

Tubes and Metrics for Solving the Dilemma-Zone Problem

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Abstract—Our research is concerned with the modeling and design of semantically-enabled, efficient, safe and performant cyber-physical transportation systems (CPTS). As a class of cyber-physical systems (CPS), CPTS are characterized by a tight integration of software and physical processes for smartness, increased performance, safety and management of system functionality. We adopt this perspective in our investigation of solutions to the dilemma zone (DZ) problem, which currently claims thousands of lives every year at traffic intersections. In this paper, we define and introduce new “dilemma metrics” to solve this problem. Coupled with an innovative tubular (3D) characterization of the decision problem that arises at the onset of the yellow light, these metrics enable simple and actionable decision capabilities to deal with unsafe configurations of the system. We also set a pathway toward integrating dilemma metrics and dilemma tubes with an ontological framework – the latter encodes the reasoning platform supporting the broad implementation of the algorithmic solutions resolving unsafe configurations of CPTS, such as the ones created by the DZ problem.

Keywords—Dilemma Zone; Metrics; Cyber-Physical Transportation Systems; Artificial Intelligence; Safety.

I. INTRODUCTION

During the past twenty years, transportation systems have been transformed by remarkable advances in sensing, computing, communications, and material technologies. The depth and breadth of these advances can be found in superior levels of automobile performance and new approaches to automobile design that are becoming increasingly reliant on sensing, electronics, and computing. The trend toward “transportation smartness” is so pervasive that by next year, as much of 40% of an automobile’s value will be embedded software and control related components [1][2]. And yet, despite an exponential increase in the number of software lines of code (SLOC) to achieve these benefits, accidents at traffic intersections claim around 2,000 lives annually within the US alone [3]. A key component of this safety problem is the dilemma zone (DZ), which is an area at a traffic intersection where drivers are indecisive on whether to stop or cross at the onset of a yellow light.

II. PROJECT SCOPE AND OBJECTIVES

Our research addresses challenges that are hindering the system-level development of cyber-physical transportation systems (CPTS). Challenges that remain to be overcome include:

(1) the integration of cyber-physical systems (CPS) technologies into existing infrastructure, (2) the realization of “zero fatality” transportation systems, and (3) the development of formal models and credible, actionable performance and safety metrics [5]. To this end, metrics for system safety are needed to: (1) evaluate the operation and control of transportation systems in a consistently and systematic way (including situations such as the dilemma zone), (2) identify, measure and predict the effects of interconnectivity between systems components as well as system performance, and (3) set standards and serve as measure of effectiveness (MoEs) guiding model-based systems engineering (MBSE) efforts.

We consider in this project the interplay among the key players of transportation systems at traffic intersections, and the consequences of their interactions on overall traffic system level safety. This work-in-progress paper focuses on one aspect of the problem – development of metrics to capture the essence of these interactions, and support the characterization of the problem and its representation using three-dimensional dilemma tubes. Section III is a review of existing approaches to the dilemma zone problem and their limitations with regard to the current trend toward CPTS. Section IV introduces the new dilemma zone metrics and their tubular representation. Section V describes our plans for ongoing research.

III. DILEMMA ZONE PROBLEM AND CYBER-PHYSICALITY OF TRAFFIC SYSTEMS

Dilemma Zone: Definition and Existing Solution Approaches. Also called the twilight zone, Amber signal or decision zone, the dilemma zone is the area at a traffic intersection where drivers are indecisive on whether to stop or cross at the onset of a yellow light. The behavior of users in “twilight zones” is responsible for hundreds of lives lost and billions worth in damages at stop light intersections in the United States [3]. Scholars distinguish two types of dilemma zone that differ by the perspective adopted on the problem. Type I DZ is viewed from the “physics of the vehicle” as in [6] and [7] while Type II adopts the driver’s perspective as reported in [8]. Both perspectives use the stop line as a reference for their measurement as shown in Figure 1. However, the boundaries of DZ of type II are sometimes measured with a temporal tag (i.e., representing the duration to the stop line) added to a probabilistic estimate [9]. In this work, the dilemma zone will be considered in the sense defined by Type I.

