Original research paper

Optimization of Freeway Patrol Operations—A Comprehensive Case Study

Pei-Sung Lin[1, *], Zhenyu Wang[1], Mohsen Parsafard[2], Xiaopeng Li[2], Chester Chandler[3]

[1] *Center for Urban Transportation Research, University of South Florida, 4202 E. Fowler Ave., CUT100, Tampa, FL 33620, United States*

[2] *Department of Civil and Environmental Engineering, University of South Florida, 4202 E. Fowler Ave., ENB118, Tampa, FL 33620, United States*

[3]*Florida Department of Transportation District 7, 11201 McKinley Dr., Tampa, FL 33612, United States*

Abstract

A freeway patrol operation is an effective element of a state department of transportation's Traffic Incident Management (TIM) program that offers direct assistance to motorists by quickly responding to, assisting with, providing maintenance of traffic (MOT) setup for, and clearing primary incidents from travel lanes in close coordination with state highway patrol and other law enforcement agencies. The major benefits of freeway patrol operations include shortened incident response time, reduced motorist delay, and reduced excess fuel consumption and emissions. Road Rangers (RR) is the Florida Department of Transportation's (FDOT) freeway patrol program. For this study, an optimization of RR operations in FDOT District 7 was conducted to maximize benefits of RR services. A mathematical optimization model was developed, including objective function, decision variables, and constraints.

Comprehensive datasets were collected from various data sources to generate model inputs and assumptions, including RR route links, geometry data, traffic data, and incident events data. The model was conducted using two strategies: patrol-only and mixed use of patrolling and stationary trucks. The optimized solutions were assessed using the Freeway Service Patrol Evaluation (FSPE) model and compared to the existing solution. Major conclusions of the study include the following: (1) The patrol-only optimized solution increases the benefit-to-cost ratio (B/C) by 60% compared to the existing solution and allocates more truck hours to weekends and to links where high RR assist demand cannot be met by the existing solution. (2) The mixed-use optimized solution increases B/C by 10% compared to the existing solution; due to the lack of knowledge and documents on detection time in a Traffic Management Center (TMC) and stationary truck cost, the mixed-use solution is unreliable. (3) Because of the significant improvement and analysis reliability of the patrol-only solution, it is recommended for fine-tuning and implementation.

Keywords:

Road Rangers; Freeway patrol operation; Traffic incident management; Optimization; Benefit-cost ratio

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*Corresponding author. Tel.: +1 8139744910, Fax: +1 8139745168
E-mail: lin@cutr.usf.edu (Pei-Sung Lin, PhD, PE, PTOE, Director, ITS, Traffic Operations and Safety Program)
zwang9@cutr.usf.edu (Zhenyu Wang, PhD, Research Associate).
m.parsafard@gmail.com (Mohsen Parsafard, PhD Candidate)
xiaopengli@usf.edu (Xiaopeng Li, PhD, Assistant Professor)
Chester.Chandler@dot.state.fl.us (Chester Chandler, P.E., District ITS Program Manager)

1 Introduction

One of the main goals of today's transportation systems is to provide a safe and reliable travel experience for road users. To achieve this goal, transportation agencies strive to implement initiatives to mitigate congestion effects. In 2010, congestion caused road users to spend 4.8 billion hours of extra time in traffic, wasting 1.9 billion gallons of fuel. In monetary terms, this was equivalent to $101 billion (Schrank, Lomax, and Eisele 2011). Factors such as crashes, special events, and hazardous weather affect the network, causing non-recurring congestion and diminishing the reliability of the transportation network. These unforeseen delays account for almost half of the congestion on the nation's roadway (Kimley-Horn and Associates 2011).

Traffic incidents are random, capacity-reducing events that range from minor debris to major vehicle crashes. Capacity reductions are not directly proportional to the number of blocked lanes. According to the *Highway Capacity Manual* (Highway Capacity Manual 2000), blockage of one lane on a three-lane freeway causes more than a 50 percent reduction in capacity instead of only 33 percent, as might be expected. Even an incident on the shoulder causes a reduction in capacity because curiosity leads to driver distraction and speed reduction (Masinick and Teng 2004).

To reduce non-recurring delays caused by incidents, many states run freeway service patrols (FSPs). FSPs are a special incident response initiative designed to alleviate non-recurrent congestion through quick detection, verification, and removal of freeway incidents (Skabardonis et al. 1998). FSP services have existed since 1960, and there are currently more than 50 freeway service patrols in the United States (Feno and Ogden 1998).

The Road Ranger program is one of the most effective elements of the Florida Department of Transportation’s (FDOT’s) Traffic Incident Management (TIM) Program (Florida Department of Transportation Road Ranger Service Patrol 2011), offering direct assistance to motorists by quickly responding to, assisting with, providing maintenance of traffic (MOT) setup for, and clearing primary incidents from travel lanes in close coordination with the Florida Highway Patrol (FHP) and other law enforcement agencies. The major benefits of the RR program include shortened incident response time, reduced motorist delay, and reduced excess fuel consumption and emissions.

