Facilitating Emergency Response Vehicles' Movement through a Road Segment in a Connected Vehicle Environment

Gaby Joe Hannoun, Pamela Murray-Tuite, Kevin Heaslip, Thidapat Chantem

***Abstract*— Emergency response vehicles' (ERVs) travel is risky, as non-ERV drivers are often unsure of the ERV's next maneuver and how to facilitate its movement. An integer linear program (ILP), introduced in this paper, facilitates the ERV's movement through a transportation link. Leveraging vehicle-to-vehicle communications, information is collected about vehicles on a link section. Then, the ILP finds the ERV's fastest intra-link path. To increase safety, the ILP assigns non-ERVs locations as far away from the ERV as possible while avoiding passing and weaving among vehicles. The ILP can be adapted to different ERV sizes, road types, surrounding conditions, etc. Sensitivity analysis indicated that scenarios with narrower road segments and higher numbers of non-ERVs led to ERV paths with lane changes and higher computation times. When compared to current practice requiring non-ERVs to move to the nearest road edge when an ERV with lights and sirens is noticed, the proposed formulation improved the ERV speed while reducing the conflicts and confusion experienced by downstream vehicles.**

***Index Terms*—Emergency services, integer linear program, intelligent transportation systems, connected vehicles**

I. INTRODUCTION

Emergency response vehicle (ERV) travel needs to be fast, which is difficult and potentially unsafe in congestion. Risky maneuvers and other drivers' responses to ERVs led to thousands of annual crashes [1] and hundreds of line-of-duty deaths [2]. First responders seek to arrive quickly to maximize their intervention's effectiveness. If firefighters arrive after the flashover (4 - 11 min after the fire starts), the response is likely to be unsuccessful [3]. High response times are most likely in urban areas during periods of heavy congestion. Drivers near the ERV path experience confusion [4] that limits the effectiveness of their efforts to facilitate the ERV's progress.

ERV movement could be facilitated on links and at intersections. ERV signal preemption has been implemented and continues to evolve. However, opportunities still exist to reduce confusion and ERV travel time on links.

This paper introduces an integer linear program (ILP) that leverages the connected vehicle environment. After collecting information about downstream vehicles (location and speed), this ILP finds the intra-link path that maximizes the ERV's speed and the free space around the ERV's path. Maneuvering instructions are incrementally disseminated to the ERV traveling through the link and to downstream vehicles requesting them to stop at specific positions along the link.

II. LITERATURE REVIEW

Aspects of emergency response, such as automatic crash notification [5-7], crash location, and routing [8-10], have improved with new technologies. The US Department of Transportation's RESCUME program enhances emergency activity [11] through staging guidance, advanced automatic crash notification, and ERV dynamic routing. Buchenscheit et al. [4] proposed a system to warn non-ERVs of an approaching ERV, relying on vehicle-to-vehicle (V2V) communications. Rizvi et al. [12] predicted if, when and where vehicles conflict with the ERV's path to send warnings. Huang et al. [13] developed a warning system using the DSRC protocol. Bratu et al.'s approach displays warning messages using Global System for Mobile communications modules on electronic boards along the ERV's path [14]. While these studies emphasized potential benefits of disseminating early warnings to vehicles that might encounter the ERV path, they do not provide the actions that non-ERVs should take.

ERV facilitation efforts can be divided into two categories: optimization (1) at intersections and (2) on links. Intersections are conflict locations. Some studies used communications to improve traffic operations at intersections in general (e.g., [15] and [16]). Others specifically addressed the ERVs' passage at intersections; reservation- [17], kinematic wave theory- ([18] and [19]), and distance-based [14] approaches have been proposed along with V2X technology use. For multiple intersections, Kamalanathsharma and Hancock [20] introduced a control system that adjusted ERV preemption at downstream intersections based on clearance times and queue lengths. More relevant to this research are studies making the ERV movement on a link safer, smoother and faster. Weinert and Düring [21] introduced a V2V application to provide a free lane, operationalizing the cooperative behavior developed by Düring and Pascheka [22]. Similarly, Toy et al.'s [23] approach moves platoons to provide space for the ERV. In these studies, the ERV path is assumed to be known by downstream vehicles, so the best ERV maneuvers are not dynamically adjusted based on downstream traffic conditions.

Yoo et al. [24] introduced a road reservation approach where non-ERVs received instructions to move away from the ERV path on the lower density lane. Likewise, Moussa's [25] cellular automata-based approach instructs non-ERVs positioned on a two-lane link to move away from the lower local density lane before pulling over, but without explicitly relying on V2X technologies. In this paper, the pulling-over of downstream non-ERVs is also considered but without assuming that the ERV is traveling on the lower density lane since the ERV may want to turn or stop on a specific lane for an incident. Thus, freeing the lowest density lane might not always be effective. The most closely related systems is

Manuscript received… Funding for this study was provided by NSF Grants 1544601 and 1618979 CPS: Synergy: Collaborative Research: Semi-Automated Emergency Response System, for which the authors are grateful. However, the authors remain solely responsible for the content.

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introduced by Djahel [26] who discussed only the vision (but no details) of communicating new driving policies (e.g., speed limit change) to vehicles downstream of an ERV.

The proposed system computes the optimal intra-link ERV path based on downstream conditions. It is not merely a warning system as it also optimizes the locations of downstream non-ERVs by instructing them where to stop. Although this paper only focuses on facilitating the passage of a single ERV along a link segment, it provides a platform for future extensions (e.g., the passage at intersections).

III. PROBLEM STATEMENT AND ASSUMPTIONS

A. Problem Statement

Given a directed link segment divided into identical cells (length *L* and width *W*) with $|J|$ non-ERVs traveling along this segment, find the set of cells constituting the ERV's path which provides the fastest passage while assigning each non-ERV to a specific cell based on its feasible stopping distance.

B. Roadway Discretization and Labeling

This study relies on a specific coding of the cells and vehicles (see Fig. 1). The x-axis represents forward motion while the y-axis represents lateral motion (e.g., lane changes). The number of lateral cells (*Y*) depends on the road's width, including shoulders and other traversable surfaces. Cells are labeled in the 'x' direction with 1 being closest to the ERV and increasing with longitudinal distance. In the 'y' direction, cells are labeled in ascending order from the right lane to the left. The non-ERVs are indexed by *j* which increases with the 'x' position. If two vehicles are located at the same 'x' position, they are labeled in ascending order from right to left. The ERV's speed and instruction variables are super-scripted by *i* since they are given at every increment *i*. An increment is a longitudinal distance (along the x-axis) that is equal to the ERV's longitudinal size (*N*) plus a buffer. Here, the buffer is 1 cell, so the increment encompasses (*N*+1) longitudinal units.