Past research has focused on finding ways to protect

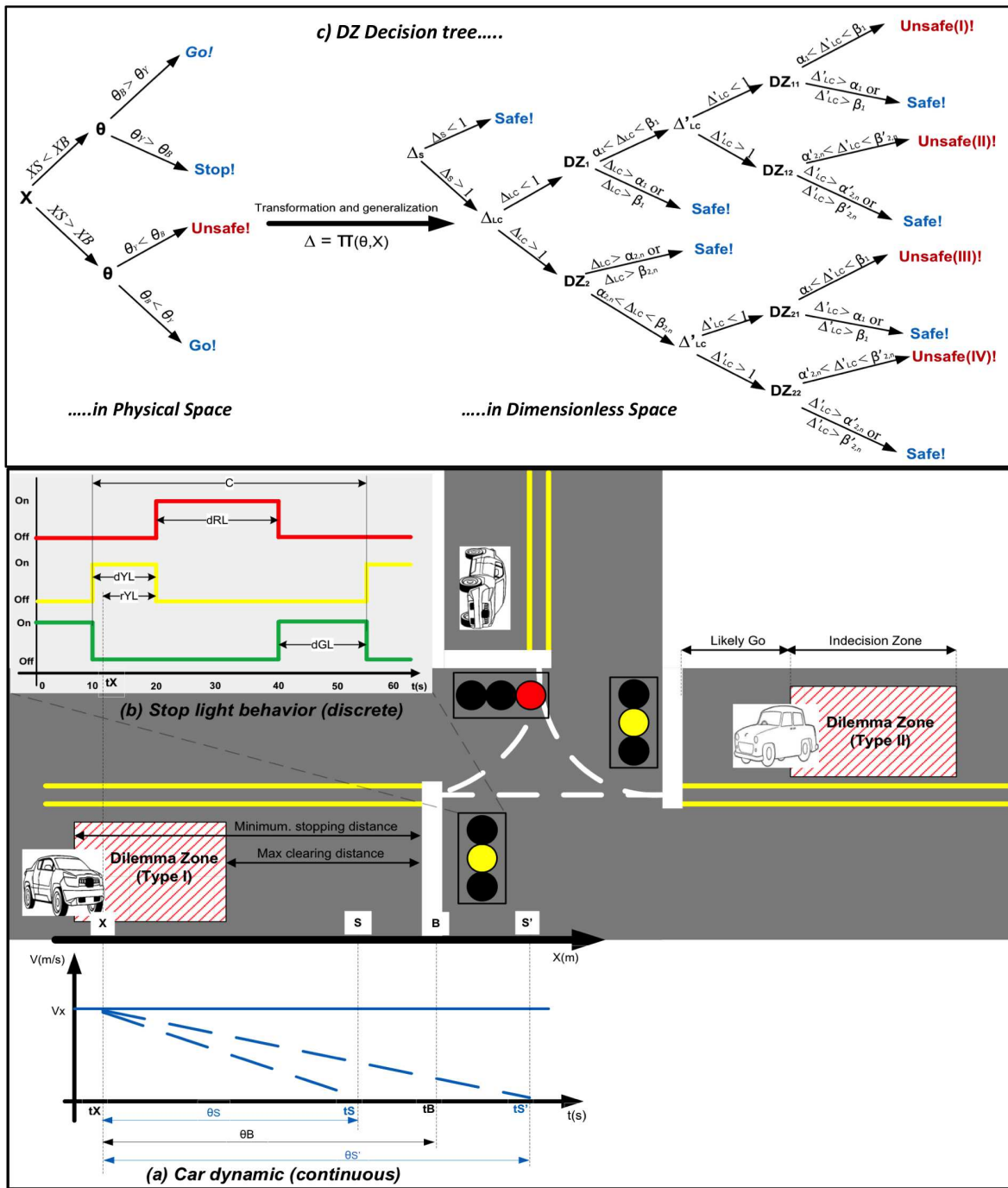


Figure 1. Type I & Type II Dilemma Zones and Decision Trees.

from, or eliminate, DZs using mostly a pure traffic control engineering view of the problem. These efforts have resulted in signal timing adjustment solutions that ignore or can't properly account for the physics of vehicles or driver's behaviors [10][11][12]. In order to deal with uncertainties, other scholars have used stochastic approaches such as fuzzy set [6] and Markov chains [7]. For all of these traditional techniques, the baseline of the solution can be either reduced (explicitly or not) to a space or temporal-based dilemma zone, but not both.