Studies conducted by the University of South Florida's Center for Urban Transportation Research (CUTR) (Lin et al. 2012; Hagen et al. 2005) found that benefit-to-cost (B/C) ratio can be improved with more patrolling on beats with heavier traffic with lower speeds and more chances of lane blockage. FDOT District 7 sought to increase fiscal responsibility by optimizing RR operations to maximize operational benefits. A study by Chou, Miller-Hooks, and Promisel (2010) summarized the methodologies for benefit-cost analyses of FSPs. Three types of models are often used to estimate the delay savings by FSPs—mathematical models based on field data, deterministic queuing models, and computer simulation models, of which the deterministic queuing model is the most widely implemented in practice.

Developing an optimization scheme for RR operations required identifying an objective function, determining the domain for the function, and optimizing the objective function over the domain. Typically, a B/C ratio serves well as the objective function and can be maximized over the domain to determine the optimal solutions or solution, if unique; it can be used to prescribe new assigned beats (zones) and truck hours to optimize RR operations.

2 Basic concepts

2.1 Capacity reduction caused by incidents

Freeway incidents such as accidents, vehicle breakdowns, or the presence of debris may cause blockages and reductions in capacity (Goolsby 1971; Qin and Smith 2001). The severity of capacity reduction depends mainly on the incident type (e.g., crash, breakdowns, debris), lateral distribution (e.g., median, in-lane, shoulder), and number of lane blockages. Increased delays occur when traffic demand exceeds the remaining freeway capacity during an incident, which translates into monetary terms when performing B/C calculations. The methodology from the Freeway Service Patrol Evaluation (FSPE) (Skabardonis and Mauch 2005; Skabardonis et al. 1998), as shown in Table 1, was adopted for this study to compute the benefits of RR operations. This methodology uses the capacity remaining factors due to incidents suggested by the *Highway Capacity Manual* (*Highway Capacity Manual* 2000).

Table 1 Remaining factors of freeway capacity due to incident (%)

Incident Type	Location	Number of Freeway Lanes/Direction			
		2	3	4	5+
Accident	Right Shoulder	81.00	83.00	85.00	87.00
	Median	81.00	83.00	85.00	87.00
	1-Lane Block	35.00	49.00	58.00	65.00
Breakdown	Right Shoulder	95.00	98.00	98.00	98.00
	Median	95.00	98.00	98.00	98.00
	1-Lane Block	35.00	49.00	58.00	65.00
Debris	Right Shoulder	95.00	98.00	98.00	98.00
	Median	95.00	98.00	98.00	98.00
	1-Lane Block	35.00	49.00	58.00	65.00

2.2 Delay reduction due to RR services

Delay reduction is one of the major benefits of an RR program. The difference in delay with and without RR service is one of the main components of the net benefit calculations of the program. The delay savings by an RR service consists mainly of reduced response and clearance times in incidents involving RR assistance. The primary reasoning behind delay reduction modeling for RR operations is presented in Fig. 1. The horizontal axis represents time, and the vertical axis represents the cumulative volume for a freeway segment. The line represents the traffic volume through the segment (demand). The slope of this line is the vehicle throughput rate of the freeway in the absence of incidents.

Fig.1 assumes that the freeway is working at or near full capacity. When an incident occurs, the capacity is reduced to C_r. During this period of reduced capacity, the incident is detected and reported, and responders are dispatched. Once the responders arrive at the location, the incident is cleared as quickly as possible. The area between the normal condition line and the reduced capacity line is a measure of the delay experienced by the general public due to the incident. Part A of Fig. 1 presents the delay without RR assistance, and part B presents the same incident with RR assistance. Generally, the detection and arrival times in part B (assisted by RR) are less than in part A (without RR assistance). When the incident is cleared, capacity is restored to its normal value of C. In this example, since there was additional volume during the incident, it took some time to recover and return to the initial conditions. The calculated delay can be translated into monetary terms for B/C evaluation. These delay-saving models require capacity reduction factors as inputs.