C. System Description

The non-ERVs of interest are located within an initial range (IR), which is at a pre-defined distance from the ERV, as shown in Fig. 2. This approach consists of collecting information from these non-ERVs and, after a time interval Δt (computation time), broadcasting the non-ERV assignment (final) locations. For negligible Δt's, non-ERVs travel a small distance that can be disregarded. Otherwise, their positions and speeds after Δt will be estimated since this formulation requires the non-ERV

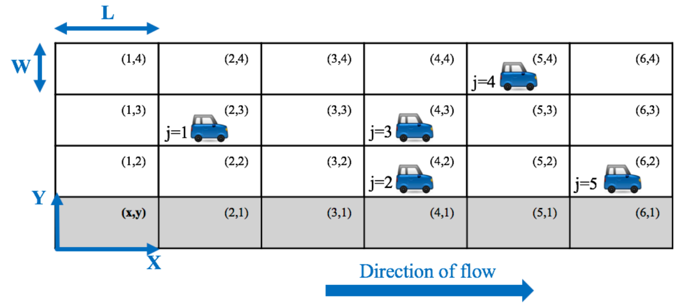

Fig. 1. Discretization of roadway network

locations (x'_j, y'_j) and speeds (σ_j) at the time they receive the message instructing them where to stop.

Each non-ERV should be assigned to a cell it can reach based on vehicle dynamics [27]. This observation forms the basis of how the feasible stopping range (FSR) for each non-ERV *j* is defined. The FSR of each vehicle *j* starts at a minimum final position (MFP_j) which is identified, using (1) and (2), based on *j*'s initial longitudinal index (x'_j) and its minimum stopping distance (MSD_j), in cells, that depends on its speed (σ_j), reaction time (t^r), and deceleration (δ_j). The length of each vehicle's FSR is *c* cells (*c* is also called the longitudinal FSR cutoff value). Constant and identical deceleration is assumed for all non-ERVs (this can be relaxed in the future). The 'ceil' function in (1) returns the next higher integer value.

$$MSD_j = ceil\left(\left(t^r\sigma_j + 0.5\frac{\sigma_j^2}{\delta_j}\right)/L\right) \quad (1)$$

$$MFP_j = x'_j + MSD_j \quad (2)$$

The optimization takes place on an assignment range (AR), downstream of the IR, that includes the FSR of each non-ERV. The AR has the same lateral size (*Y*) as the IR; however, its longitudinal size (*LL*) may be different. The AR's starting longitudinal location (AR_{start}) depends on where the first FSR (among all the non-ERVs) is located along the link. As Fig. 2 illustrates, the AR starts one increment before the smallest (MFP_j). Similarly, the AR's ending longitudinal location depends on where the last FSR is located along the link. The AR ends at or after the highest possible longitudinal final position (i.e., maximum $(MFP_j$ + c)). Hence, the AR's longitudinal size (*LL*) is a multiple of the ERV size plus buffer, to obtain an integer number of ERV instructions in the AR. For each vehicle *j*, the minimum final longitudinal index (x''_j) with respect to the start of the AR is computed using (3).

$$x''_j = MFP_j - AR_{start} + 1 \quad (3)$$

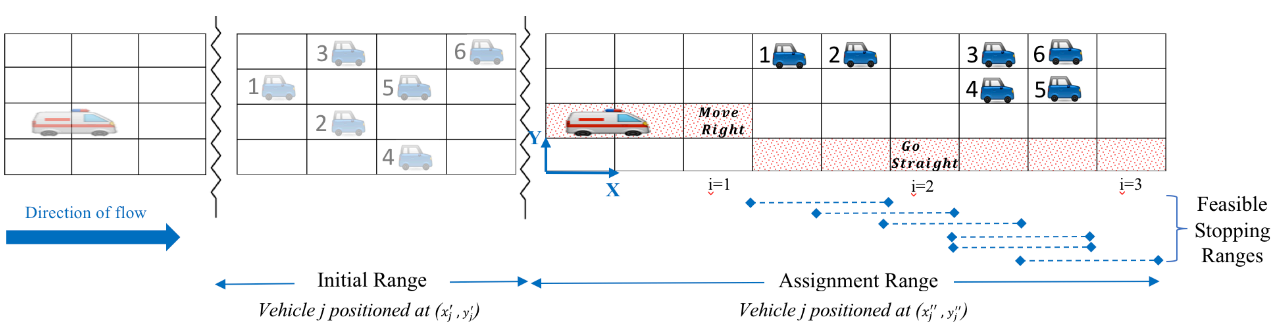

Fig. 2. Initial range, feasible stopping ranges, and assignment range

TABLE I
VARIABLE NOTATION

Notation	Type	Description
$w^{x,y}$	Binary	ERV assignment variable that takes the value 1 if ERV is assigned to cell (x, y), 0 otherwise (i.e. 1 if the cell is part of ERV's path during the time step)
s^i	Integer	ERV speed variable denoting the speed of the ERV at every increment *i*
$d_k^{i,y}$	Binary	ERV instruction variable that takes the value 1 if the ERV is given instruction *k* at increment $i < LL/(N+1)$, and lateral position y (k= 1 means move right, k= 2 means go straight, k= 3 means move left)
$v_j^{x,y}$	Binary	Non-ERV assignment variable that takes the value 1 if non-ERV *j* is assigned to cell (x, y) and 0 otherwise
s_{env}^i	Integer	ERV speed environment variable denoting the speed of the ERV only based on the ERV surrounding, computed at every increment i >1
s_{temp}^i	Integer	Temporary ERV speed variable denoting the speed of the ERV based on the ERV surrounding and previous instruction but without accounting for minimum and maximum speed, computed at every increment i >1
v^i	Binary	Variable that takes the value of 1 when $s_{temp}^i \geq S^{min}$ and 0 otherwise, where i >1

TABLE II
PARAMETER NOTATION

Notation	Default Value	Description
$\boldsymbol{L}, \boldsymbol{W}$	n/a	Length/width of a cell in longitudinal/lateral direction
$\boldsymbol{N}$	n/a	Number of longitudinal cells required to accommodate the ERV
$\boldsymbol{LL}, \boldsymbol{Y}$	n/a	Number of longitudinal/lateral cells in the AR
$\boldsymbol{AR_{start}}$	n/a	Distance (in cells) from the start of the Initial Range to the start of the Assignment Range
$\boldsymbol{t^r}, \boldsymbol{\sigma_j}, \boldsymbol{\delta_j}$	2.5 s, n/a, 5 fps^{-2}	Reaction time, initial speed in fps, and deceleration of vehicle j
$\boldsymbol{x'_j}, \boldsymbol{y'_j}$	n/a	Longitudinal index and lateral index of vehicle j in the IR
$\boldsymbol{b_{jj'}}$	Binary	Binary parameter that takes the value of 1 if $y'_j \geq y'_{j'}$, and 0 otherwise
$\boldsymbol{MSD_j}, \boldsymbol{MFP_j}$	n/a	Minimum stopping distance of vehicle j and minimum final position of vehicle j (in cells)
$\boldsymbol{x''_j}$	n/a	Minimum final longitudinal index of vehicle j in cells with respect to the start of the AR
$\boldsymbol{c}$	2	Longitudinal FSR cutoff value (in cells)
$\boldsymbol{S^{min}}, \boldsymbol{S^{free}}$	1, n/a	Minimum and maximum ERV speed (in speed stage)
$\boldsymbol{M}$	99999	Large number used to apply the Big M method

D. Assumptions

In the proposed model, it is assumed that the speed, position and other physical characteristics of the ERV and the non-ERVs are available as inputs (e.g., from the connected vehicle environment or machine vision). It is assumed that no additional vehicles enter or leave the section during the ERV's movement. We also assume that the ERV speed increases if a straight path is maintained while it decreases when the ERV performs a lane change, and that the speed depends on the non-ERV presence on cells adjacent to the ERV path (as discussed further near (26-31)). This paper is limited to a single ERV; for simplicity, ERVs are not indexed. Given the space limitation, this paper focuses on facilitating the ERV's passage along a link segment and intersections are not considered.

