Check the box in front of “Delimiters > Semicolon”
 - ii. Deselect all other checkboxes.
 - c. In step 3 of “Text Import Wizard”:
 - i. Click on “Finish” button
8. Now this creates five columns with the following names:
 - a. time, latitude, longitude, velocity(knots) and heading
9. Insert two columns
 - a. First column in between “longitude” and “velocity(knots)” fields and rename this column as “height (meters)”
 - b. Second column after “heading” field and rename this column as “velocity (kmh)”
10. Using the following below, create a dependency between “velocity (knots)” and “velocity (kmh)” fields.
 - a. $\text{Velocity(kmh)} = \text{velocity(knots)} * 1.852$
11. Copy the height column from the “VBox-00x_1sec_resample.csv” and paste it into the corresponding column in the current excel file.
12. Rename the time field using updates such as “0.00, 1.00, etc.,” until rows containing data are populated.
13. Save this file using the name “VBox-00x_1sec.xls” file.

CAUTION: Do not close this excel file.

Step 4: Creating the data file from template

1. Open a new Microsoft Excel window and open “Data_Analysis_Template.xls” file.
2. Select “CD_Data” worksheet from the tabs in the bottom.
3. Copy the fields “time, latitude, longitude and height (meters)” and paste it into the corresponding fields in the template file.
4. Save this file as an excel workbook using the name “Trial##_Analysis.xls”.
5. This is the corresponding one-second update (excel spreadsheet) file with confederate driver data!

TIP:

- *Insert subject driver data into this file for each scenario to understand the relationship between the path traversed by subject and confederate driver.*
- *Repeat these steps for both drivers during each scenario to obtain the complete data set.*

Appendix E

DRIVER INSTRUCTIONS

E.1 Instructions provided to the drivers during the experiment

In this appendix, the instructions provided to both SD (Mercury Tracer or Car Driver) and CD (Mini-van driver) are summarized.

Instructions provided to the drivers participating as observers during the first four practice trials (1–4):

1. Practice Trial 1: Both Car Driver (Mercury Tracer) & Van Driver (Mini-van) as observers (DRIVERS IN SAME VAN)
 - a. Starting lane: Lane 3, Starting line: SL2
 - b. Demonstrate: Overall goal of exiting through Lane 1
 - c. Answer questions.

2. Practice Trial 2: Both Car Driver (Mercury Tracer) & Van Driver (Mini-van) as observers (DRIVERS IN SAME VAN)
 - a. Starting lane: Lane 3, Starting line: SL2
 - b. Demonstrate: Lane Change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1
 - c. Answer questions.

3. Practice Trial 3: Both Car Driver (Mercury Tracer) & Van Driver (Mini-van) as observers (DRIVERS IN SAME VAN)
 - a. Instructions to Car Driver (Mercury Tracer) & Van Driver (Mini-van)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL1
 - iii. Desired constant velocity : 20 mph
 - b. Demonstrate:
 - i. Constant velocity + Lane Change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1
 - c. Answer questions.

4. Practice Trial 4: Both participant drivers (Car Driver (Mercury Tracer) & Van Driver (Mini-van)) as observers with another expert Van Driver (Mini-van) (Bridget) present on the track.
 - a. Instructions to Car Driver (Mercury Tracer) & Van Driver (Mini-van)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 40 mph
 - b. Test equipment and initialize data logging on observer vehicle.

- c. Start data logging on observer vehicle.
- d. Demonstrate:
 - i. With another expert Van Driver (Mini-van) (Bridget) + Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1
- e. Instruct participant drivers (Car Driver (Mercury Tracer) & Van Driver (Mini-van)) about Car Driver (Mercury Tracer) & expert Van Driver (Mini-van) stopping locations.
- f. Stop data logging & save driver output file on observer vehicle.
- g. Answer questions.