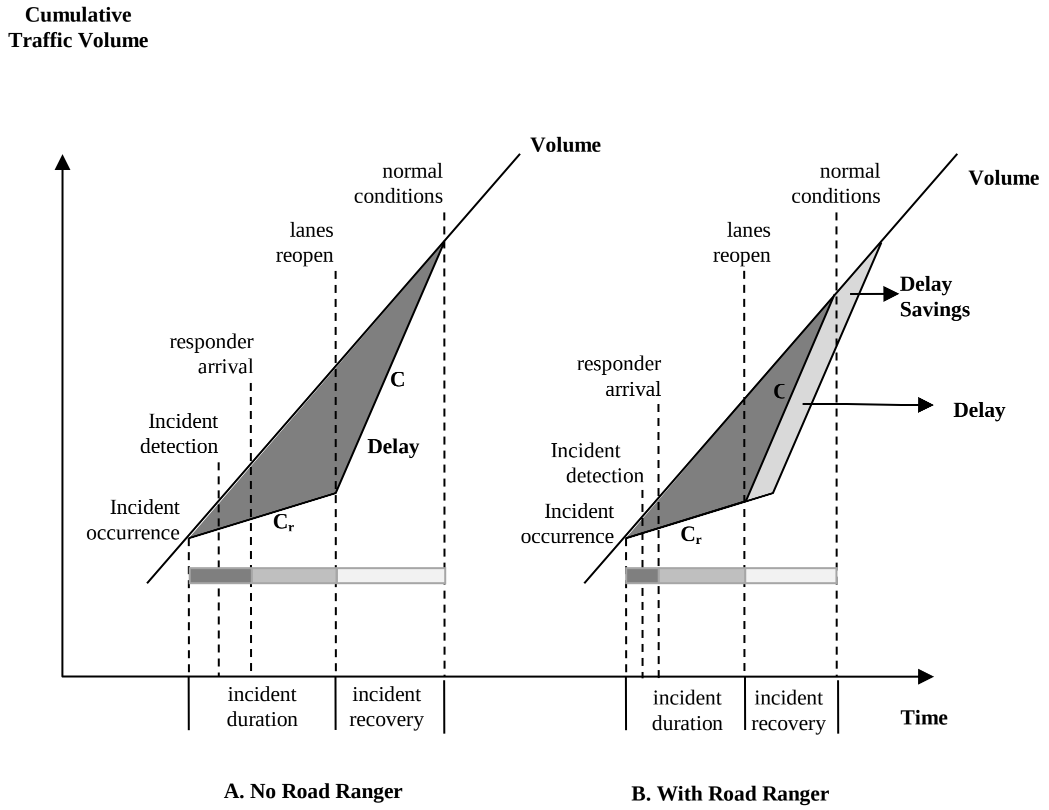

Fig. 1 Conceptual model of delay reduction related to RR services (Lin et al. 2012)

2.3 Fuel consumption and emissions savings due to RR services

Wasted fuel and excess emissions occur during incident-induced delays. For measuring fuel and emission savings from RR services, the selected evaluation methodology in this study used the EMissions FACtor (EMFAC) model with the mobile source emission rates published by the California Air Resource Board (CARB). Emissions rates and fuel consumption rates in the selected model were implemented as the function of average speed (Barth, Scora, and Younglove 1999). Three pollutants were modeled using the EMFAC emission rates in the form of a lookup table: reactive organic gases (ROG), which are equivalent to volatile organic compounds (VOC); carbon monoxide (CO); and nitrogen oxides (NOx). Table 2 represents the emissions rates and fuel consumption for the three pollutants (Skabardonis and Mauch 2005).

Table 2 Fuel and emission rates by speed (Source: WashCOG, 2005)

Speed (mph)	ROG (gr/mi)	CO (gr/mi)	NOx (gr/mi)	Fuel (mi/gal)
5	1.563	11.415	2.258	7.510
10	0.716	6.819	1.668	9.996

15	0.489	5.524	1.361	12.778
20	0.394	5.229	1.307	15.708
25	0.343	5.131	1.272	18.581
30	0.307	5.106	1.254	21.159
35	0.278	5.262	1.248	23.203
40	0.260	5.700	1.274	24.510
45	0.244	6.153	1.322	24.950
50	0.231	6.620	1.392	24.487
55	0.221	7.100	1.490	23.184
60	0.215	7.629	1.626	21.184
65	0.211	8.178	1.815	18.685

2.4 Costs of road ranger services

The main cost components of a service patrol program are capital, operating, and administrative. The annual cost of an FSP depends upon the number of centerline miles covered, hours of operation, and number of vehicles maintained. The hours of operation for a freeway segment may range from 0–24 hours, depending on levels of traffic congestion and budget.

3 Optimization model

3.1 RR rescue modes

Several previous studies have been developed for optimizing freeway patrolling service (Geroliminis 2006; Yin 2008; Lou, Yin, and Lawphongpanich 2011; Khattak et al., 2004; Yin 2006; Pal and Sinha 2002). All these studies considered patrolling trucks only. In this study, two modes of RR rescue trucks were considered—patrolling and stationary, as described in Table 3. Patrolling trucks keep running along the assigned roadway segment (beat or zone) and assist incidents they detect on roads. Stationary trucks stand by at roadside (usually at the middle point of a segment) and wait for the rescue command from the Traffic Management Center (TMC). Patrolling trucks is the traditional freeway patrol mode and does not rely on a TMC command, but its operational cost is higher than the stationary mode. The stationary mode can reduce gasoline consumption, but incident detection is fully based on the TMC. The effectiveness of rescue modes fully depends on beat length, headway of RR trucks, detection time in TMC, distribution of incidents, and fuel/maintenance price. To assess the effectiveness of the two modes, this study compared two RR rescue strategies—patrolling truck only and mixed-use of patrolling truck and stationary truck.

Table 3 Comparison of road Ranger truck modes

	Patrolling Truck	**Stationary Truck**
Operations	Rescue vehicles continue to patrol within their given beats during operation hours.	Rescue vehicles wait at off-road parking area and start rescue activities when dispatch command received from Traffic Management Center (TMC).
Incident Detection	Patrolling vehicles detect incidents independently.	Stationary vehicles rely on incident detection in TMC.
Response Time	Depends on average headway between patrolling vehicles in a given beat.	Depends on detection time in TMC and location of parking lot (usually at mid-point of beat).
Cost	More fuel consumption and higher maintenance requirements.	Relatively lower fuel consumption and maintenance requirements (vehicle engines required in running status for RR vehicle monitoring).