IV. MATHEMATICAL FORMULATION

This formulation improves on initial work with nonlinear components [28]. Decision variables and parameters are described in Tables I and II.

A. Objective Function

The objective function (4) maximizes the ERV's speed while traveling within a link and the number of free cells adjacent to its path. The (s^i) component is constrained by the previous instruction, the presence of surrounding non-ERVs during the last movement and the minimum and maximum ERV speeds. The (s_{env}^i) component is only constrained by the presence of surrounding non-ERVs. Maximizing the summation of (s_{env}^i) causes non-ERVs to be positioned further away from the ERV's path to increase safety from human errors. [If the summation of (s^i) were the only component of (4), the non-ERVs would be positioned as far as possible from the ERV path when the ERV maintains a straight path with a speed below the maximum (S^{free}).When the ERV changes lanes or when the speed cannot increase due to S^{free}, the non-ERVs are not guaranteed to provide the ERV path with unoccupied adjacent cells, even if it were physically possible.]

The ERV speed variables are discrete but cannot be considered in cells per unit time since a discrete speed increase or decrease within an increment (short distance) would result in unrealistic acceleration/deceleration. So, the ERV speed variables (s^i), (s_{env}^i) and (s_{temp}^i) are considered as integers and expressed in speed stages. Conversion from speed stage to speed (mph) depends on the ERV size (N), ERV acceleration/deceleration capabilities, and cell length (L) and is further discussed in the Appendix. Note that LL represents the longitudinal size of the AR and that (α_1) and (α_2) are the weights attributed to each term (see Section VI.A.9).

$$\text{Max}\, z = \alpha_1 \sum_{i=2}^{LL/(N+1)} s^i + \alpha_2 \sum_{i=2}^{LL/(N+1)} s_{env}^i \tag{4}$$

B. Constraints

The constraints ensure that the ERV motion, ERV instructions, and non-ERV's final positions are coordinated.

1) One vehicle per cell

Only one vehicle can occupy any given cell. At each cell (x, y), the sum of the ERV assignment variable ($w^{x,y}$) and all the non-ERV assignment variables ($v_j^{x,y}$) should be 0 or 1.

$$w^{x,y} + \sum_{j=1}^{J} v_j^{x,y} \leq 1; \ \forall(x,y) \quad (5)$$

2) Non-ERVs stop in the feasible stopping range

To reduce the conflict between vehicles and to improve the computation time, the feasible space to which each of the non-ERVs can be assigned is reduced by setting a longitudinal FSR cutoff value (c) beyond the minimum requirement. As indicated in (6), each non-ERV is assigned to one cell in its corresponding FSR (i.e., cells with a longitudinal index between x_j'' and $x_j'' + c$), while equation (7) ensures that each non-ERV is assigned to exactly one cell in the AR.

$$\sum_{x=x_j''}^{x_j''+c} \sum_{y=1}^{Y} v_j^{x,y} = 1; \ \forall j \quad (6)$$

$$\sum_{x=1}^{LL} \sum_{y=1}^{Y} v_j^{x,y} = 1; \ \forall j \quad (7)$$

3) No passing among non-ERVs

To reduce conflicts between vehicles, passing among non-ERVs is not allowed, as indicated in (8). If vehicle j is assigned to cell (x,y), vehicle j' which was initially located downstream of j in the IR cannot stop at a cell upstream of j in the AR (i.e., cannot stop at a cell with a longitudinal index $< x$). Note that M is a large number (equal to 99999 here) used to apply the Big M method that allows the linearization of the constraint.

$$\sum_{x'=1}^{x-1} \sum_{y=1}^{Y} v_{j'}^{x',y} \leq M(1 - \sum_{y=1}^{Y} v_j^{x,y}); \ \forall x \geq 2; \forall j' > j \quad (8)$$

4) No weaving among non-ERVs

Lateral conflicts (weaving) between vehicles are limited using (9-11). If vehicles j and j' are positioned on the same x index and j' is greater than j, according to the labeling, vehicle j' is on the left of vehicle j in the IR. If vehicle j is assigned to cell (x,y), vehicle j' can only stop on the left of or in front of j (i.e., at a cell with a lateral index $\geq y$), as indicated in (9).

$$\sum_{y'=1}^{y-1} \sum_{x=1}^{LL} v_{j'}^{x,y'} \leq M(|x_{j'}' - x_j'|) + M\left(1 - \sum_{x=1}^{LL} v_j^{x,y}\right); \ \forall y; \forall j' > j \quad (9)$$

If vehicles j and j' are not initially on the same x (i.e., j' is downstream of j) nor on the same y and if the final assignment places them on the same x, they should be laterally positioned in the same way as in the IR, as indicated in (10) and (11). Note that (y_j') is the initial lateral index of vehicle j in the IR. The binary parameter $(b_{jj'})$ takes the value of 1 when $(y_j' \geq y_{j'}')$ and 0 otherwise. For example, if vehicle j' is on the left of j in the IR (i.e., $y_{j'}' > y_j'$) then $(b_{jj'} = 0)$, and if vehicle j is assigned to cell (x,y) in the AR, vehicle j' can stop at a cell with the same longitudinal index x only if the lateral index is strictly greater than y. According to constraints (10), j' cannot stop on cells with longitudinal index x and lateral index less than y. (In this case (11) is not a binding constraint).

