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Systemwide Safety and Reliability for Intelligent Intersections in Hybrid Systems

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Abstract: ***There is an increasing interest in the automation of driving tasks highway traffic management. We address intelligent intersections design problems, where traffic lights are removed. Cars exercise an interaction of centralized and distributed decision making to negotiate the intersection through. Intelligent intersections are a representative of complex hybrid systems, where the challenge is to design a tractable distributed algorithm that guarantee safety and provide better performance. The architecture should allow distributed freedom of action to cars yet should watch against worst-case behavior of other cars to ensure collision avoidance.***

Keywords: intelligent intersections, vehicle safety, traffic control, networked control systems.

I. INTRODUCTION

In the future, cars will gain access to a wide range of information from the Global Positioning System (GPS) and onboard sensors such as lidar, radar, cameras, and gyroscopes with regard to position, velocity, acceleration, and brake pressure, that are made available through Controller Area Network (CAN) bus. Cars which are equipped with dedicated short-range communication (DSRC) radios can exchange information with other cars and the road-side infrastructure [11]. In this paper, we will converge on safety applications.

Collision avoidance technologies are largely vehicle-based systems which are offered by original equipment manufacturers as autonomous packages which broadly perform the following two functions: collision warning and driver assistance. However, such systems are passive and depend on the human driver to accurately respond.

In this paper, we focus on intelligent intersections, where conventional traffic control devices, like traffic signals, are removed. Vehicles make use of a combination of centralized and distributed real-time decision making to coordinate their movement across the intersection. The intelligent intersection is provoked by potential benefits in comfort, safety, and efficiency.

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One significant challenge in design is that safety in intelligent intersections has to do with ensuring collision avoidance on entering the intersection, within the intersection and, on exiting the intersection.

Our approach is a hybrid technique that engages an appropriate separation of concerns between safety and liveness.

In Sections II–IV, we consider problems of escalating complexity, ranging from perpetual collision avoidance for two cars to several cars on a single lane, and, subsequently, to cars on different streams that cross at an intersection. In Section V, we present a comparative simulation study of performance against traffic lights.

II. TWO CARS ON A LANE

In an automated vehicle system, one critical goal in the design work is to ensure collision avoidance in perpetuity. We develop a general set-theoretic formulation of the problem to recognize whether safety is a perpetually maintainable relation [8].

A. Point cars with bounded velocity and non-negative acceleration

Consider two cars A and B on a single lane. The rear car, i.e., car B, is responsible for perpetual safety, in spite of the worst-case behavior of the front car A. Each car is restricted to nonnegative velocity and has both an upper bound and a lower bound on its acceleration as well, where the lower bound is a negative quantity. Let $x_A=(s_A,v_A)$ be the state vector for the front car with position s_A and velocity v_A, similarly for $x_B=(s_B,v_B)$. Thus, $s_B<s_A$, $v_A\geq 0$, and $v_B\geq 0$. The acceleration of the rear car a_B is chosen as the control input. Let the minimum acceleration that car A can apply be $\underline{a}_A<0$ that car B can apply be $\underline{a}_B<0$. Let us consider point cars of zero area and declare a collision if $s_A = s_B$.

Theorem 1 - Perpetual Safety for Two Cars on a Lane:

Given $s_A>s_B$, the necessary and sufficient condition for perpetual collision avoidance (perpetual safety) by car B is

$$s_B+\int_0^t v_B(\tau)d\tau < s_A + \int_0^t\left(v_A + \underline{a}_A\tau\right)^+ d\tau \quad \forall t\geq 0 \qquad (1)$$

where $r^+=\max(r,0)$. There is an open-loop input that maintains safety denoted as $\{s_B(\tau):\tau\geq 0\}$ and $\{v_B(\tau):\tau\geq 0\}$, the resulting position and velocity trajectories of car B, respectively, when input $\{a_B(\tau):\tau\geq 0\}$ is applied.

Proof of Theorem 1:

Necessity: Note that $s_A > s_B$. Suppose that the aforementioned condition is violated, such that

$$s_B+\int_0^t v_B(\tau)d\tau < s_A + \int_0^t \left(v_A + \underline{a}_A\tau\right)^+ d\tau \quad \forall t \geq 0$$

Now, consider the situation when the front car A brakes at maximum with an acceleration of a_A. The best choice for B is to brake at maximum with an acceleration of a_B. However, even this approach can cause a collision by time t^*.

Sufficiency: Assuming (1), it is sufficient to show that there exists a safe input $\{a_B(t) : t \geq 0\}$ for the rear car for all time. This case is insignificant, because the rear car chooses $a_B(t) \equiv a_B$ for all $t \geq 0$.