3.2 Objective function

The major goal of RR optimization is to maximize the B/C of RR services. Since the RR budget is assumed to be constant, the optimization objective in this study was expressed as maximization of RR benefits. The objective function and constraints are given as follows:

$$MAX \sum_{b\in B}\sum_{t\in T} Y_{b,t} M_{b,t}(Y_{b,t}, X^{\mathrm{p}}_{b,t}, X^{\mathrm{s}}_{b,t}) \quad (1)$$

$$\sum_{t\in T_1} Y_{b,t} \geq 1, \forall b \in B \quad (2)$$

$$Y_{b,t} \geq 1, \forall b \in B_1, t \in T \quad (3)$$

$$\sum_{b\in B_a} Y_{b,t} \leq 1, \forall a \in A, t \in T \quad (4)$$

$$\sum_{b\in B} Y_{b,t} = \bar{B} \quad \forall t \in T \quad (5)$$

$$\sum_{b\in B}(X^{\mathrm{p}}_{b,t} + X^{\mathrm{s}}_{b,t}) \leq \bar{V} \quad \forall t \in T \quad (6)$$

$$X^{\mathrm{p}}_{b,t} + X^{\mathrm{s}}_{b,t} \leq \bar{V} Y_{b,t}, \quad \forall b \in B, t \in T \quad (7)$$

$$X^{\mathrm{p}}_{b,t} + X^{\mathrm{s}}_{b,t} \geq Y_{b,t}, \quad \forall b \in B, t \in T, a \in A_b \quad (8)$$

$$\sum_{b\in B}\sum_{t\in T}(X^{\mathrm{p}}_{b,t} c^{\mathrm{p}}_t + X^{\mathrm{s}}_{b,t} c^{\mathrm{s}}_t) < U \quad (9)$$

$$Y_{b,t} = Y_{b,t'} \quad \forall b \in B, \ t, t' \in T_1 \quad (10)$$

$$Y_{b,t} = Y_{b,t'} \quad \forall b \in B, \ t, t' \in T_2 \quad (11)$$

$$X^{\mathrm{p}}_{b,t} \ \textit{positive integers}, \forall b \in B, t \in T \quad (12)$$

$$X^{\mathrm{s}}_{b,t}, Y_{b,t} \in \{0,1\}, \forall b \in B, t \in T \quad (13)$$

where A – set of links; B – set of all candidate beats; $\bar{B}$ – total number of beats; B_1 – set of beats for 24-hour service ($B_1 \subset B$); T_1 – set of day-time operational segment on a beat; T_2 – set of night-time operational segment on a beat; T – operational time set ($T = T_1 \cap T_2$); A_b – set of all the links in a candidate beat b, $\forall\, b \in B$; B_a – set of candidate beats that cover link a, $\forall\, a \in A$; $\bar{V}$ – total number of trucks; U – total budget (constant); M – big constant (no need for data); s_b – average truck speed on beat b, $\forall b \in B$; c^{p}_t – average operational cost of a patrolling truck in time section $t \in T$; c^{s}_t – average operational cost of a stationary truck in time section $t \in T$; l_a – length of link a, $\forall a \in A$; l_b – length of beat b, $\forall b \in B$; l^{c} – average TMC camera coverage length on each beat in the network; t^{c} – average camera slide show time on a monitor in TMC; $t^{\mathrm{p}}_{b,t}$ – average time of patrolling beat b at time section t, $\forall b \in B, t \in T$, ($t^{\mathrm{p}}_{b,t} = \frac{l_b}{s_b}$); $\bar{t}^{\mathrm{p}}_{a,b,t}$ – maximum time of capturing (detection time + response time) an incident in link a; $t^{\mathrm{p}}_{a,b,t}$ – time of capturing (detection time + response time) an incident in link a; $t^{\mathrm{s}}_{b,t}$ – average incident detection time for stationary trucks on beat b at time t; $l^{\mathrm{s}}_{a,b}$ – average distance between link a and stationary truck located in beat b; $t^{\mathrm{s}}_{a,b,t}$ – time of capturing an incident (detection time + response time) in link a; $\bar{t}_a$ – average time of capturing an incident in link a without road ranger trucks; $t_{a,b,t}$– time of capturing (response time) an incident in link a; $M_{b,t}$– network improvement (monetary benefits due to reduction in delay, usually in US$) by covering beat b in time section t with a patrolling or stationary truck; $Y_{b,t}$ – 1 if beat b is selected at time section t (active beat); – number of trucks assigned to patrol beat b at time section t; and $X^{s}_{b,t}$ – number of a truck assigned in a stationary station on beat b at time section t (the maximum value is 1).