Instructions provided during to the Car Driver (SD: Mercury Tracer) while participating as an actual test driver during the next two practice trials (5–6):

- 5. Practice Trial 5: Car Driver (Mercury Tracer) as a single driver on the track.
 - a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
 - b. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
 - c. Conduct trial with:
 - i. Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1
 - d. Refresh Car Driver (Mercury Tracer) about his respective stopping location.
 - e. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
 - f. Answer questions.

- 6. Practice Trial 6: Car Driver (Mercury Tracer) as a single driver on the track.
 - a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 40 mph
 - b. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
 - c. Conduct trial with:
 - i. Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1
 - d. Refresh Car Driver (Mercury Tracer) about his respective stopping location.
 - e. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
 - f. Answer questions.

Instructions provided during to the Van Driver (CD: Mini-van) while participating as an actual test driver during the next two practice trials (7–8):

- 7. Practice Trial 7: Van Driver (Mini-van) as a single driver on the track.
 - a. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
 - b. Test equipment, initialize and start data logging on Van Driver (Mini-van).

- c. Conduct trial with:
 - i. Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1
 - d. Refresh Van Driver (Mini-van) about his respective stopping location.
 - e. Stop data logging & save driver output file on Van Driver (Mini-van).
 - f. Answer questions.
8. Practice Trial 8: Van Driver (Mini-van) as a single driver on the track.
- a. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 40 mph
 - b. Test equipment, initialize and start data logging on Van Driver (Mini-van).
 - c. Conduct trial with:
 - i. Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1
 - d. Refresh Van Driver (Mini-van) about his respective stopping location.
 - e. Stop data logging & save driver output file on Van Driver (Mini-van).
 - f. Answer questions.

Instructions provided to both drivers (SD: Mercury Tracer, CD: Mini-van) while participating as actual test drivers during the last two practice trials (9–10):

9. Practice Trial 9: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.
- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
 - b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 2
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
 - c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
 - d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
 - e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
 - f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
 - g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
 - h. Stop data logging & save driver output file on Van Driver (Mini-van).
 - i. Answer questions.
10. Practice Trial 10: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.
- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 40 mph

- b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 2
 - ii. Starting line : SL1
 - iii. Desired constant velocity : 20 mph
- c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
- d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
- e. Conduct trial with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
- f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
- g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
- h. Stop data logging & save driver output file on Van Driver (Mini-van).
- i. Answer questions.

Instructions provided to both drivers while participating as test drivers during the actual trial scenarios (1 – 12):

Actual Scenario 1: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
- b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 2
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
- c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
- d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
- e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
- f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
- g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
- h. Stop data logging & save driver output file on Van Driver (Mini-van).

Actual Scenario 2: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 40 mph
- b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 2
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
- c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
- d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
- e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
- f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
- g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
- h. Stop data logging & save driver output file on Van Driver (Mini-van).

Actual Scenario 3: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
- b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL1
 - iii. Desired constant velocity : 20 mph
- c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
- d. Test equipment, initialize and start data logging on Van Driver (Mini-van).

- e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
- f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
- g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
- h. Stop data logging & save driver output file on Van Driver (Mini-van).

Actual Scenario 4: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 40 mph
- b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL1
 - iii. Desired constant velocity : 20 mph
- c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
- d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
- e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
- f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
- g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
- h. Stop data logging & save driver output file on Van Driver (Mini-van).

Actual Scenario 5: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
- b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 2
 - ii. Starting line : SL1
 - iii. Desired constant velocity : 20 mph
- c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
- d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
- e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
- f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
- g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
- h. Stop data logging & save driver output file on Van Driver (Mini-van).

Actual Scenario 6: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 40 mph
- b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 2

- ii. Starting line : SL1
- iii. Desired constant velocity : 20 mph
- c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
- d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
- e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
- f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
- g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
- h. Stop data logging & save driver output file on Van Driver (Mini-van).

Actual Scenario 7: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 2
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
- b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
- c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
- d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
- e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
- f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
- g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
- h. Stop data logging & save driver output file on Van Driver (Mini-van).

Actual Scenario 8: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 2
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 40 mph
- b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
- c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
- d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
- e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
- f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
- g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
- h. Stop data logging & save driver output file on Van Driver (Mini-van).