If vehicles j and j' have different longitudinal positions in the AR but the same lateral index y (i.e. $y_{j'}'=y_j'$), no lateral constraint is needed. If vehicle j' stops on the same final longitudinal index as j, it can either stop on the right or left of vehicle j (no preference). Otherwise, vehicle j' stops at a position downstream of j (due to the no passing constraint); in this case, the vehicles trajectories do not conflict.

$$(1 - b_{jj'}) \times \left(\sum_{y'=1}^{y-1} v_{j'}^{x,y'}\right) \times (|y_{j'}' - y_j'|) \leq M(1 - v_j^{x,y}); \quad \forall x; \forall y; \forall j' > j \quad (10)$$

$$(b_{jj'}) \times \left(\sum_{y'=y+1}^{Y} v_{j'}^{x,y'}\right) \times (|y_{j'}' - y_j'|) \leq M(1 - v_j^{x,y}); \quad \forall x; \forall y; \forall j' > j \quad (11)$$

5) ERV passing lane

A minimum of one empty cell at every x is reserved for the ERV, as shown in (12).

$$\sum_{y=1}^{Y} \sum_{j=1}^{J} v_j^{x,y} \leq Y - 1; \ \forall x \quad (12)$$

6) ERV instruction constraints

Only one set of instructions is sent to the ERV at each increment $i < LL/(N+1)$, as indicated in (13).

$$\sum_{y=1}^{Y} \sum_{k=1}^{3} d_k^{i,y} = 1; \ \forall \ i = 1, \ldots, LL/(N+1) - 1 \quad (13)$$

The ERV cannot move in a direction if no cell is available in that direction. This is reflected in (14) for 'Move Right' or k=1 and in (15) for the 'Move left' or k=3 instruction.

$$d_1^{i,1} = 0; \ \forall i \quad (14)$$

$$d_3^{i,Y} = 0; \ \forall i \quad (15)$$

7) The relationship between ERV assignment and ERV instruction variables

The ERV's continuous longitudinal motion is ensured by (16). Constraints (17-22) link the ERV assignment and ERV instruction variables and ensure continuous lateral motion. For example, if the ERV occupies a cell $(x = i(N+1), y)$ and is instructed to move to the right lane at this cell then $(w^{i(N+1),y} = 1)$ and $(d_1^{i,y}=1)$. Using (17) and (18), the ERV assignment variable of each of the $(N+1)$ downstream cells with lateral index $(y-1)$ will be set to 1. Similarly, when the 'Go straight' or 'Move left' instructions are applied, the ERV assignment variables of the corresponding cells are set to 1.

$$\sum_{y=1}^{Y} w^{x,y} = 1; \ \forall x \quad (16)$$

$$d_1^{i,y} \leq \frac{w^{i(N+1),y} + w^{i(N+1)+t,y-1}}{2}; \quad \forall i = 1, \ldots, LL/(N+1) - 1; \ \forall t = 1,2, \ldots, N+1; \ \forall y > 1 \quad (17)$$

$$d_1^{i,y} \geq w^{i(N+1),y} + w^{i(N+1)+t,y-1} - 1; \quad \forall i = 1, \ldots, LL/(N+1) - 1; \ \forall t = 1,2, \ldots, N+1; \ \forall y > 1 \quad (18)$$

$$d_2^{i,y} \leq \frac{w^{i(N+1),y} + w^{i(N+1)+t,y}}{2}; \quad \forall i = 1, \ldots, LL/(N+1) - 1; \ \forall t = 1,2, \ldots, N+1; \ \forall y \quad (19)$$

$$d_2^{i,y} \geq w^{i(N+1),y} + w^{i(N+1)+t,y} - 1; \quad \forall i = 1, \ldots, LL/(N+1) - 1; \ \forall t = 1,2, \ldots, N+1; \ \forall y \quad (20)$$

$$d_3^{i,y} \leq \frac{w^{i(N+1),y} + w^{i(N+1)+t,y+1}}{2}; \quad \forall i = 1, \ldots, LL/(N+1) - 1; \ \forall t = 1,2, \ldots, N+1; \ \forall y < Y \quad (21)$$

$$d_3^{i,y} \geq w^{i(N+1),y} + w^{i(N+1)+t,y+1} - 1; \quad \forall i = 1, \ldots, LL/(N+1) - 1; \ \forall t = 1,2, \ldots, N+1; \ \forall y < Y \quad (22)$$

8) The relationship between ERV instructions and non-ERV assignment variables

Constraints (23-25) ensure that cells which are part of the ERV's path are empty and not occupied by non-ERVs. For forward motion (23), it is assumed that the ERV needs $(N+1)$ cells in the same y open. Thus, when $(d_2^{i,y})$ is equal to 1 (i.e., ERV instructed to 'Go straight'), the sum of all the non-ERV assignment variables of the cells with a longitudinal index between $(x+1)$ and $(x+(N+1))$ and lateral index y should be equal to 0. For lane changing (24) and (25), the ERV is assumed to need (N) forward cells in the same y to be able to maneuver and move to the adjacent lane in which $(N+1)$ forward cells are free.

$$\sum_{x=t'}^{T'}\sum_{j=1}^{J} v_j^{x,y} \le M\left(1-d_2^{i,y}\right); \qquad \forall y; \forall i = 1, \dots, LL/(N+1)-1;$$
$$t' = (N+1)i+1; T'=(N+1)i+(N+1) \quad (23)$$

$$\sum_{x=t'}^{T''}\sum_{j=1}^{J} v_j^{x,y} + \sum_{x=t'}^{T'}\sum_{j=1}^{J} v_j^{x,y-1} \le M\left(1-d_1^{i,y}\right); \qquad \forall y > 1;$$
$$\forall i = 1, \dots, LL/(N+1)-1; t' = (N+1)i+1;$$
$$T'=(N+1)i+(N+1); T''=(N+1)i+N \quad (24)$$

$$\sum_{x=t'}^{T''}\sum_{j=1}^{J} v_j^{x,y} + \sum_{x=t'}^{T'}\sum_{j=1}^{J} v_j^{x,y+1} \le M\left(1-d_3^{i,y}\right); \qquad \forall y < Y;$$
$$\forall i = 1, \dots, LL/(N+1)-1; t' = (N+1)i+1;$$
$$T'=(N+1)i+(N+1); T''=(N+1)i+N \quad (25)$$

9) *ERV Speed Constraints*

In this formulation, three speed variables are used (s^i, s_{env}^i and s_{temp}^i). To determine the ERV speed (s^{i+1}) at increment $(i+1)$, (s_{env}^{i+1}) and (s_{temp}^{i+1}) are first identified based on the ERV speed (s^i) at the previous increment (i).

While traveling, the ERV adjusts its speed based on its surroundings. A free side (no non-ERVs) enables the ERV to increase its speed while occupied sides make its movement slower. As shown in (26-31), a speed (s_{env}^i) is assigned at each increment and is only constrained by the number of nearby stopped vehicles. The summation of (s_{env}^i) is maximized in (4) to ensure that the non-ERVs are positioned as far as possible from the ERV path when the ERV is performing a lane change or when the ERV speed is at the maximum (S^{free}).

If the ERV is in a middle lane (26-27), and its right and left downstream cells are unoccupied, the ERV can increase its speed by 1. If one side is occupied, the speed can remain constant. If both sides are occupied, the ERV's speed decreases by 1. If the ERV is positioned in the rightmost lane $(y=1)$ (28-29) and its left side is unoccupied, the ERV speed can increase by 1. Otherwise, the speed remains constant. Constraints (30-31) present the analogous situation for the ERV positioned in the leftmost lane $(y=Y)$.