3.3 Network improvement function

Assuming the following notations:

$\lambda_{t,a}$ – arrival rate during incident in link a during time section t

μ_a – normal departure rate (capacity) in link i

$\mu'_{I,t,a}$ – departure rate during incident (reduced capacity) in link i during time section t for incident type I

$T^{1}_{I,t,b}$– incident duration in beat b during time section t for incident type I, if not RR assisted

$T^{2}_{I,t,b}$– incident duration in beat b during time section t for incident type I, if RR assisted

$T^{1,R}_{t,b}$ – incident response time in beat b during time section t, if not RR assisted (assuming 30 mins)

$T^{1,C}_{I,t}$ – incident clearance time during time section t for incident type I, if not RR assisted

$T^{2,R}_{t,b}$ – incident response time at in time section t, if RR assisted;

$T^{2,C}_{I,t}$ – incident clearance time at during time section t for type I, if RR assisted

$D^{1}_{I,t,a}$ – total delay in link i during time section t for type I, if not RR assisted

$D^{2}_{I,t,a}$ – total delay in link i during time section t for type I, if RR assisted

$\Delta D_{I,t,a}$ – delay reduction due to RR assistance in link i during time section t for type I

I – incident type indicator (Table 1)

t – time section (Table 4)

a – link index, $a \in A$

b – beat (zone) index, $b \in B$

The benefit due to delay reduction is calculated as:

$$\Delta D_{I,t,a} = D^1_{I,t,a} - D^2_{I,t,a} \qquad (14)$$

$$D^1_{I,t,a} = \frac{\left(T^1_{I,t,b}\right)^2 (\lambda_{t,a} - \mu'_{I,t,a})(\mu_a - \mu'_{I,t,a})}{2(\mu_a - \lambda_{t,a})} \qquad (15)$$

$$D^2_{I,t,a} = \frac{\left(T^2_{I,t,b}\right)^2 (\lambda_{t,a} - \mu'_{I,t,a})(\mu_a - \mu'_{I,t,a})}{2(\mu_a - \lambda_{t,a})} \qquad (16)$$

Substitute Eq. 15 and 16 in Eq.14:

$$\Delta D_{b,I,t,a} = \frac{(\lambda_{t,a} - \mu'_{I,t,a})(\mu_a - \mu'_{I,t,a})}{2(\mu_a - \lambda_{t.a})} \times \left(\left(T^1_{I,t,b}\right)^2 - \left(T^2_{I,t,b}\right)^2\right) \qquad (17)$$

We also have

$$T^1_{I,t,b} = T^{1,R}_{t,b} + T^{1,C}_{I,t} \qquad (18)$$

$$T^2_{I,t,b} = T^{2,R}_{t,b} + T^{2,C}_{I,t} \qquad (19)$$

Assume the average clearance time is a constant by incident type I and time section t with and without RR assistance:

$$T^{1,C}_{I,t} = T^{2,C}_{I,t} = T^C_{I,t} \qquad (20)$$

$$\Delta T_{I,t} = T^2_{I,t} - T^1_{I,t} = T^{2,R}_t - T^{1,R}_t \qquad (21)$$

Assume the arrival rate is constant during a time section t:

$$\lambda_{t,a} = AADT_a \times P^T_t \qquad (22)$$

where $AADT_a$ – annual average daily traffic in link a; P^T_t – traffic proportion in time section t. The normal departure rate is the capacity of in link a:

$$\mu_a = c \times n_a \qquad (23)$$

where c – ideal capacity per lane, assuming 2,100 pcphpl (HCM); n_a – number of through lanes in link a. The departure rate during incident in link a is the reduced capacity due to lane blockage:

$$\mu'_{I,t,a} = \mu_a \times P^c_{I,n} \qquad (24)$$

where $P^c_{I,n}$ – capacity reduction factor for incident type I with n through lanes. The benefits due to delay reduction in link a during time section t can be converted to monetary values:

$$M_{t,a}^{d} = \sum_{I} \left(\Delta D_{I,t,a} \times N_{I,t,a} \right) \times C^{d} \quad (25)$$

$$C^{d} = C^{d,p} \times O^{p} \times (1 - P^{T}) + C^{d,t} \times P^{T}$$

where $M_{t,a}^{d}$ – total monetary value of delay reduction in the target year in link a during time section t; $N_{I,t,a}$ – total number of incidents by incident type I in link a during time section t in the target year; C^{d} – average delay cost (\$/hour); $C^{d,p}$ – time value per person (\$/person-hour); $C^{d,t}$ – time value per truck (\$/truck-hour); O^{p} – average occupancy per passenger car; P^{T} – truck percentage (%). The network improvement (total benefit improvement) can be derived as

$$M_{b,t} = \sum_{a} M_{t,a}^{d} \quad (26)$$

Note that the monetary values of fuel consumption and emission savings were not included in the total benefit improvement ($M_{b,t}$) to reduce the computing load in optimization. Since the benefits of fuel consumption and emission savings are a monotone function of delay reduction with RR service, the exclusion of fuel consumption and emission savings in optimization will not influence the optimized result. The benefits of fuel consumption and emission savings were considered in the assessment of optimized solutions.