Actual Scenario 9: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 2
 - ii. Starting line : SL2

- iii. Desired constant velocity : 20 mph
 - b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL1
 - iii. Desired constant velocity : 20 mph
 - c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
 - d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
 - e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
 - f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
 - g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
 - h. Stop data logging & save driver output file on Van Driver (Mini-van).

Actual Scenario 10: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- i. Starting lane : Lane 2
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 40 mph
 - b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 3
 - ii. Starting line : SL1
 - iii. Desired constant velocity : 20 mph
 - c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
 - d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
 - e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
 - f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
 - g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
 - h. Stop data logging & save driver output file on Van Driver (Mini-van).

Actual Scenario 11: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- i. Starting lane : Lane 2
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 20 mph
 - b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 2
 - ii. Starting line : SL1
 - iii. Desired constant velocity : 20 mph
 - c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
 - d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
 - e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
 - f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
 - g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
 - h. Stop data logging & save driver output file on Van Driver (Mini-van).

Actual Scenario 12: Car Driver (Mercury Tracer) & Van Driver (Mini-van) as concurrent drivers on the track.

- a. Instructions to Car Driver (Mercury Tracer)
 - i. Starting lane : Lane 2
 - ii. Starting line : SL2
 - iii. Desired constant velocity : 40 mph
- b. Instructions to Van Driver (Mini-van)
 - i. Starting lane : Lane 2
 - ii. Starting line : SL1
 - iii. Desired constant velocity : 20 mph
- c. Test equipment, initialize and start data logging on Car Driver (Mercury Tracer).
- d. Test equipment, initialize and start data logging on Van Driver (Mini-van).
- e. Conduct trail with: Constant velocity + Lane change maneuver (Lane 3 → Lane 2 → Lane 1) + Overall goal of exiting through Lane 1.
- f. Refresh Car Driver (Mercury Tracer) & Van Driver (Mini-van) about their respective stopping locations.
- g. Stop data logging & save driver output file on Car Driver (Mercury Tracer).
- h. Stop data logging & save driver output file on Van Driver (Mini-van).

After 24 trails (12 scenarios x 2) are complete, pay the subject and wrap up!

Appendix F

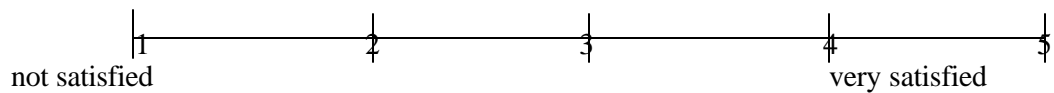
DRIVER SURVEY AND CONSENT FORMS

F.1 Post-experiment Driver Survey and Informed Consent Form

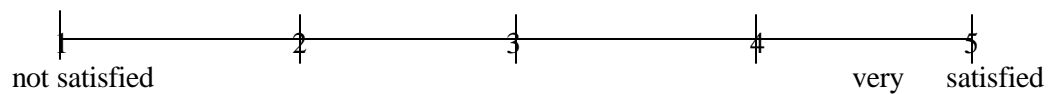
Subject Code: _____

1. If a friend of yours were to participate in this experiment, what tricks would you tell them about to make their job easier?

2. Please rate your satisfaction with the initial briefing and training intervention that was provided to you; 1 being not satisfied up to 5 being very satisfied in your answers.



3. Please rate your performance in the driver task; 1 being very poor up to 5 being very good.



Informed Consent Form for Biomedical Research
The Pennsylvania State University

ORP USE ONLY: IRB#24008 Doc. #1
The Pennsylvania State University
Office for Research Protections
Approval Date: 10/04/06 JKG
Expiration Date: 09/25/07 JKG
Biomedical Institutional Review Board

Title of Project: *Developing a Formalism for Gibson's Affordance
Using Colored Petri Nets (CPN)*