Separate constraints (27), (29) and (31) were introduced for the last increment $(i = LL/(N+1))$ due to the end of the AR that limits the ERV surrounding space affecting the ERV speed environment after the last movement ($s_{env}^{LL/(N+1)}$).

$$s_{env}^{i+1} \le s^i + 1 - \sum_{j=1}^{J} v_j^{(N+1)i+t,y-1} - \sum_{j=1}^{J} v_j^{(N+1)i+t,y+1} + M\left(1-w^{(N+1)i+t,y}\right);$$
$$\forall i = 1, \dots, LL/(N+1)-2;$$
$$\forall t = 0,1, \dots, N+2; \forall y = 2,3, \dots, Y-1 \quad (26)$$

$$s_{env}^{LL/(N+1)} \le s^{LL/(N+1)-1} + 1 - \sum_{j=1}^{J} v_j^{LL-(N+1)+t,y-1} - \sum_{j=1}^{J} v_j^{LL-(N+1)+t,y+1}$$
$$+M\left(1-w^{LL-(N+1)+t,y}\right);$$
$$\forall t = 0,1, \dots, N+1; \forall y = 2,3, \dots, Y-1 \quad (27)$$

$$s_{env}^{i+1} \le s^i + 1 - \sum_{j=1}^{J} v_j^{(N+1)i+t,2} + M\left(1-w^{(N+1)i+t,1}\right);$$
$$\forall i = 1, \dots, LL/(N+1)-2; \forall t = 0,1, \dots, N+2 \quad (28)$$

$$s_{env}^{LL/(N+1)} \le s^{LL/(N+1)-1} + 1 - \sum_{j=1}^{J} v_j^{LL-(N+1)+t,2} + M\left(1-w^{LL-(N+1)+t,1}\right);$$
$$\forall t = 0,1, \dots, N+1 \quad (29)$$

$$s_{env}^{i+1} \le s^i + 1 - \sum_{j=1}^{J} v_j^{(N+1)i+t,Y-1} + M\left(1-w^{(N+1)i+t,Y}\right);$$
$$\forall i = 1, \dots, LL/(N+1)-2; \forall t = 0,1, \dots, N+2 \quad (30)$$

$$s_{env}^{LL/(N+1)} \le s^{LL/(N+1)-1} + 1 - \sum_{j=1}^{J} v_j^{LL-(N+1)+t,Y-1} + M\left(1-w^{LL-(N+1)+t,Y}\right);$$
$$\forall t = 0,1, \dots, N+1 \quad (31)$$

A temporary variable (s_{temp}^i) is assigned at each increment and is constrained by the surrounding conditions (32) and the instruction given at the previous increment (33). The assumption is that the ERV can increase its speed by 1 if it is going straight. However, if it moves right or left, its speed decreases by 1.

$$s_{temp}^{i+1} \le s_{env}^{i+1}; \quad \forall i = 1, \dots, LL/(N+1)-1 \quad (32)$$

$$s_{temp}^{i+1} \le s^i + 2\sum_{y=1}^{Y} d_2^{i,y} - 1; \quad \forall i = 1, \dots, LL/(N+1)-1 \quad (33)$$

The ERV speed (s^{i+1}) is the actual speed that can be adopted by the ERV and is limited by the maximum allowable ERV speed (S^{free}), as shown in (34).

$$s^{i+1} \le S^{free}; \quad \forall i = 1, \dots, LL/(N+1)-1 \quad (34)$$

Since the speed of the ERV (s^{i+1}) cannot decrease below the minimum speed (S^{min}), s^{i+1} should be equal to the minimum of s_{env}^{i+1} and $s^i + (instruction\ factor)$ if their minimum is greater than S^{min}. Otherwise, s^{i+1} should take the value of S^{min}. In other words, s^{i+1} should be equal to the maximum of (S^{min}) and (s_{temp}^{i+1}), as reflected in (35-38). Note that (s_{temp}^{i+1}) is primarily introduced for practical purposes, as a temporary ERV speed variable taking the minimum of s_{env}^{i+1} and $s^i + (instruction\ factor)$ (i.e., right hand side of (33)).

$$s^{i+1} \ge S^{min}; \quad \forall i = 1, \dots, LL/(N+1)-1 \quad (35)$$
$$s^{i+1} \ge s_{temp}^{i+1}; \quad \forall i = 1, \dots, LL/(N+1)-1 \quad (36)$$
$$s^{i+1} \le M(1-v^{i+1}) + s_{temp}^{i+1}; \quad \forall i = 1, \dots, LL/(N+1)-1 \quad (37)$$
$$s^{i+1} \le Mv^{i+1} + S^{min}; \quad \forall i = 1, \dots, LL/(N+1)-1 \quad (38)$$

10) *Binary, integer and initial conditions constraints*

Based on the variables' type, integer and binary constraints are added along with constraints indicating the ERV's initial lateral position and speed at the beginning of the AR.

V. DESCRIPTION OF THE EXPERIMENT

The experimental analysis has two parts: sensitivity to initial parameters and comparison to current practice. The cell size is the regular vehicle size plus buffers (*L*= 21 feet and *W*=10 feet).

A. *Sensitivity analysis*

For each test, a given parameter is varied while fixing the other parameters to default values shown in Table III. The six base scenarios are described by road and ERV type: Arterial/Ambulance, Major Collector/Ambulance, Minor Collector/Ambulance, Arterial/Police, Major Collector/Police, Minor Collector/ Police. Speed limits are 55, 35, and 25 mph, and the number of lateral cells *Y* is 5, 4, and 3 for arterials,

TABLE III
BASE CASE SCENARIOS PARAMETERS AND RESULTING ERV PATH DESCRIPTION

ERV size	Road type	ERV initial speed (stage)	ERV initial lateral index	Road composition	Number of non-ERVs	Non-ERV initial position	Non-ERV speed (mph)
Ambulance (N=2 cells)	Arterial	8	3	1 shoulder and 4 lanes	15	Dispersed	Homogenous =40
	Major collector	4	3	1 shoulder and 3 lanes			Homogenous =30
	Minor collector	3	2	1 shoulder and 2 lanes			Homogenous =20
Police car (N=1 cells)	Arterial	6	3	1 shoulder and 4 lanes			Homogenous =40
	Major collector	3	3	1 shoulder and 3 lanes			Homogenous =30
	Minor collector	2	2	1 shoulder and 2 lanes			Homogenous =20

major collectors, and minor collectors, respectively. The ERV minimum speed is five mph while its maximum speed is ten mph above the speed limit. The speeds in mph are converted to the corresponding ERV stage based on the ERV type. (A sample speed-stage table is in the Appendix).

In the base scenarios, the ERV's initial speed stage is in the middle of its range; the ERV is positioned on the middle lane and roads have only a right shoulder. The IR is ten cells (210 feet) long. For each base scenario, equal weights ($\alpha_1 = \alpha_2 = 1$) are assigned in the objective function.

B. Comparison to local practice

The formulation's output is compared to the one obtained from the local practice "Go to the nearest edge" (rightmost or leftmost lane). Seven tests are executed: six for the base scenarios and one test with an ambulance positioned initially on the rightmost lane of a Major Collector.