Autonomous Cars and Intelligent Traffic Control Systems. Recent work, such as that found in [13] and [14] illustrates the switch of researcher's interest toward investigating solutions to the DZ problem that incorporate both the car physics and light timing, while also providing a pathway forward for vehicle-to-infrastructure (V2I) interactions and integration. These solutions will soon become a reality, in part, because of an increased use of artificial intelligence in automating the command and operation of both cars and traffic signals. For automobiles, many aspects of autonomy – from braking to

cruise control and driving functions – are in advanced stages of experimentation. Finding ways to put smartness into vehicles has contributed to reduced fatalities on highways mostly in the developed world. Looking ahead, even more automation is coming with self-driving cars [15][16].

The addition of artificial intelligence to traffic signal controls now makes sense due to an ability to determine the position, speed and direction of vehicles, and adjust light cycling times in a coordinated way to make the intersection crossing more efficient. Researchers have been developing and testing various technologies with mixed results [17][18][19]. As a case in point, a pilot study conducted by Carnegie Mellon University, reports a 40% reduction of intersection waiting times, an estimated 26% decrease in travel time, and a projected 21% decrease of CO_2 emissions [19]. Tapping into the full potential of these intelligence capabilities is hard as: (1) most vehicles can't currently communicate with traffic light controllers, and (2) autonomous vehicles still struggle in operating safely in adversary weather conditions (heavy rain, snow covered roads, etc.) and changing environment (temporary traffic signals, potholes, human behaviors, etc.). We assume in this paper that these problems will be resolved by ongoing research activities.

Toward Cyber-Physical Traffic Management Systems. Real-time situational awareness (e.g., traffic, location, speed) and decision, combined with vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications and control are valid and effective pathways for a solution to both congestion and safety at intersections. As such, we fully adopt a CPS view of the traffic system with regard to the DZ problem.

The value of this perspective has already been demonstrated by Petnga and Austin [20]. Autonomous vehicles (i.e., the physical system) interact with the light (i.e., the cyber system) with the objective of maximizing traffic throughput, while ensuring vehicle crossings are safe at the intersection. Enhanced performance and safety at the intersection have been proven possible, thanks to the critical role of temporal semantics in improving system level decision making. Also, when bi-directional connections between the vehicle and light are possible, new relationships can be established to characterize their tight coupling – this, in turn, enables the various computers in the CPTS to exchange information, reason, and make informed decisions. These capabilities are critical for those cases where the vehicle physics is such that they can neither stop nor proceed without entering and occupying the intersection while the traffic light is red. Therefore, the development of metrics for the DZ problem will greatly benefit from (and enrich) this CPTS perspective.

IV. METRICS FOR CHARACTERIZING THE DILEMMA ZONE PROBLEM

Safety Requirements to Decision Trees and Dilemma Metrics. The core safety requirement of the system car-light that should prevail all the time at intersection can be expressed as follows. “No vehicle is allowed to cross the intersection when the light is red”. This is a non-functional requirement, a hard constraint whose violation is the driving force behind accidents at intersections. As shown on Figure 1 a) and b), the continuous dynamic of the vehicle and discrete behavior

of the light illustrate the very different nature of both entities. This complicates the ability of the system to satisfy the safety requirement at the onset or in the presence of the yellow light.

Understanding the mechanisms by which system-level safety is achieved or violated is critical in addressing the DZ challenge. Decision trees appear to be the most suitable analysis tool to explore the different possible paths the system could follow and identify safe and unsafe ones. The tree shown on the left-hand side of Figure 1 c) shows the decision tree of the autonomous car - in the physical space - when it knows the traffic lights critical parameters at the time the decision is made. Petnga and Austin [20][21] have shown that the probability of the car making the right decision is higher when it knows before hands the following: (1) Duration Θ_Y of the yellow light before it turns red; (2) Vehicle stopping distance X_S , and (3) Travel duration Θ_B or distance to light X_B . However, moving forward requires a deep understanding of the interrelationships between cross-cutting system parameters from the various domains (car, light, time, space) involved at meta level. Also, the ability of the system to efficiently reason about unsafe situations and propose a satisfactory way out is critical.

