SAFETY CONSIDERATION IN SIGNAL COORDINATION AND ROAD DESIGN ON URBAN STREETS

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ABSTRACT

Traffic signals are coordinated mainly with traffic mobility in mind while the impact on safety is not well known. It is not clear how strong this impact is under specific conditions and which coordination solutions increase or reduce this impact. Engineers who set coordinated signals have at their disposal a number of tools to improve traffic mobility along urban streets but no tool to account for safety. In this paper, we study the impact of arterial signal coordination on the frequency and severity of rear-end and right-angle collisions – the two types of crashes that are prevalent at signalized intersections - the frequency and severity of which are likely to be affected by signal coordination.

Multinomial logit models were developed to estimate crash likelihood in 15-minute intervals as well as the severity of crash outcome on arterial intersection approaches. The obtained models were used to investigate the safety impact of signal coordination and other road and traffic variables. We determined the following. (1) Signal coordination can significantly affect crash likelihood and severity. The concentration of vehicle arrivals in the second half of a green phase is associated with significantly lower crash likelihood and severity. (2) Certain components of the traffic flow are most susceptible to crashes. (3) Short distances between intersections and short cycle lengths are associated with a lower risk of crash. (4) The presence of a right-turn bay is associated with a considerable improvement in safety manifested by a lower risk of rear-end and right-angle collisions. The developed models can be used as a tool for evaluating alternative signal coordination plans from the standpoint of safety.

Topic area: Urban street and intersection design, operation and safety.

INTRODUCTION

Although most of the conflicting vehicle movements at signalized intersections receive green signals in separate signal phases, these intersections experience more crashes than might be expected. Among the 6.3 million crashes reported in 2003 in the United States, about 20% occurred at signalized intersections. As a result of these crashes, nearly a half-million people were injured and three thousand killed (NHTSA, 2005). The most frequent types of crashes are rear-end and right-angle collisions.

Coordinating the timings of adjacent traffic signals has proven to be a low-cost and highly efficient means of reducing delays, traffic interruptions, and vehicle queues. On the other hand, past research on the safety impact of signal timing mainly focused on non-coordinated signals. Extensive studies have documented the dilemma zone issue (Gazis et al. 1960) and proposed treatment methods by advanced signal control techniques (Zimmerman and Bonneson 2004; Tarko et al., 2006).

Improving signal coordination was considered a way to improve traffic safety based on two case studies (TRB, 2000). The two studies directly compared crash frequencies before and after signal modernization projects without controlling other important safety factors (Parsonson 1983; Parsonson and Thomas 1978).

Research pertaining to the safety impact of signal coordination is in its early stages. Recent published work has found that better signal coordination improves safety on an aggregated level. For example, a predictive model of rear-end crashes developed by Wang et al. (2003) included a binary variable that represents the presence of signal coordination. Poch and Mannering (1996) included a number of signal phases as a predictive variable in their crash model. Rakha et al. (2000) projected crash reduction through existing models. Some others suggested better coordination may also harm traffic safety. Tindale and Hsu (2005) found that the percentage of road crashes caused by signal violation was 3-5 times higher for urban one-way streets than for all road types on average. Bonneson et al. (2002) proposed a red-light running frequency model with cycle length, flow rate, yellow interval, and platoon ratio. This is a significant step towards establishing the link between signal coordination and traffic safety. Grembek et al. (2007) modeled red-light running likelihood with real-time traffic monitoring data and found a correlation between red-light running likelihood and different components of traffic flows, which demonstrated the potential to improve safety without much loss of mobility through the simulation.

The mentioned past research suggests that signal coordination indeed affects safety. This effect, however, is much more difficult to investigate than road and aggregate traffic variables. In contrast to the AADT and road geometry usually examined in the traffic safety literature, signal timings exhibit far stronger variability. Although coordination plans impose certain restrictions on traffic signals through a background cycle and signal offsets, signal splits adjust to traffic volumes making traffic signals strongly dependent on traffic in short intervals. Also, typically more than one coordination plan is executed, and these plans are based on the time of day and day of week. The models estimated with aggregated data, such as AADT, inevitably lack the capability to capture the impact of various coordination plans and signal splits. Consequently, the aggregated crash models are not very useful in evaluating the signal coordination parameters from the safety point of view. Although past research has started building valuable knowledge about safety at coordinated traffic signals, additional research is needed to provide more insight into coordination plans that are safer than others and elements of coordination plans that are particularly important for traffic safety.