Suppose that cars should maintain a minimum separation distance K >0 so that cars that are separated by less than K m are said to "collide." Then,

$$K+s_B+\int_0^t v_B(\tau)d\tau < s_A + \int_0^t \left(v_A + \underline{a}_A\tau\right)^+ d\tau \quad \forall t \geq 0 \qquad (2)$$

B. Sampling With Intermediate Safety

Suppose that the acceleration of car A is constrained to lie in the interval $[\underline{a}_A, \bar{a}_A]$, the acceleration of car B lies in $[\underline{a}_B, \bar{a}_B]$, and the rear car B receives updates on the state of the front car every T s which is the sampling interval. Based on the information about the lead car A at time nT, car B chooses an acceleration input $\{a_B(t): t \in [nT, (n + 1)T)\}$. For simplicity, let us restrict ourselves to T-horizon strategies, where, if the current time is nT, $a_B(\cdot)$ is identically chosen equal to a_B, except on the interval $[nT, (n + 1)T)$.

C. Robustness of the Scheme

The aforementioned collision avoidance strategy is robust to the nominal assumptions that noiseless undelayed information about the front car is periodically available or the resort to maximal braking

Consider a scenario in which the sensor samples at instants $T_1, T_2, \ldots, T_k, \ldots$, where is $T_k \in (kT - \delta_j, kT + \delta_j)$. Suppose that there is a bounded communication delay d_c, with $0 \leq d_c \leq \delta_c$. Finally, suppose that there is a bounded actuation delay d_a, with $0 \leq d_a \leq \delta_a$. Then, the rear car can ensure worst-case safety by planning over the worst-case interval between two successive actuations, i.e., $T + 2\delta_j + \delta_c + \delta_a$.

Noisy information from the sensors, with bounded noise, can be handled by assuming that each sensor measurement is corrupted by the worst-case noise. The modified safety condition is

$$K+(s_B+\Delta s_B)+\int_0^t \left((v_B+\Delta v_B)+\underline{a}_B\tau\right)^+ d\tau \leq (s_A-\Delta s_A)+\int_0^t \left((v_A-\Delta v_A)+\underline{a}_A\tau\right)^+ d\tau \quad \forall t \geq 0 \qquad (3)$$

where $\Delta s_A, \Delta v_A, \Delta s_B, \Delta v_B$ are the magnitudes of the worst-case errors in the position and velocity for cars A and B.

III. MULTIPLE CARS ON A LANE

The solution to the problem of two cars on a lane can easily be expanded to the case of several cars on a lane; see Fig. 1. In the figure, there is an arrow of "responsibility" between any pair of adjacent cars. The car at the head of the arrow should make worst-case assumptions about the car at the tail of the arrow to ensure that it does not collide with it. The result is a distributed solution.

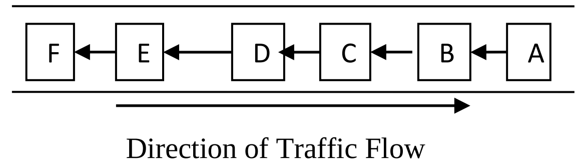

Fig. 1: Many cars on a lane

IV. COLLISION AVOIDANCE AT INTERSECTIONS

We now focus on intelligent intersection problem, where two or more streams of cars cross at an intersection. We create the "electronic equivalent" of a traffic light, that ensures safety.

A. Description of Intersection

The route taken by a car *i* is described by an ordered pair R*(i)* = (O*(i)*,D*(i)*), indicating origin and destination, respectively. Two routes are considered to be intersecting if they cross each other. Two routes R*(i)* and R(j) are said to be nonintersecting if O*(i)* = O(j) or D*(i)* = D(j). Thus, we have an "intersection relation" *I* defined on the set of routes. If two routes are intersecting, we say R*(i) I* R(j).