We argue that this complexity can be kept in check by casting the problem in dimensionless terms and setting up a transformation $\Delta = \Pi(\Theta, X)$ of the initial decision tree from the physical space to a dimensionless space. Expressing the system decision tree in dimensionless space as a result of the transformation Π necessitates the definition of intermediary variables and parameters. We begin by noting that the car will not always catch the onset of the yellow light; thus, what is really relevant for efficient decision making here is the time left before the stop light turns red. Using the remaining duration of the yellow light r_{YL} , its full duration d_{YL} and the ones of the green and red lights ie d_{GL} and d_{RL} , we define the duration of a stop light cycle C , reduced cycle C_{YL} and cycle index k . The short (α_1) and full (α_2) yellow light duration as well as the short (β_1) and full (β_2) stop light indexes are also defined. The details are as follows.

$$C = d_{YL} + d_{RL} + d_{GL} \quad (1)$$

$$C_{YL} = r_{YL} + d_{RL} + d_{GL} \quad (2)$$

$$k = \frac{C}{r_{YL}} \quad (3)$$

$$\alpha_1 = \frac{r_{YL}}{C_{YL}} \quad (4)$$

$$\alpha_2 = \frac{d_{YL}}{C_{YL}} \quad (5)$$

$$\beta_1 = \frac{r_{YL} + d_{RL}}{C_{YL}} \quad (6)$$

$$\beta_2 = \frac{d_{YL} + d_{RL}}{C_{YL}} \quad (7)$$

We add to the aforementioned physical variables the stopping duration Θ'_B of the car – should it decide to stop – and define the **car stopping distance metric** Δ_S , the **light-car crossing time metric** Δ_{LC} and the **light-car stopping time**

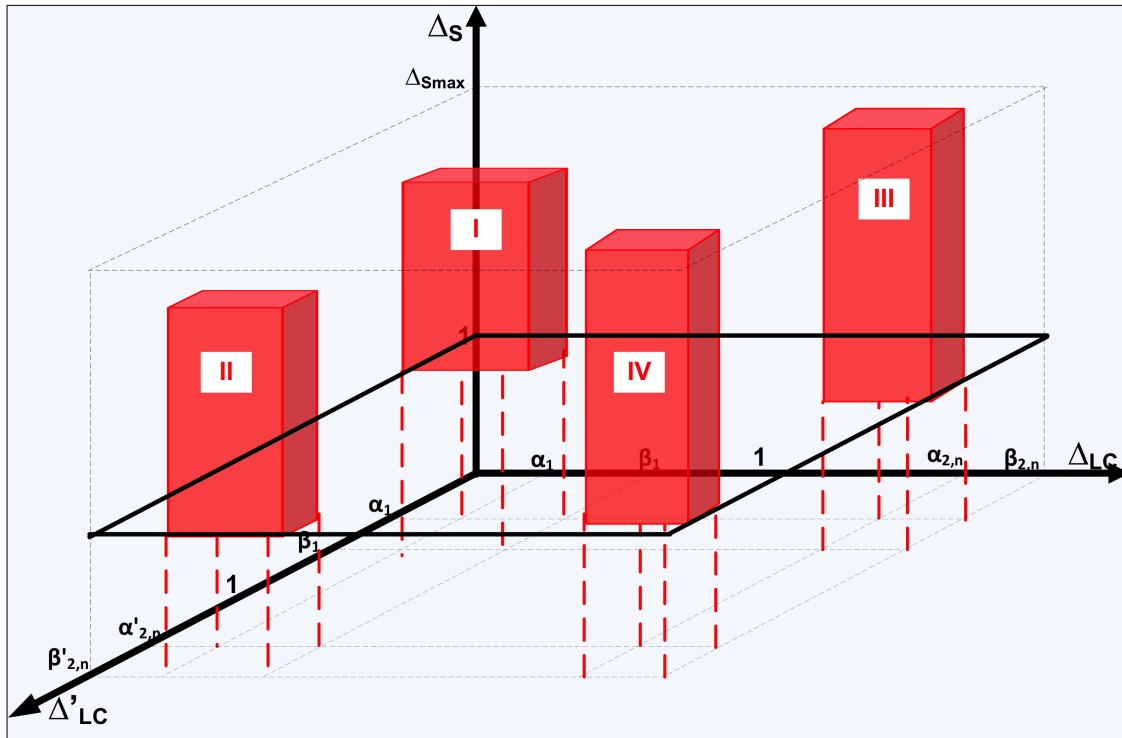


Figure 2. Dilemma Tubes in the Dimensionless (Δ) space.