Principal Investigator: Mr. Hari Thiruvengada, Graduate Student
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Other Investigator(s): Dr. Ling Rothrock, Assistant Professor (Faculty Advisor)
310 Leonhard Building
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1. The purpose of this study is to validate a model for lane change behaviors on US Highway Systems using human participant data from expert drivers. The model would help us understand the lane change actions afforded to participant drivers based on the surrounding environment.
2. If you agree to take part in this research, you will be asked to drive an automatic transmission vehicle (car) fitted with data capturing equipment at the Pennsylvania Transportation Institute (PTI) facility alongside another expert driver. The car would provide controls that are similar to a standard automatic transmission car. The experiment consists of 10 practice trials and 24 actual trials lasting approximately 5 minutes each. You will also be asked to complete a single screening questionnaire:
 - Subject experience level questionnaireYou will be one of the four drivers participating in this experiment and your data will be used to draw conclusions about a model for lane change behaviors on US Highway Systems.
3. This study involves no risks to your physical or mental health beyond those encountered during everyday driving situation on standard US Highway System. By participating in this research, you may experience minimal fatigue from driving the test vehicle. These risks are mitigated by a safety protocol that would be provided to you in written form during initial experimental debriefing and in verbal form prior to each trial. You are free to take a break at any time during the experiment if necessary.
4. In conducting this research, we hope to understand in a better manner the action capabilities, judgment and decision making of human participant drivers while executing lane change behaviors on highway systems. Additionally, the benefits to society include improving the future design of highway systems and informing the design of automated driving tools.
5. Your participation in this research will take approximately 4 hours to complete the pre-test driving experience questionnaire, practice and actual trials.
6. Your participation in this research is confidential. In the event of publication of this research, no personally identifying information will be disclosed. To make sure your participation is confidential; you will be assigned a code number before you begin your experiment and the data will be stored and analyzed without any identifiers. The following may review and copy records related to this research: The Office of Human Research Protections in the U.S. Department of Health and Human Services, the Biomedical Institutional Review Board and the PSU Office for Research Protections.

7. You have the right to ask questions about the research procedures, and these questions will be answered. Further questions should be directed to Hari Thiruvengada (hzt103@psu.edu, 717-320-2590) or Prof. Ling Rothrock (lrothroc@psu.edu, 814-865-7241). If you have any further questions about your rights as a research participant, please contact the Penn State's Office for Research Protections at (814) 865-1775.
8. Compensation: You will receive \$23.95 + taxes (hourly wage rate @ PTI based on agreement with the PTI director) for completing the experiment.
9. Participation is voluntary. You are free to stop participating in the research at any time or to decline to answer any specific questions. Refusal to take part in or withdrawing from this study will involve no penalty or loss of benefits you would receive otherwise.

In the unlikely event you become injured as a result of your participation in this study, you would be covered under your work-related injury benefit because you are participating as a PTI employee. By signing this document, you are not waiving any rights that you have against The Pennsylvania State University for injury resulting from negligence of the University or its investigators.

You must be 18 years of age or older to participate.

If you agree to participate in this study and to the conditions outlined above, please sign and date below. You will receive a signed copy of this consent form.

Participant Signature

Date

Investigator Signature

Date

Appendix G

TEST RESULTS

DEPENDENT PAIRED T-TESTS FOR LANE POSITION (Δ LP) BETWEEN TRIALS:

Lane Position (Δ LP) for subject driver 1 (SD1):

t-Test: Paired Two Sample for Means

<i>Deviation in Lane Position (LP)</i>		
Mean	0.1972524	0.153498
Variance	0.0264335	0.012284
Observations	12	12
Pearson Correlation	0.862853	
Hypothesized Mean Difference	0	
df	11	
t Stat	1.736256	
P(T<=t) one-tail	0.0552018	
t Critical one-tail	1.7958837	
P(T<=t) two-tail	0.1104036	
t Critical two-tail	2.2009863	