VI. EXPERIMENTAL ANALYSIS

The tests were executed using the CPLEX solver on the NEOS server (with CPU at 2.2-2.8 GHz and 64-192 GB RAM) [29-31]. CPLEX uses the branch-and-bound technique to optimize integer programs. In this formulation, the number of variables and constraints varies with the number and speeds of non-ERVs, the ERV size, and the AR's length and geometry.

A. Sensitivity Analysis

1) ERV initial position

The ERV initial lateral position in the AR varies between y=1 and y=Y. As shown in Fig. 3, when traveling on the widest tested road type (arterial), the ERV's initial position does not affect the ERV speed. A straight movement, allowing a linear speed increase, results since the side(s) of the ERV can be free at all times. For narrower links (major or minor collectors), if positioned on an edge, the ERV maintains a straight path and the speed increases until reaching a plateau at S^{free}. If positioned on a middle lane, the ERV either continues straight or moves to one of the edge lanes. Even though a lane change decreases the ERV speed, it can improve the objective function value, as travelling on an edge necessitates freeing fewer cells to allow a speed increase than traveling on a middle lane. The narrower the link, the earlier the ERV changes to an edge lane.

2) ERV initial speed

The minimum and maximum ERV speed stages change with the ERV size and road type. This test varies the ERV initial speed between the corresponding minimum and maximum allowable ERV speeds. *On arterials*, for all initial speeds, the ERV maintains a straight path and increases its speed until reaching the maximum speed (S^{free}). This means both sides of the ERV can be freed at all downstream cells. When the ERV

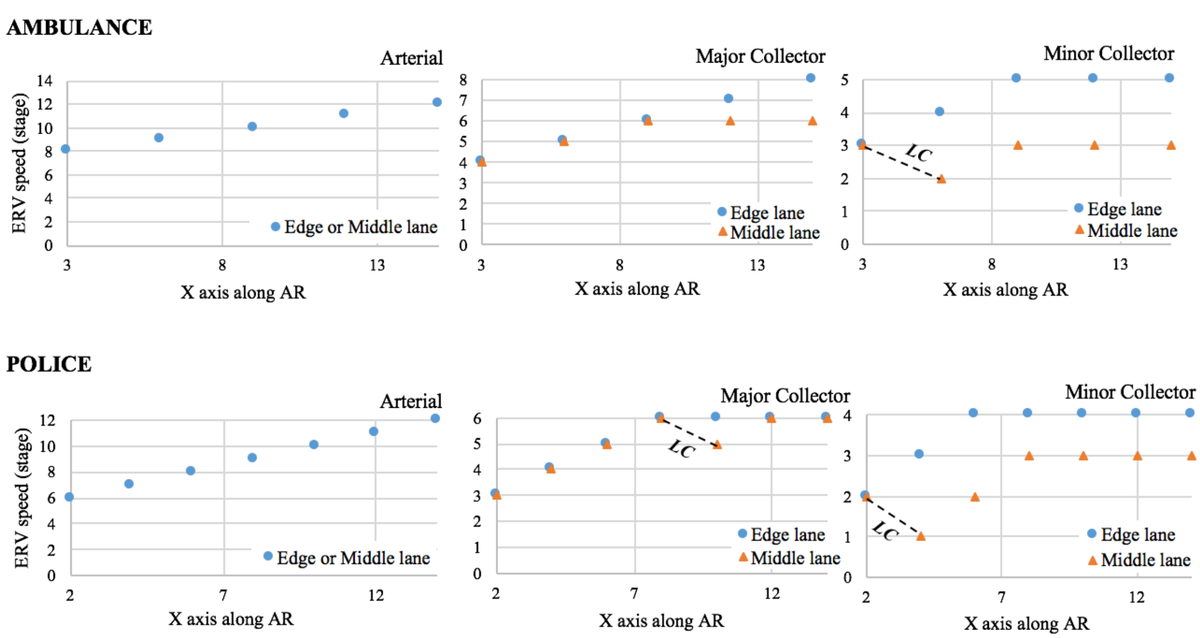

Fig. 3. Variation of ERV speed in the AR with different ERV initial positions (per road type and ERV size). LC refers to "Lane Change", so charts without "LC" indications represent a straight ERV path

speed is initially s^{free}, it remains constant. On *major collectors*, when the initial speed is less than s^{free}, the ambulance maintains a straight movement and the speed increases until reaching a plateau due to the presence of non-ERVs on one of its sides. For the scenario with maximum initial speed, the ambulance "moving to the closest edge" and "maintaining a straight path and constant speed" are alternate optimal solutions. At all initial speeds, police cars move to the closest edge when "maintaining a straight path" will not result in a speed increase due to the presence of non-ERVs on the side of the ERV path. Moving to the nearest edge is preferred to "maintaining a straight path" due to the s^i_{env} term in the objective function (see also Section VI.A.9). On *minor collectors*, and in all scenarios, both ERV types move to the nearest edge at the beginning of the AR. Once there, the speed increases until non-ERVs on cells adjacent to the ERV path force the speed to remain constant.

3) Road composition

Different road compositions dictate different non-ERV IR lateral positions since they are not initially on shoulders. A link with 4 lateral cells has 3 lanes and 1 shoulder or 2 lanes and 2 shoulders. With 3 lanes and 1 shoulder, non-ERVs are more dispersed. For different compositions with the same number of lateral cells, the same objective value, ERV path, ERV speed and non-ERV assignment (or alternate optimum) are obtained. In the tested scenarios, the output is insensitive to road composition for a given number of non-ERVs.

4) ERV size

Size affects the number of instructions and maneuvers that can be made in a given AR. Smaller ERVs can make more maneuvers, allowing them to achieve more speed increases.

5) Number of non-ERVs

To evaluate congestion effects, the base scenarios are tested with 10, 15 and 20 non-ERVs. When the ERV is traveling on an arterial, the output is insensitive to the tested increase in non-ERVs. The ERV follows the same straight path with free adjacent cells on both sides along the AR. With these demands, on arterials, the link is wide enough to free both sides of the ERV even with 20 non-ERVs in the AR. For narrower links, as the number of non-ERVs increases, the ERV speeds are reduced due to the positioning of non-ERVs on adjacent cells, and the ERV path involves lane changes.

6) Non-ERV initial position

For each ERV size and road type, three non-ERV initial positions are tested: dispersed, clustered at the beginning, and clustered at the end of the IR. Dispersed non-ERVs resulted in higher ERV speeds along the AR than the scenarios with initially clustered positions, for all road types and ERV sizes. With dispersed non-ERVs and homogenous speeds, the FSRs of the non-ERVs are dispersed in the AR allowing more effective use of the AR space and free ERV path sides.

With dispersed non-ERVs, the model positions the non-ERVs as far downstream as possible to allow the ERV to increase its speed before being forced to remain constant. When non-ERVs are clustered at the end of the IR, the non-ERVs' FSRs are located toward the end of the AR. This is why (1) the scenario with non-ERV positions clustered at the end of the IR and the scenario with dispersed non-ERVs led to close results and (2) clustering non-ERVs at the end of the IR resulted in better ERV speeds than when they are clustered at the beginning, for all road types and ERV sizes. To improve the output for non-ERVs clustered at the beginning of the IR, the longitudinal FSR cutoff value (c) could be increased.