In this study, we carefully analyzed crash records for three coordination systems to learn about the prevailing patterns in crash data. This initial analysis, although rather crude, gave us valuable insight about crash occurrence at coordinated signals. The results helped us formulate two types of safety models applicable to approaches to signalized intersections coordinated with other signalized intersections: (1)

models of crash likelihood in short intervals and (2) models of likelihood of severe outcome of a crash given that a crash happens. These models use the information available to traffic engineers designing traffic signals, supplemented with crash data obtained from the Indiana State Police. The likelihood of a crash is modeled separately for two types of crashes prevailing at signalized intersections: rear-end or right-angle collisions. The model of crash severity estimates the likelihood that at least one person has been killed or injured in a crash. The developed models allowed examining the impact of various traffic arrival patterns generated by signal coordination and other signal, geometry, and traffic factors.

PRELIMINARY ANALYSIS OF CRASHES AT COORDINATED SIGNALS

Before developing of statistical models can begin, it is frequently beneficial to spend time learning the data and the patterns exhibited by these data. In our study, we directly reviewed the police reports of crashes on three coordinated arterial systems. Some critical information is usually not available in crash records and has to be recovered from original police reports. Such information includes, for example, the signal status when a crash occurs. This exercise was quite revealing and helped us successfully postulate certain safety factors confirmed later through more advanced modeling.

Three signal coordination systems for which we obtained electronic copies of the original crash reports included 18 intersections:

1. Danville system (one arterial street) on US 36 between Mackey Road and Tennessee Street,
2. Frankfort system (two crossing arterial streets) on SR 28 between Columbia and Clay Streets, and on SR39 between Washington and Armstrong Streets,
3. West Lafayette system (one arterial street) on US52 between Purdue Research Park and Nighthawk Street.

A total of 1,345 crashes were reported in the 2003-2006 period to occur in the vicinity of the studied intersections. Thirty-four percent of them were rear-end crashes, and 21% of them were right-angle crashes. We further examined the police reports and descriptions of these crashes and selected only right-angle and rear-end collisions involving vehicle moving on the arterial street and relevant to arterial signalization (e.g., driveway crashes and crashes with parking vehicles were excluded). The final crash data used in the crash pattern analysis include 324 rear-end and 70 right-angle collisions (Table 1).

We observed that among the 189 rear-end crash reports, in which signal status was specifically mentioned, 114 of the collisions occurred during red signals, 15 occurred during green, and 60 occurred during signal change periods. These facts suggest that most rear-end crashes happen between a vehicle stopped in a queue and a vehicle arriving during a red signal, although it is known that there are a number of crashes during a green signal when the queue is still present on the approach. Considering the short duration of transition periods, vehicles that arrive in these periods are susceptible to rear-end crash risks. Nevertheless, in this study we found only 15 out of the 189 crash reports that pointed to the dilemma issue as a potential cause of a crash. Thus, the presence of a queue seems to be the predominant circumstance of a rear-end crash.

Table 1 shows the right-angle crashes at the three studied systems broken down by signal violation type. An arterial vehicle running a red light was the most frequent scenario of right-angle crashes, followed by a crossing street vehicle violating a red light. The third most common of crashes was violation of the permitted left-turn signal on the arterial, while right-angle crashes related to right turn on red (RTOR) were quite infrequent. Traffic violations by arterial vehicles lead to about 70% of all right-angle crashes.

Table 1 Signal-related conditions of rear-end and right-angle crashes on the three Indiana coordinated systems

Rear-end Crash Signal Status	**All Systems**	**Frankfort**	**Danville**	**West Lafayette**
Green[a]	15	0	1	14
Red turning Green[b]	31	1	4	26
Yellow turning Red	18	1	1	16
Green turning Yellow	11	0	1	10
Red	114	7	21	86
Unknown	135	8	18	109
Total	**324**	**17**	**46**	**261**
Right-angle Crash Violation Type	**All Systems**	**Frankfort**	**Danville**	**West Lafayette**
Arterial Through Red	26	5	4	17
Arterial Left Turn Red	4	2	0	2
Arterial Permitted Left Turn	16	1	1	14
Crossing Street Red	17	6	1	10
Arterial RTOR	1	0	0	1
Crossing Street RTOR	2	0	0	2
Other	4	0	2	2
Total	**70**	**14**	**8**	**48**

[a] The descriptive part of the crash report indicates that crash happen during the green signal and the signal change (red to green) could not be pointed out as a contributing factor.