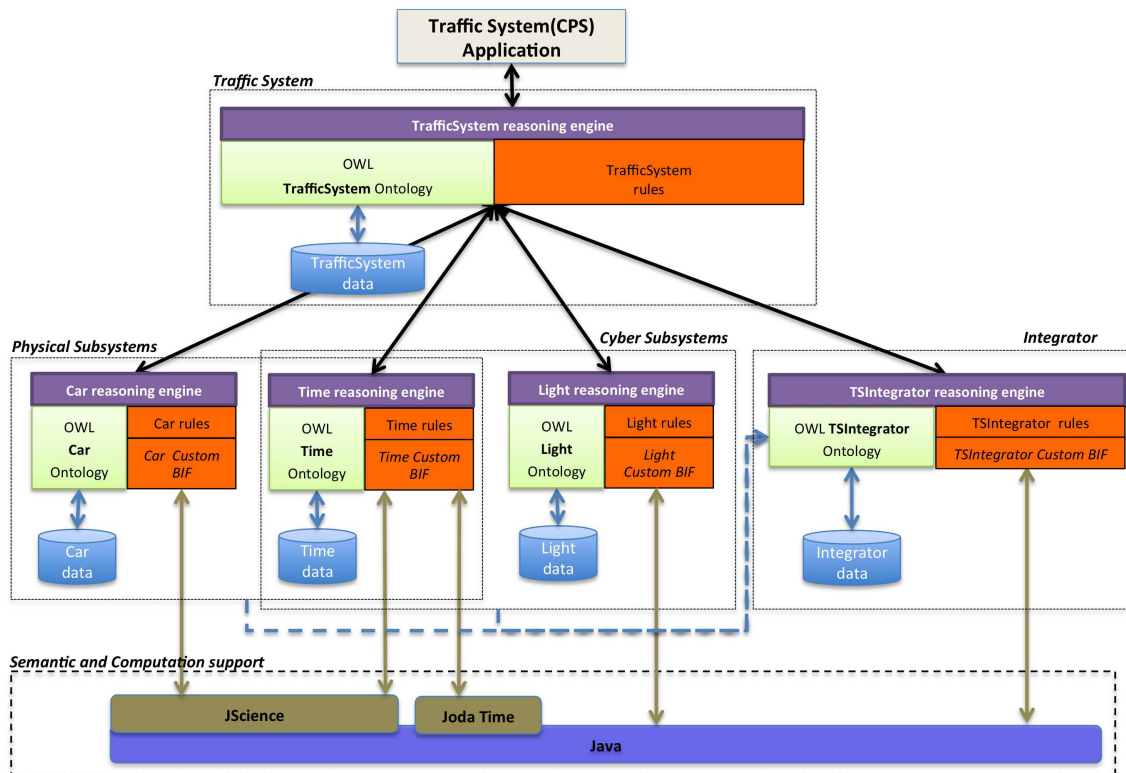


Figure 3. Architecture of the traffic system as a CPS.

metric Δ'_{LC} as follows.

$$\Delta_S = \frac{XS}{XB} \quad (8)$$

$$\Delta_{LC} = \frac{\Theta_B}{C_{YL}} \quad (9)$$

$$\Delta'_{LC} = \frac{\Theta'_B}{C_{YL}} \quad (10)$$

All these metrics are dimensionless and serve as the key decision points of the dimensionless decision tree shown on the right-hand side of Figure 1 c). However, in order for us to be able to navigate the decision tree, we need additional information. We use the integer part function E to define n and n' indexes in (11) and (12) as follows.

$$n = E\left(\frac{\Delta_{LC} - 1}{k}\right) \quad (11)$$

$$n' = E\left(\frac{\Delta'_{LC} - 1}{k}\right) \quad (12)$$

They help specify the counterparts of α and β indexes when $\Delta_{LC} > 1$ or $\Delta'_{LC} > 1$ as follows.

$$\alpha_{2,n} = k * \alpha_2 + k * n + 1 \quad (13)$$

$$\beta_{2,n} = k * \beta_2 + k * n + 1 \quad (14)$$

$$\alpha'_{2,n} = k * \alpha_2 + k * n' + 1 \quad (15)$$

$$\beta'_{2,n} = k * \beta_2 + k * n' + 1 \quad (16)$$

Along with (4) through (7), the values of α and β in (13) through (16) are necessary and sufficient to constraint the dimensionless metrics Δ_S , Δ_{LC} and Δ'_{LC} and render a complete view of all possible outcomes of the decision tree in a dimensionless space Δ . Now, we can see that there are four possible configurations of the system for which it's unsafe as shown by the right-hand side of Figure 1 c).