7) Heterogeneous Non-ERV speed

In all previous tests, the non-ERV speeds are homogenous, and the longitudinal FSR cutoff default value (c) is 2 cells beyond the minimum final longitudinal index ($x_j^{\prime\prime}$). When random speeds are assigned to non-ERVs and c is 2, the formulation did not result in a feasible solution for all tested scenarios. For instance, suppose vehicle *j'* is downstream of vehicle *j*. Vehicle *j*, travelling with a higher speed, has a more downstream FSR than vehicle *j'* travelling at a lower speed. Since the formulation ensures that each vehicle is assigned to a cell within its corresponding FSR and passing is not allowed, no feasible solution is generated because the FSR of *j'* ends before the start of the FSR of *j*. A larger c value extends the FSRs and allows vehicle *j'* to travel to a cell at the same or higher longitudinal index than the final position of vehicle *j*, resulting in a feasible solution.

On arterials (for both ERV sizes), c should increase from 2 to 22, while on major collectors it should be extended to 11 to obtain a feasible solution. On minor collectors, no adjustment is needed. As the link type gets narrower, the variance of the non-ERVs speeds gets smaller resulting in closer FSRs and less need for cutoff value extensions.

With homogenous non-ERV speeds, higher ERV speeds can be achieved since the AR space can be used effectively. With random speeds, some cells in the AR cannot be occupied by any non-ERVs since the cells are not in their FSRs.

8) Computation time

The average computation times increase as the road type becomes narrower, going from arterial (0.22 s) to major collector (0.24 s) to minor collector (0.32 s). As the road gets narrower (with fewer lateral cells and variables), the search for the optimal ERV path becomes more challenging given that the number of non-ERVs remains the same. If the ERV is initially positioned on middle lanes, it likely moves to an edge on narrower roads. Paths that include lane changes result in higher average computation times (0.34 s) than straight paths (0.21 s). When changing lanes, more downstream cells have to be freed to perform the maneuver, activating more constraints.

As the number of non-ERVs increases (10 - 20), the average computation time increases (0.33 - 1.33 s) due to the increased number of variables. In addition, with more congestion,

TABLE IV
LIMITING SCENARIOS INPUT/OUTPUT DATA

	Test 1	Test 2
Input		
Road type	Arterial	
ERV Size	Ambulance	
Number of non-ERVs	50	75
IR Longitudinal size	27 cells = 567 feet	43 cells = 903 feet
Output		
AR Longitudinal size	33 cells = 693 feet	48 cells = 10008 feet
Computation time	25.42 s	140.6 s

right/left ERV maneuvers become more likely. Thus, the computation time is sensitive to the number of non-ERVs.

To examine the implications that further increases in the IR size and number of non-ERVs have on the computation times, the tests shown in Table IV were executed. The computation time obtained in Test 2 is relatively high (more than 2 minutes) given that the non-ERV speeds are homogenous and the non-ERVs are dispersed in the IR (see above). In Test 1, if the non-ERVs are traveling at a homogenous speed of 40 mph at the time of data collection, after the computation time of 25.42 s, they would have traveled approximately 1500 ft. The initially retrieved non-ERV positions should be adjusted to reflect the location at which the non-EVRs receive the assignments.

9) *Objective Function Weight Analysis*

The objective function is the summation of two elements with the same units. Initially, equal weights ($\alpha_1 = \alpha_2 = 1$) were assigned. To evaluate the impact that weight combinations have on the output, the six base scenarios were tested with the weights: ($\alpha_1 = 2, \alpha_2 = 1$); ($\alpha_1 = 1, \alpha_2 = 1$); ($\alpha_1 = 1, \alpha_2 = 2$).

As shown in Table V, on *arterials*, the same ERV straight paths were observed since there is enough space to achieve the highest values of s^i and s^i_{env}. On *minor collectors*, due to limited space, moving to the edge is better; even if s^i decreases at the increment after the lane change, s^i and s^i_{env} will then be able to reach higher values by freeing one side of the ERV while, if the ERV remains on the middle lane and one side is free, the s^i_{env} and subsequently s^i values will not increase. On *major collectors*, with the different weight sets, different outputs were obtained. As more weight is attributed to element (1) ($\alpha_1 > \alpha_2$), a straight path results. However, as more weight is given to element (2) ($\alpha_2 > \alpha_1$), a lane change (to the edge) that can achieve higher s^i_{env} occurs. Equal weights once generated a solution like weight set (1) and once like weight set (3). This unbiased weight set was used in the sensitivity analysis tests. Selecting weights is subjective. If keeping the ERV further away from non-ERVs is preferred, more weight should be assigned to element (2) in the objective function.

B. *Comparison to local practices*

Local practices attempt to reduce confusion by providing simple rules, such as stopping at the nearest edge when an ERV approaches [32]. Passing and weaving between vehicles may occur as each driver acts independently. To compare the ERV path and speeds that could be generated with the local practice "Go to the nearest edge" and the solution generated by the proposed formulation, the six base scenarios are tested with both approaches. On arterials, the ERV paths and speeds were identical. Even though no speed benefits are observed on arterials, this formulation could eliminate confusion, as well as passing and weaving among vehicles, improving their safety.

When traveling along a major or minor collector, the speed benefits of the proposed formulation are substantial. For local practice, due to the positioning of non-ERVs along the edges, and as the road becomes narrower, the ERV (initially positioned on a middle lane) travels on cells that have adjacent occupied cells, resulting in a speed plateau or decrease. However, the proposed model pushes the non-ERVs away from the ERV, to allow the ERV's speed to increase. When non-ERVs are positioned according to the formulation, the ERV reaches greater speeds at the end of the AR (Table VI).

TABLE VI
FINAL SPEEDS FOR LOCAL PRACTICE VS FORMULATION

	Major Collector		**Minor Collector**	
Speeds (in stage)	Ambulance	Police car	Ambulance	Police car
Initial speed	4	3	3	2
Final speed (local practice)	4	3	1	1
Final speed (formulation)	6	6	3	3

In a scenario in which an ambulance is initially positioned on the right edge of a major collector, under local practice, non-ERV drivers may move to the edge before identifying the lane on which the ERV is traveling. The ERV may be forced to change lanes to avoid the non-ERVs on the same lane. As shown in Fig. 4, using the proposed formulation, the final non-ERV positions are optimized and the ERV remains on the same lane, increases its speed and reaches the maximum allowed speed. In this scenario, the ERV needs 4.54 seconds to travel the 252-feet link segment (average speed of 37.85 mph) in which the non-ERVs' final positions are optimized while it needs 6.78 seconds to travel the same link segment when the non-ERVs stop at the nearest edge (average ERV speed of 25.34 mph). This travel time improvement on a relatively short segment (252 feet) is promising. As a link becomes narrower, shorter travel times are observed when using the proposed formulation. Specifically, the travel time improvements observed when an ambulance is initially positioned on the right edge of a minor collector are more significant; the average ERV speed with optimized non-ERV positions is 31.94 mph compared to ERV speed of 7.48 mph when non-ERV positions are not optimized. Additional figures are available from the authors upon request. Travel time improvements for larger transportation link segments will be discussed in future research as strategies will be adopted to control the timing overhead resulting from the increase in the problem size.