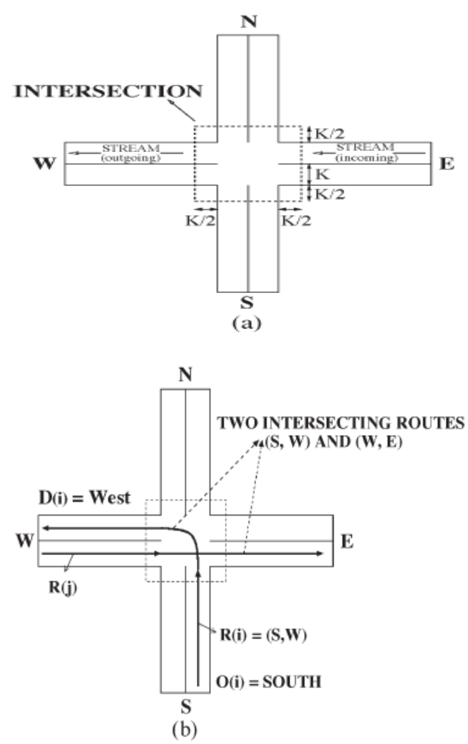

Fig. 2. Description of intersection. a)Intersection b)Intersecting routes

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B. Hybrid Architecture

We propose hybrid architecture for collision avoidance at intersections. It consists of an interaction between a centralized component and distributed agents. The intersection infrastructure will operate as a scheduler and assigns a time slot to a car that comes within the communication range of the intersection. The car should be strictly outside the area covered by the intersection during all other times. This is accomplished by the time-slot allocation algorithm which is implemented at the intersection.

A time-slot assignment is a mapping σ that maps each car i in $\{1, 2, \ldots, m\}$ to an interval of time $\sigma(i)=[t_{start}(i), t_{end}(i))$, called the *time slot* allocated to i. For any two cars i and j, if $R(i)$ i $R(j)$, then $\sigma(j)\cap\sigma(i)=\emptyset$. This condition ensures that two cars with intersecting routes have nonintersecting slots.

Definition 1- For each car i at time nT, an open-loop sequence of inputs called the *failsafe maneuver* is maintained, denoted by $\{a_i^{F,n}(k)\}_{k\geq n}$. This approach specifies an open-loop future trajectory for car i at time nT. This serves as an infinite-horizon open-loop contingency plan it then follows and stays perpetually safe.

Definition 2- Consider that car i begins a new allocation epoch at time nT, i.e., $\sigma^{(n-1)}(i)\neq\sigma^{(n)}(i)$. A slot reallocation policy is *admissible* if it satisfies the following conditions.

1) The reallocated slot should be in the future, i.e.,$t_{start}^{(n)}(i) \geq nT$.
2) If the available failsafe maneuver at time nT is implemented at time nT, then car i will come to a stop before the intersection.
3) Slot reallocation cannot be done too early. We need $nT \geq t_{end}^{n-1}(i) - \tau_{max} + T$, where τ_{max} is the length of time that is enough for any car that starts from a dead stop to get through the intersection.

V. BUFFER INDEX

Objectives in the area of travel time reliability intend to reduce the variability in travel time so that transportation system users experience a consistent and predictable trip time. Unexpected delay is lowered for people and goods. This category focuses on the buffer time index, which reflects the amount of extra time that the travelers need to add to their average travel time to account for non-recurring delay. The buffer index represents the extra time (buffer) most travelers add to their average travel time when planning trips. This is the extra time between the average travel time and the near-worst case travel time. The buffer index is affirmed as a percentage of the average travel time.

$$\text{Buffer Index} = \frac{95^{th}\text{ percentile of average travel time} - \text{Average travel time}}{\text{Average travel time}} \quad (4)$$

The buffer index represents the extra buffer time that most travelers add to their average travel time when planning trips to ensure on-time arrival. This extra time is added to account for any unexpected delay. The buffer index is expressed as a percentage and its value gets increased as reliability gets worse.

The buffer index is computed as the difference between the 95thpercentile travel time and the average travel time, divided by the average travel time. This formulation of the buffer index uses 95th percentile travel time to represent a near-worst case travel time. Whether expressed as a percentage or in minutes, it represents the extra time a traveler should allow to arrive on-time for 95 percent of all trips.

VI. PERFORMANCE EVALUATION

The aforementioned algorithm and architecture can ensure systemwide safety and liveness provide freedom in the design space for policies to improve throughput or reduce delay. We attempt to explore this design space and devise schemes for improving performance. In particular, we find the admissible time-slot assignments and locally maximize an appropriate performance metric.

We have developed a simulator of the entire system in MATLAB. The performance metric under concern is the average time taken by a system that consists of m cars to travel from 200 m away from the start of the intersection to 200 m away from the end of the intersection. All cars start at maximum velocity which is equal to 25 m/s and are assumed to have equal braking power that is equal to −3.5 m/s2 for simplicity. The average number of cars that enter the system per second is taken as a tangible measure of the load of the intersection and is calculated as $4.v_M/(K + (1/\lambda))$, where the factor of 4 arises since there are four input streams.

The abovementioned simulation framework has been expanded to simulate worst-case stop signs and worst case traffic lights with guaranteed safety.

For stop signs, the scheduler assigns time slots in a first-come–first served (FCFS) fashion to cars only when they are very close to the intersection. For traffic lights, the cycle length and green period duration are set by measuring headway saturation, critical-lane volumes, and lost time. We determined the appropriate cycle length and green periods by an examination of what values work best for a given load because we do not have access to these parameters in our simulations.