Lane Position (Δ LP) for subject driver 2 (SD2):

t-Test: Paired Two Sample for Means

<i>Deviation in Lane Position (LP)</i>		
Mean	0.287289	0.286806
Variance	0.035549	0.034943
Observations	12	12
Pearson Correlation	0.898866	
Hypothesized Mean Difference	0	
df	11	
t Stat	0.019817	
P(T<=t) one-tail	0.492272	
t Critical one-tail	1.795884	
P(T<=t) two-tail	0.984544	
t Critical two-tail	2.200986	

DEPENDENT PAIRED T-TESTS FOR TURN DIRECTION (Δ TD) BETWEEN TRIALS:**Turn Direction (Δ TD) for subject driver 1 (SD1):**

t-Test: Paired Two Sample for Means

<i>Deviation in Turn Direction (TD)</i>		
Mean	0.0981888	0.104746
Variance	0.0021941	0.003928
Observations	12	12
Pearson Correlation	0.5229204	
Hypothesized Mean Difference	0	
df	11	
t Stat	-0.411215	
P(T<=t) one-tail	0.3444063	
t Critical one-tail	1.7958837	
P(T<=t) two-tail	0.6888126	
t Critical two-tail	2.2009863	

Turn Direction (Δ TD) for subject driver 2 (SD2):

t-Test: Paired Two Sample for Means

<i>Deviation in Turn Direction (TD)</i>		
Mean	0.104707	0.106893
Variance	0.003928	0.003123
Observations	12	12
Pearson Correlation	0.8933	
Hypothesized Mean Difference	0	
df	11	
t Stat	-0.268806	
P(T<=t) one-tail	0.396527	
t Critical one-tail	1.795884	
P(T<=t) two-tail	0.793054	
t Critical two-tail	2.200986	

DEPENDENT PAIRED T-TESTS FOR TIME TO EXIT (Δ TTE) BETWEEN TRIALS:**Time to Exit (Δ TTE) for subject driver 1 (SD1):**

t-Test: Paired Two Sample for Means

<i>Deviation in Time to Exit (TTE)</i>		
Mean	3.166667	2.416667
Variance	5.6060606	2.44697
Observations	12	12
Pearson Correlation	0.8386229	
Hypothesized Mean Difference	0	
df	11	
t Stat	1.9148542	
P(T<=t) one-tail	0.0409321	
t Critical one-tail	1.7958837	
P(T<=t) two-tail	0.0818642	
t Critical two-tail	2.2009863	

Time to Exit (Δ TTE) for subject driver 2 (SD2):

t-Test: Paired Two Sample for Means

<i>Deviation in Time to Exit (TTE)</i>		
Mean	4.083333	3.666667
Variance	6.083333	4.424242
Observations	12	12
Pearson Correlation	0.917055	
Hypothesized Mean Difference	0	
df	11	
t Stat	1.448874	
P(T<=t) one-tail	0.087637	
t Critical one-tail	1.795884	
P(T<=t) two-tail	0.175274	
t Critical two-tail	2.200986	

DEPENDENT PAIRED T-TESTS FOR UTILIZATION OF EXIT LANE (ΔU) BETWEEN TRIALS:**Utilization of Exit (ΔU) for subject driver 1 (SD1):**

t-Test: Paired Two Sample for Means

<i>Deviation in Utilization of Exit (UE)</i>		
Mean	0.1387077	0.108788
Variance	0.0103507	0.005505
Observations	12	12
Pearson Correlation	0.8334904	
Hypothesized Mean Difference	0	
df	11	
t Stat	1.8118096	
P(T<=t) one-tail	0.0486881	
t Critical one-tail	1.7958837	
P(T<=t) two-tail	0.0973762	
t Critical two-tail	2.2009863	

Utilization of Exit (ΔU) for subject driver 2 (SD2):

t-Test: Paired Two Sample for Means

<i>Deviation in Utilization of Exit (UE)</i>		
Mean	0.17814	0.158333
Variance	0.011651	0.008157
Observations	12	12
Pearson Correlation	0.929187	
Hypothesized Mean Difference	0	
df	11	
t Stat	1.668337	
P(T<=t) one-tail	0.061716	
t Critical one-tail	1.795884	
P(T<=t) two-tail	0.123432	
t Critical two-tail	2.200986	