3.4 Decision-making variables and constraints

The optimization updates the decision-making variables to maximize the RR benefits. The decision-making variables include:

- Beat (zone) coverage (unit roadway segment for RR service assignment) – the unit space in which FDOT District 7 assigns RR services. It may consist of several successive basic freeway segments, which are defined as freeway links between two neighboring interchanges. Beat coverage may be varied based on RR assist demands. In general, a shorter beat is assigned to freeway segments with higher traffic volume and incident density. This study searched the optimal solution to reconfigure the beat coverage considering temporal and spatial distributions of traffic volume and incidents for weekdays and weekends, respectively.
- Patrolling truck hours in each beat

- Stationary truck hours in each beat

The major constraints for this RR operations optimization include (1) upper limit of FDOT District 7 RR annual budget of $5,000,000, (2) minimum beat length of 3.5 miles, (3) minimum truck hours of four hours for each beat during each week day, and (4) three specified segments with 24 hours of RR service every day throughout a year.

3.5 Optimization solver and codes

The RR optimization model was coded in Julia (Julia Language 2016), a high-level, high-performance, dynamic programming language for technical computing that provides a sophisticated compiler, distributed parallel execution, numerical accuracy, and an extensive mathematical function library. The non-linear mixed integer programming technology using the solver of Bonmin (Basic Open-source Nonlinear Mixed INteger programming) in the JuMP (Julia for Mathematical Optimization) package was used to implement the optimization (*Bonmin Users' Manual 2016)*. An Intel i7 (3.6GHz)-based computer powered by Linux (Ubuntu 14) was used to execute the optimization.

3.6 Optimization procedure

For this study, optimization was a complex process involving 903 candidate beats with a combination of 6 time sections for weekdays and weekends. The model searched different combinations of beat coverage and truck type (patrolling or stationary) in each time section to maximize the total benefits of delay reduction due to the implementation of RR service. With the mixed-use strategy, the selection of a patrolling truck or a stationary truck in a given beat was determined by the relative difference in the average response time of the two modes. Incident detection time (IDT) for stationary trucks is fully based on notification from TMC operators who monitor cameras along the RR routes; no knowledge or documents on the characteristics of IDT in TMCs were found in previous studies. Thus, a sensitivity analysis was conducted to compare optimization of mixed use of patrolling and stationary trucks with the five IDT scenarios of 15, 30, 45, 60, and 90 seconds per mile. From the optimization results for mixed use of patrolling and stationary trucks, an IDT of 15 seconds per mile produced the best results.

Once the optimal solutions were produced, the FSPE model (ver. 14) was used to comprehensively assess the solutions. With this model, the benefits from delayed reduction, fuel consumption savings, and emission decreases were calculated for three RR solutions (existing, optimized solution with patrol only, optimized solution with mixed use of patrolling and stationary trucks). Costs for the optimal solution were also calculated. Based on the calculated benefits and costs, B/Cs for the optimal RR solutions were derived.

4 Data preparation

Data and associated sources collected for this study are listed in Table 4.

Table 4 Data collection and sources

Data Sheet	Items	Format	Source
Road Ranger Operation Configuration	Beat layout (weekdays)	GIS	RR Operation Routes 11/2015, FDOT District 7
	Beat layout (weekends)		
	Beat shift hours		
Geometry	Number of lanes	GIS	FDOT GIS Layers (Florida Department of Transportation 2010)
	Right shoulders		
	Median		
Traffic	AADT (2012–2014)	Database	FDOT Traffic Information DVD 2014
	D-factor (2012–2014)		
	K-factor (2012–2014)		
	K-factor (2012–2014)		
Incident	Incident events (2012–2015)	Database	SunGuide® system (Florida Department of Transportation 2010)
Additional Parameters	Delay and fuel costs	Value	Expected gas price in Florida for target year, value of time from TTI Urban Mobility report
	Patrolling hourly cost ($55/h)	Value	FDOT D7 RR Manager
	Stationary hourly cost ($50/h)	Value	Estimated (truck engines always required to be in “on” status)

4.1 Prediction of traffic demand

A simple linear regression based on the collected Annual Average Daily Traffic (AADT) was developed to predict directional AADTs on each link at the target year (2018). An example is shown in Fig. 2.