TABLE V
OBJECTIVE FUNCTION WEIGHT ANALYSIS RESULTS

<table>
<tr><th colspan="9">Base case scenarios</th></tr>
<tr><th colspan="3">Weights</th><th colspan="3">Ambulance</th><th colspan="3">Police car</th></tr>
<tr><th>Weight set</th><th>α_1</th><th>α_2</th><th>Arterial</th><th>Major Collector</th><th>Minor Collector</th><th>Arterial</th><th>Major Collector</th><th>Minor Collector</th></tr>
<tr><td>(1)</td><td>2</td><td>1</td><td rowspan="3">Straight ERV path</td><td rowspan="2">Straight ERV path</td><td rowspan="3">Lane change in ERV path</td><td rowspan="3">Straight ERV path</td><td>Straight ERV path</td><td rowspan="3">Lane change in ERV path</td></tr>
<tr><td>(2)</td><td>1</td><td>1</td><td rowspan="2">Lane change in ERV path</td></tr>
<tr><td>(3)</td><td>1</td><td>2</td><td>Lane change in ERV path</td></tr>
</table>

MAJOR COLLECTOR

LOCAL PRACTICE

Position					v1	v3	v4	v6	v7	v9	v10	v12	v13	v15	
				ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV
	ERV	ERV	ERV			v2		v5		v8		v11		v14	
Speed			4			3			3			3			3

PROPOSED FORMULATION

Position				v1	v3	v4			v6		v9	v10	v12	v13	v15
					v2		v5			v7	v8		v11		v14
	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV	ERV
Speed			4			5			6			7			8

Fig. 4. Variation of ERV speed in the AR with different practices (Major Collector/Ambulance)

VII. SUMMARY AND CONCLUSIONS

This paper presented an ILP to assist an ERV by delineating its intra-link path and providing maneuvering instructions at every increment. It limits the confusion experienced by non-ERVs by assigning each of them a position along the link depending on the non-ERV's feasible stopping distance. The ILP's objective is to maximize the ERV's speed and the free space surrounding its path. The program can adapt to various ERV characteristics, road types and other parameters.

A sensitivity analysis was conducted to evaluate the impact of varying the main parameters on the output and computation time. On narrower roads, as the number of non-ERVs increased and they were more clustered, the ERV's speed was less likely to increase, and its path involved a lane change in cases when the ERV was initially positioned on a middle lane. Given the same AR length, scenarios with a narrower road, a larger number of clustered non-ERVs and whose output ERV path involved lane changes required longer computation times. Yet, the computation times were small in the examined scenarios with an average of 0.46 s (for an AR 15 cells long for ERV size =2 and 14 cells long for ERV size =1) and were the most sensitive to the number of non-ERVs. If non-ERVs have random speeds, larger longitudinal FSR cutoff values may be required to obtain a feasible solution. The proposed formulation generated higher ERV speeds than current practice requiring non-ERVs to move to the nearest edge, especially when the link is narrow and in scenarios where the ERV is initially on an edge. On wide links, current practice and this formulation led to the same results. The advantages of the ILP, in this case, are reduced confusion, passing/weaving among vehicles, and other safety issues.

In the future, this ILP will be extended to a complete link (multiple segments) and intersections. With the initial benefits on a small segment, more notable travel time savings are anticipated over the complete journey. In addition, some assumptions will be relaxed, and simulations will be used to for further evaluation and to test market penetration levels.

APPENDIX

In this mathematical formulation, the ERV speed variables are integers expressed in speed stages and not in units of distance per time. Based on our approach, the ERV speed can either increase or decrease within an increment (fixed, short distance). If the speed were expressed in units of distance per time with continuous values, maintaining a straight path with free adjacent cells when traveling at lower speeds would be prioritized compared to travelling at higher speeds. (When traveling at lower speeds, the ERV requires a longer time to travel a fixed distance. If it were accelerating with a uniform magnitude for a longer time, a greater speed change would result, and thus a greater improvement to the objective function, compared to what would result from higher speeds.) To assign the same priority to all ERV speeds, we assume that the ERV speed variables can increase or decrease by one unit within an increment and hence take integer values. Furthermore, if the ERV speeds variables were expressed in one of the common units of speeds (such as mph, ft/sec and km/h), to achieve an increase or decrease of X units of speed within an increment (short distance), unrealistic accelerations and decelerations would arise (very small or very large magnitudes depending on X, the unit of speed adopted, and the initial ERV speed). This is the second reason why the ERV speed variables are expressed in speed stages and may increase or decrease by one unit within an increment. Moving to a higher stage means increasing the speed but with a practical acceleration. To identify the ERV speed in distance per time at each speed stage, a preprocessing step that consists of developing a lookup table corresponding to each ERV type and road type is executed as follows: First, the following parameters are identified: (1) minimum and maximum allowable ERV speeds based on the roadway type and the ERV type, (2) cell length L, (3) ERV longitudinal size N (in cells), and (4) ERV acceleration capabilities a. Second, the speed (in distance per time) corresponding to each stage is computed. The speed at stage 1 is simply the minimum allowable ERV speed. The speed at stage g (g>1) is computed as follows:

- Find the time t needed to travel the distance $d = (N + 1) \times L$ with an initial speed V_i (the speed at stage g-1) and acceleration a: $d = V_i t + \frac{1}{2} a t^2$.
- Find V_f (the speed at stage g) after the elapsed time t: $V_f = V_i + at$.

Third, stages are added until reaching the maximum.

	ERV speed		Road type		
	stage	**mph**	**Arterial**	**Major Collector**	**Minor Collector**
ERV type: Ambulance (N=2)	1	5.00	min speed	min speed	min speed
	2	17.83			
	3	24.71			mid speed
	4	30.06		mid speed	
	5	34.59			max speed
	6	38.59			
	7	42.22			
	8	45.55	mid speed	max sped	
	9	48.66			
	10	51.58			
	11	54.35			
	12	56.98			
	13	59.49			
	14	61.91			
	15	64.23			
	16	66.47	max speed		

**mid ERV speed: initial ERV speed in base case scenarios*

The lookup table corresponding to each ERV type is developed using a cell size L=21 ft, ERV longitudinal size N=2 (ambulance) and N=1 (police car) and acceleration/ deceleration = 5 ft/s^2 (for ambulance) and 10 ft/s^2 (for police). The ERV minimum speed is 5 mph while its maximum speed is 10 mph above the speed limit. The lookup table corresponding to an ambulance is shown above.

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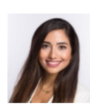

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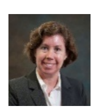

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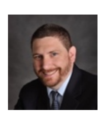

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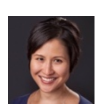

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