DEPENDENT PAIRED T-TESTS FOR COMPARISON OF AFFORDANCE-BASED AND RANDOM CPN MODELS

t-Test: Paired Two Sample for Means of ΔLP			t-Test: Paired Two Sample for Means of ΔTD		
	ΔLP for Model1	ΔLP for Model2		ΔTD for Model1	ΔTD for Model2
Mean	0.231	0.548	Mean	0.104	0.499
Variance	0.018	0.006	Variance	0.002	0.010
Observations	12	12	Observations	12	12
Pearson Correlation	-0.142		Pearson Correlation	0.129	
Hypothesized Mean Difference	0		Hypothesized Mean Difference	0	
df	11		df	11	
t Stat	-6.701		t Stat	-13.370	
P(T<=t) one-tail	1.68569E-05		P(T<=t) one-tail	1.9004E-08	
t Critical one-tail	1.795883691		t Critical one-tail	1.795883691	
P(T<=t) two-tail	3.37139E-05		P(T<=t) two-tail	3.80079E-08	
t Critical two-tail	2.200986273		t Critical two-tail	2.200986273	
t-Test: Paired Two Sample for Means of ΔTTE			t-Test: Paired Two Sample for Means of ΔU		
	ΔTTE for Model1	ΔTTE for Model2		ΔU for Model1	ΔU for Model2
Mean	3.333	9.691	Mean	0.145992245	0.318471962
Variance	3.197	6.824	Variance	0.006334466	0.003768276
Observations	12	12	Observations	12	12
Pearson Correlation	-0.078		Pearson Correlation	-0.381023902	
Hypothesized Mean Difference	0		Hypothesized Mean Difference	0	
df	11		df	11	
t Stat	-6.716		t Stat	-5.081387715	
P(T<=t) one-tail	1.65205E-05		P(T<=t) one-tail	0.000177105	
t Critical one-tail	1.795883691		t Critical one-tail	1.795883691	
P(T<=t) two-tail	3.30411E-05		P(T<=t) two-tail	0.00035421	
t Critical two-tail	2.200986273		t Critical two-tail	2.200986273	

**COMPARING SCENARIOS USING PIVOT TABLE:
DEPENDENT PAIRED T-TESTS FOR LANE POSITION (Δ LP)**

t-Test: Two-Sample Assuming Unequal Variances
Measure: Lane Position (Student Faster = No)

	Variable 1	Variable 2
Mean	0.276721014	0.094655797
Variance	0.017450497	0.00523828
Observations	10	2
Hypothesized Mean Difference	0	
df	3	
t Stat	2.755974313	
P(T<=t) one-tail	0.035194534	
t Critical one-tail	2.353363435	
P(T<=t) two-tail	0.070389068	
t Critical two-tail	3.182446305	

t-Test: Two-Sample Assuming Unequal Variances
Measure: Lane Position (SD Faster = Yes)

	Variable 1	Variable 2
Mean	0.170833333	0.442105263
Variance	0.030605958	0.013743075
Observations	10	2
Hypothesized Mean Difference	0	
df	2	
t Stat	-2.721971601	
P(T<=t) one-tail	0.056310784	
t Critical one-tail	2.91998558	
P(T<=t) two-tail	0.112621567	
t Critical two-tail	4.30265273	

DEPENDENT PAIRED T-TESTS FOR TURN DIRECTION (Δ TD)

t-Test: Two-Sample Assuming Unequal Variances
Measure: Turn Direction

	Variable 1	Variable 2
Mean	0.068374187	0.121263587
Variance	0.001247263	0.002556128
Observations	8	16
Hypothesized Mean Difference	0	
df	19	
t Stat	-2.976835202	
P(T<=t) one-tail	0.003874413	
t Critical one-tail	1.729132792	
P(T<=t) two-tail	0.007748827	
t Critical two-tail	2.09302405	