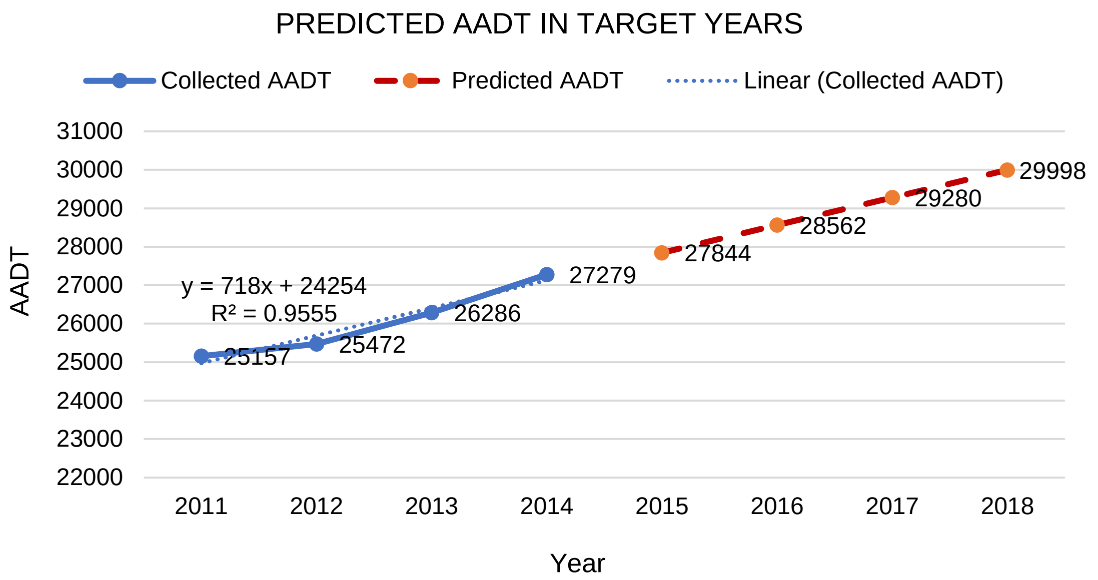

Fig. 2 Example of AADT prediction

In addition, hourly traffic profiles by direction for weekdays and weekends were collected and predicted for each link in the target year. An example is given in Fig. 3.

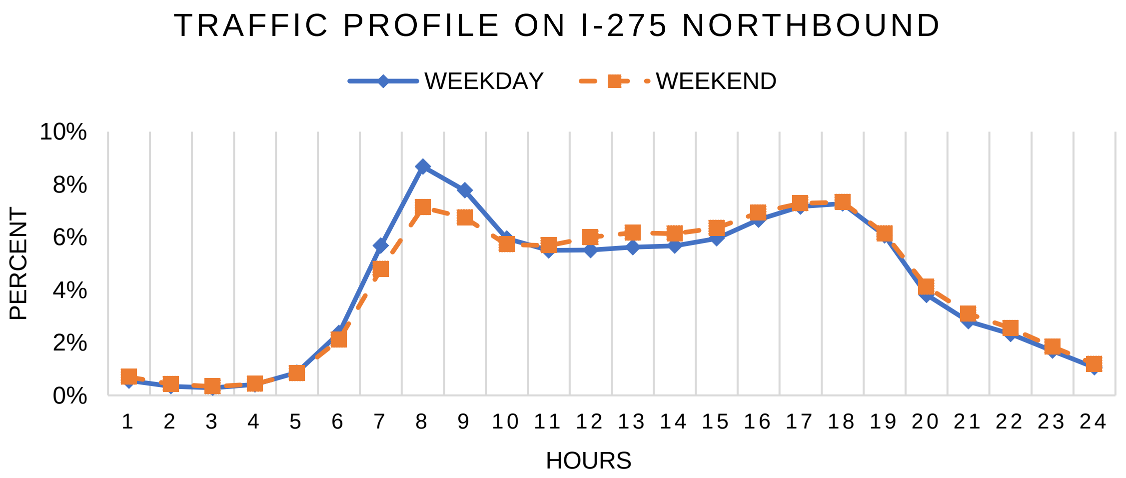

Fig. 3 Example of Traffic Profile

Directional factors were collected from the Florida Traffic Information DVD for each link. The predicted hourly traffic volume by direction for each link was calculated for weekdays and weekends, respectively, using Eq. 27.

$$\text{Hourly Traffic Volume} = \text{AADT} \times \text{Directional Factor} \times \text{Hourly Profile Factor} \quad (27)$$

The calculated hourly traffic volume for each link was aggregated into six time sections (Table 5). The traffic demand by direction and time section for each link in the target year (2018) was produced.

Table 5 Definition of time sections

Time Section	Hours	Nighttime
1	6:00 AM – 10:00 AM	No
2	10:00 AM – 2:00 PM	No
3	2:00 PM – 6:00 PM	No
4	6:00 PM – 10:00 PM	Yes
5	10:00 PM – 2:00 PM	Yes
6	2:00 PM – 6:00 PM	Yes

4.2 Prediction of incident events

The research team collected information on incident events that occurred on RR routes in FDOT District 7 for four years (2012–2015). The incident events were spatially matched to each link by time section and incident type, which are defined by three event types (Accident, Breakdown, Debris), combining the lateral position of incidents (Right shoulder, Median, on Road). A simple linear regression was developed based on the historical incident data (2012–2015) to predict the incident distribution on each link by incident types and time sections in the target year (2018).

4.3 Optimization assumptions

Based on the collected data, the researchers made some assumptions as shown in Table 6.