From Dilemma Metrics to Dilemma Tubes. Each system unsafe configuration identified above corresponds to a “dilemma tube” in the Δ space as shown in Figure 2. For instance, (4), (6) and (8) through (10) provide the foundational elements for defining Tube I. However, in order to fully define the boundaries of each of the four tubes (i.e., I, II, III and IV), we add to the parameters introduced above, the maximum value of Δ_S ie Δ_{Smax} which is the maximum value of all the Δ_S for the system. Physically, it is determined by the physics of the family of vehicles crossing the intersection and the configuration of the traffic intersection as captured by (8). If at any instant the system is projected to enter an unsafe state, this situation will be materialized as a point coordinate $P_{\Delta}(\Delta_S, \Delta_{LC}, \Delta'_{LC})$ inside a particular tube. The physical interpretation of this phenomenon is that the autonomous car does not have a good decision option, and will need external help to safely cross the intersection. Scenarios that lead to unsafe system configurations will follow Unsafe branches of the decision tree on the right-and of Figure 1 c). While they won't necessary unfold in the order presented in the tree, the result will invariably be the same, i.e., the system will be projected to enter an unsafe state. In practice, the calculations can be done concurrently and the location of the resulting point

coordinate relative to any of the four dilemma tubes easily determined. However, a vehicle can only be in one of the four dilemma tubes at a time - as they are mutually exclusive - or in any location in the remaining part of the Δ space i.e., a safe region.

Knowing in which tube the unsafe state has been materialized is critical in determining the appropriate course of action to prevent the occurrence of an accident.

V. FUTURE WORK

The key driver of our research is the modeling and design of semantically-enabled, efficient, safe and performant cyber-physical transportation systems. We are systematically working toward the platform infrastructure in Figure 3 (customized for the traffic system). The main aspects of this effort are as follows.

Topic 1. Architectural, ontological and reasoning infrastructures. The CPS perspective introduced above is translated into an ontological architecture where the subdomains involved in the transportation system are formally described at the appropriate level of detail. Thus, cyber, physical and meta domains (such as time and space) will be captured by description logic-enabled domain specific ontologies (DSO), each with its own rules engine. Spatio-temporal reasoning supported by appropriate implemented semantic extensions (such as Jscience or Joda time) will enhance traffic agents decision making capabilities. For the traffic system, the architectural framework will support reasoning in the dimensionless space and enable light reconfiguration, should a car be heading into a dilemma tube. The dilemma metrics introduced in this paper will be implemented in the Integrator rules engine. This entity (physically a smart traffic controller) will be the ultimate responsible of system level decisions. More details on the underlying semantic platform infrastructure supporting this architecture along with illustrative examples (ontologies, rules, extensions. etc.) can be found in [22].

Topic 2. Scripting language support for systems integration. Bringing together the various pieces of the above-mentioned architecture requires their bottom up integration in an organized but systematic way. Beside the necessary ontological integration of DSOs, we need a way to assemble system models. Our plans are to solve this problem with Whistle [23][24], a tiny scripting language where physical units are deeply embedded within the basic data types, matrices, branching and looping constructs, and method interfaces to external object-oriented software packages. Whistle is designed for rapid, high-level solutions to software problems, ease of use, and flexibility in gluing application components together. During the next iteration of development, Whistle will be extended to support co-simulation, graph databases, reasoning with ontologies and rules, and connections to external software packages through JFMI, the Java functional-mockup interface. Computational support will be added for input and output of model data from/to files in various formats (XML, Open Street Map (OSM), Java, etc.).

Topic 3. System modeling, simulation and performance evaluation. CPTS ontological modeling with the platform

architecture of Figure 3 will provide insight into the reasoning structure needed to improve decision making at traffic intersections. It is especially important that computation and implementation of Allen's temporal logic and reconfiguration of the light behaviors are handled properly. We also need a component-based framework that is hooked to the ontological platform. The platform will be used for time-history simulations of traffic and light behaviors, and evaluation and visualization of the dilemma metrics and 3D dilemma tubes. Extensions of the platform to support the development and experimentation of V2V and V2I systems will be investigated.

VI. CONCLUSION

The purpose of this paper has been to describe a new and innovative tubular (3D) characterization of the dilemma zone problem, which enables quick and simple visual representation of the state of the traffic system. In traditional approaches to the DZ problem, cars and stoplights are treated separately. Our dilemma zone tubes result from a systems perspective where the cars and stoplights are treated as a whole. The second purpose of this paper has been to lay down the foundation for integrating these metrics and the tubular representation with an ontological framework for reasoning and decision making support to resolve unsafe configurations of the system. The next iteration of our work will include implementation and scripting of CPTS simulation scenarios with Whistle.

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