DEPENDENT PAIRED T-TESTS FOR TIME TO EXIT (Δ TTE)

t-Test: Two-Sample Assuming Unequal Variances
Measure: Time to Exit (SD Faster = No)

	Variable 1	Variable 2
Mean	4.65	0
Variance	1.336111111	0
Observations	10	2
Hypothesized Mean Difference	0	
df	9	
t Stat	12.721305	
P(T<=t) one-tail	2.3381E-07	
t Critical one-tail	1.833112923	
P(T<=t) two-tail	4.6762E-07	
t Critical two-tail	2.262157158	

t-Test: Two-Sample Assuming Unequal Variances
Measure: Time to Exit (SD faster = Yes)

	Variable 1	Variable 2
Mean	2.4	4.75
Variance	3.988888889	1.125
Observations	10	2
Hypothesized Mean Difference	0	
df	3	
t Stat	-2.396725591	
P(T<=t) one-tail	0.048078647	
t Critical one-tail	2.353363435	
P(T<=t) two-tail	0.096157293	
t Critical two-tail	3.182446305	

DEPENDENT PAIRED T-TESTS FOR UTILIZATION OF EXIT LANE (Δ U)

t-Test: Two-Sample Assuming Unequal Variances
Measure: Utilization of Exit (SD Faster = No)

	Variable 1	Variable 2
Mean	0.195108696	0
Variance	0.002241191	0
Observations	10	2
Hypothesized Mean Difference	0	
df	9	
t Stat	13.03278248	
P(T<=t) one-tail	1.89995E-07	
t Critical one-tail	1.833112923	
P(T<=t) two-tail	3.79991E-07	
t Critical two-tail	2.262157158	

t-Test: Two-Sample Assuming Unequal Variances
Measure: Utilization of Exit (SD faster = Yes)

	Variable 1	Variable 2
Mean	0.107246377	0.240131579
Variance	0.008031226	0.002431614
Observations	10	2
Hypothesized Mean Difference	0	
df	3	
t Stat	-2.957440782	
P(T<=t) one-tail	0.029833268	
t Critical one-tail	2.353363435	
P(T<=t) two-tail	0.059666537	
t Critical two-tail	3.182446305	

VITA

Hari Thiruvengada

Education:

- Ph.D. Industrial Engineering, Penn State University, 2007
- M.S. Industrial Engineering, Penn State University, 2005
- M.S. Computer Science and Engineering, University at Buffalo, 2001
- B.E. Computer Science and Engineering, University of Madras, India, 1999

Research Experience:

- HCI Research Intern, Robert Bosch Corporation, Pittsburgh, PA, 2007 - Present
- Research Assistant, Human Performance Assessment and Modeling Laboratory, Department of Industrial Engineering, Penn State University, PA, 2002 - 2006
- Research Scientist, Emerging Technologies Group, Streaming21, Inc., Los Gatos, CA, 2001

Teaching Experience:

- Teaching Assistant, Penn State University, 2006 (Cognitive Work Design)
- Teaching Assistant, University at Buffalo, 2000 (Introduction to Computer Programming)

Publication:

- Thiruvengada, H., and Rothrock, L. (2007). Time Windows Based Team Performance Measures: A Framework to Measure Performance in Dynamic Team Environments. *Cognition, Technology and Work*.
- Thiruvengada, H., and Rothrock, L. (2007). Team Training. In D. Nembhard (Ed.), *Workforce Cross Training Handbook*. CRC Press.
- Thiruvengada, H., and Rothrock, L. (2006). HCI Implications of a Colored Petri Net Model for Gibson's Affordance. Paper presented at 2006 *Annual Conference of the Institute of Industrial Engineers*, Orlando, FL.
- Thiruvengada, H., and Rothrock, L. (2006). *Using Petri Nets for Gibson's Affordances: First Steps into Perception-based Task Analysis*. Paper to be presented at 2006 *Annual Conference of the Human Factors and Ergonomics Society*, San Francisco, CA.

Professional Affiliations:

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(Title: *HCI Implications of a Colored Petri Net Model for Gibson's Affordance*)