Table 6 Optimization assumptions

Parameter	Value	Source
Stationary hourly cost rate	$50.1 per hour	US Department of Energy, Vehicle Technology Office–Office of Energy Efficiency & Renewable Energy • Fuel consumption of patrolling truck = 23 mpg, 2.39 gal/hour (in 55 mph) • Fuel consumption of stationary truck = 0.44 gal/hour • Assume operational cost difference between patrolling truck and stationary truck is fuel consumption • Gasoline price = $2.5 per gal • Cost difference = $2.5 × (2.39 – 0.44)

		gal/hour = $4.875 per hour
Average response time without RR service	30 min	Previous reports (Lin et al. 2012)
Time value per person	$13.75 per person-hour	Previous reports (Lin et al. 2012)
Time value per truck	$72.65 per truck-hour	Previous reports (Lin et al. 2012)
Average occupancy per car	1.22 per car	Previous reports (Lin et al. 2012)
Average time value	$18.92 per passenger car-hour	Default value in FSPE model
Ideal capacity	2,100 pcplph	*Highway Capacity Manual* 2000
Gas price in target year (2018)	$2.5 per gal	"US Energy Information – Analysis & Projections," 2016

5 Optimization results and assessment

The optimization results are given in Table 7. The results show that both the patrol-only optimization and mixed-use optimization improve the benefit-cost ratio of the RR service. Compared to the existing solution, the patrol-only solution increases the B/C of RR service by 60% ([14.7 – 9.16] / 9.16 × 100%); the mixed-use solution of patrolling and stationary trucks increases the B/C by 10% ([10.07 – 9.16] / 9.16 × 100%). For weekdays, the patrol-only solution improves the B/C by 34% (= [15.22-10.3]/10.3). However, the mixed-use solution decreases the B/C by only a small amount (9.70 vs 10.03) for weekdays. For weekends, the existing solution provides a relatively low B/C value (5.97). This means that the existing truck-hours assigned to weekends (180 truck-hours per day) are too low to satisfy incident assistance needs for weekends. The optimal solutions increase the truck-hours for weekends (248 truck-hours per day for patrol-only and 268 + 28 = 296 truck-hours per day for mixed-use) so that the B/Cs for weekends are greatly improved (13.39 vs. 5.97 for patrol-only and 10.76 vs. 5.97 for mixed-use).

Compared to the mixed-use solution, the patrol-only solution presents a more effective improvement in B/C ratio for weekdays and weekends. The operations of stationary trucks for incident management are not well documented in existing reports. The average incident detection time in the TMC, which is the critical factor influencing the benefits of stationary trucks, are not clear in this study. An assumption of two minutes was adopted. In addition, the cost of stationary truck could not be estimated accurately. The assumption of $50.1 per hour considered only the difference of fuel assumption from the patrolling trucks. The benefit-cost assessment on the mixed-used solution was unrealizable and inaccurate. Thus, the patrol-only solution is preferred to the existing solution and the mixed-use solution.

Table 7 Comparison of benefits, costs and B/C ratios

RR Performance Measures	Existing Solution	Optimal Solution	
		Patrol-only	Mixed-use
Weekdays (261 days per year)			
Daily patrolling truck-hours	262	244	60
Daily stationary truck hours	*n/a*	n/a	168
Annual benefits due to delay reduction ($)	31,452,008	44,457,917	24,722,042
Annual benefits due to fuel consumption and emission savings ($)	6,268,896	8,861,187	4,927,507
Annual total benefits – B ($)	31,452,008	53,319,103	29,649,549
Annual cost – C ($)	3,761,010	3,502,620	3,058,085
B/C	**10.03**	**15.22**	**9.70**
Weekends (104 days per year)			
Daily patrolling truck-hours	180	248	268
Daily stationary truck hours	*n/a*	n/a	28
Annual benefits due to delay reduction ($)	5,123,486	15,840,822	15,062,141
Annual benefits due to fuel consumption and emission savings ($)	1,021,194	3,157,335	3,002,124
Annual total benefits – B ($)	6,144,678	18,998,159	18,064,265
Annual cost – C ($)	1,029,600	1,418,560	1,678,851
B/C	**5.97**	**13.39**	**10.76**
Total			
Annual total benefits – B ($)	43,865,583	72,317,262	47,713,814
Annual cost – C ($)	4,790,610	4,921,180	4,736,936
B/C	**9.16**	**14.70**	**10.07**

6 Conclusions and Recommendations

The major conclusions and recommendations of this study are the following:

- Delay reduction is a major benefit of the RR program, with delay saving consisting mainly of reduced response and clearance times in incidents.
- Compared to the existing solution, the two optimized solutions of patrol-only and mixed use of patrolling and stationary trucks improve the performance of RR services in FDOT District 7 in terms of an increased B/C.
- The patrol-only optimized solution increases B/C by 60% compared to the existing solution by allocating more truck hours to weekends and links in which high RR assist demand cannot be met by the existing solution. This optimized solution could greatly increase the B/C and obtain an additional approximately $28 million of benefit.
- The mixed-use optimized solution increases B/C by 10% compared to the existing solution.
- The performance of the mixed-use strategy was determined by detection time in the TMC, beat

length, and relative costs of the patrol and stationary modes. Because of the lack of knowledge and documents on detection time in the TMC and stationary truck cost, the mixed-use optimization result is unreliable.

- Considering the significant improvement and reliability of the patrol-only optimized solution, it is recommended for fine-tuning and implementation.
- The optimization model includes assumptions such as gas prices and location of construction zones that may vary frequently in the future. It is suggested that the RR solution be optimized annually using the optimization model developed in this study with new model inputs and assumptions.

Disclaimer

The opinions, findings, and conclusions expressed in this publication are those of the author(s) and not necessarily those of the Florida Department of Transportation or the US Department of Transportation.

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