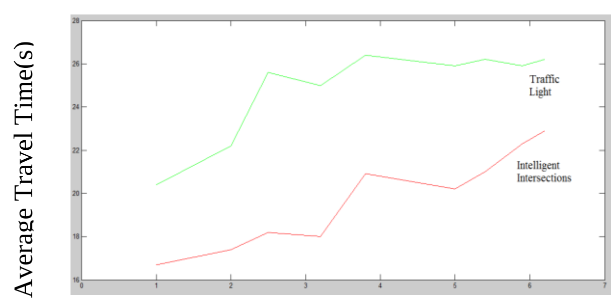

Fig3. Clearing 10 Cars Load (cars/s)

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The load is varied from low (0.2 cars/s) to moderate (1 car/s) and high (2 cars/s). We can observe that the intelligent intersection consistently outperforms traffic lights at low and moderate loads by fairly good margins.

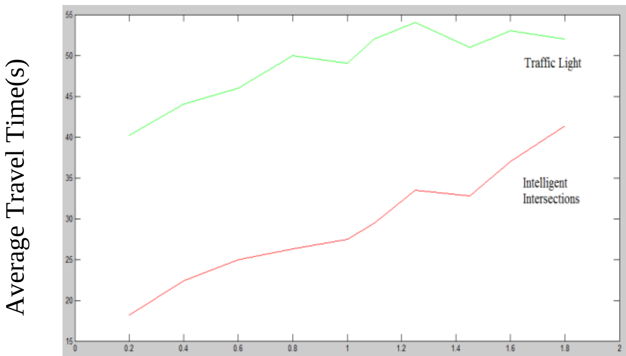

Fig. 4. Clearing 30 cars Load(cars/s)

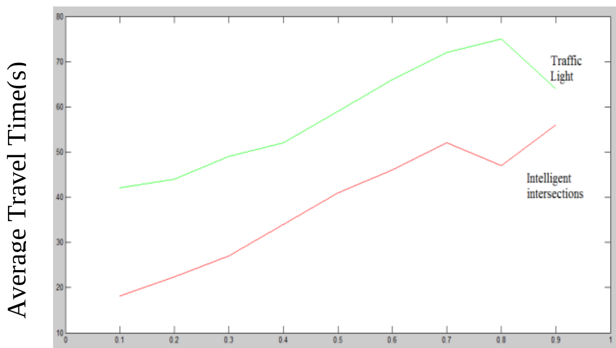

Fig. 5. Pesistent Traffic Load(cars/s)

This result suggests that a dynamic slot assignment mechanism outperforms a periodic service discipline as in traffic lights. For this same reason, a fully actuated traffic light may have performance at high loads, particularly, that is closer to the intelligent intersection.

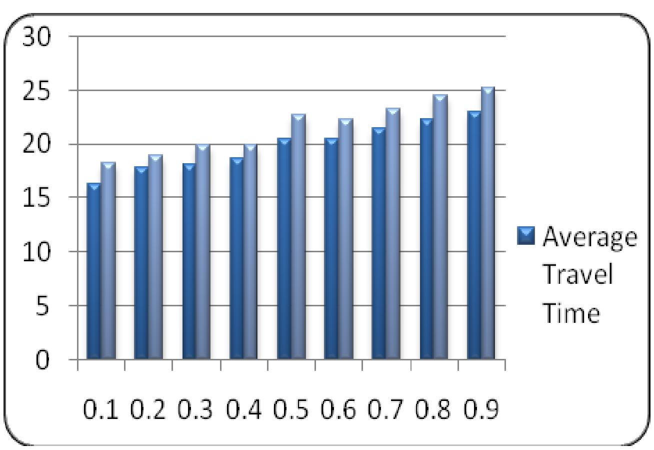

Fig. 6. Pesistent Traffic

The planning time index signifies the total travel time that should be planned when an adequate buffer time is included. The planning time index varies from the buffer index in that it includes typical delay as well as unexpected delay. Thus, the planning time index compares near-worst case travel time to a travel time in light or free-flow traffic.

VII. CONCLUSION

Technological advancements in in-vehicle sensing and computation, along with wireless networking of automobiles with other automobiles and the roadside infrastructure, and global positioning, are leading to automated vehicle systems. This paper has examined an significant safety application, i.e., intelligent intersections, that can also potentially provide better efficiency. Intelligent intersections are a representative of the class of complex distributed hybrid systems. It is important to ponder alternative designs that can provide guarantees against undesirable behavior of cars after they enter the intersection and approaches for system re-initialization by withdrawing time-slot assignments. Approaches described in this paper may also be useful in the design of other tractable complex distributed hybrid systems.

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