[b] The descriptive part of the police report implies that the crash occurred in relation to the signal change from red to green and most likely happened shortly after the signal change.

The permitted left turn violations account for 20% right-angle collisions. Only a very small fraction of all right-angle crashes are related to right turn on red violations.

SYSTEMS AND DATA FOR MODELS DEVELOPMENT

Signal Coordination Systems

Data collected for six Indiana arterial systems during a four-year period between 2003 and 2006 were utilized in our investigation (see Table 2). We could not include the Danville and West Lafayette systems in our modeling due to a slow and considerable “drift” of offsets at these systems. The six selected systems have 35 intersections with at least three to four signal coordination plans for each weekday. The SR 28 and SR 135 systems were updated after 2003. Crashes that occurred before these updates were excluded from the research because they happened under the coordination plans that were different from the ones reflected with our data. Table 3 provides a summary of important traffic, signal, and geometric characteristics of the arterial systems studied. These characteristics are strongly diversified which is an important condition of being able to estimate their impacts on safety. The data used to estimate the models include 286 rear-end property-damage-only (RE-PDO) crashes, 70 rear-end injury-fatal (RE-IF) crashes, 44 right-angle property-damage-only (RA-PDO) crashes, and 23 right-angle injury-fatal crashes (RA-IF).

Table 2 Arterial systems used to estimate safety models

Arterial System	SR 28	SR 135	SR 431	US 41	US 30A	US 30B
Arterial ID	3	5	6	7	8A	8B
City (County)	Frankfort (Clinton)	Indianapolis (Marion)	Indianapolis (Hamilton)	(Lake)	(Lake)	(Lake)
Interconnected	Yes	Yes	Yes	Yes	Yes	Yes
No. of Coordinated intersections	7	7	7	5	4	5
No. of timing plans	3	3	6	4	4	4
Month of signal implementation	Feb-2004	Jul-2004	Dec-2002	Aug-2001	Dec-2001	Dec-2001

Table 3 Summary of Coordinated Arterial Characteristics

Variable	Mean	Std. Dev.	Min	Max
Approach Volume (vphpl)	465.8	247.1	0.0	1840.0
Upstream Primary Volume[a] (vphpl)	411.4	215.2	6.0	1776.0
Upstream Secondary Volume[b] (vphpl)	77.5	65.2	0.0	396.0
Speed limit (mph)	43.0	7.4	30.0	50.0
Distance from upstream intersection (ft)	1808.6	1308.4	350	5400
Expected travel time from upstream (sec)	26.8	17.2	8.0	73.6
No. of through lanes	2.1	0.7	1.0	3.0
No. of exclusive left turn lanes	1.0	0.5	0.0	2.0
No. of exclusive right turn lanes	0.5	0.5	0.0	1.0
Intersection width along side street (ft)	109.1	26.5	60.4	236.0
Intersection width along arterial (ft)	132.1	35.7	59.7	181.3
Cycle length (sec)	120.4	27.7	80.0	154.0
Maximum green (sec)	61.8	22.8	18.8	125.0
Minimum green (sec)	21.9	5.5	8.0	34.3
Yellow interval (sec)	4.2	0.5	3.0	5.1
All-red interval (sec)	1.6	0.4	1.0	3.0
Offset from upstream intersection (sec)	51.1	44.0	0.0	147.0

[a] Volume of traffic leaving an upstream intersection towards the subject intersection during an arterial green signal at the upstream intersection.

[b] Volume of traffic leaving an upstream intersection towards the subject intersection during an arterial red signal (turning volumes).

The data obtained for these systems are summarized in Table 3 and include:

(1) Geometry. This includes the location of the system, the distance between intersections, the number of through and turning lanes, the posted speed limit at each approach, and the intersection width along and across the arterial. We have confirmed with the Indiana Department of Transportation (INDOT) that the selected systems did not undergo any major changes of geometry since 2003.

(2) Traffic volume. The latest available traffic counts of all the movements at all the studied intersections were obtained from INDOT. The traffic counting was conducted in 15-minute intervals and typically spanned at least 12 consecutive hours.
(3) Signal timing. The coordination plan variables were background cycles, offsets, and splits. Other timings included duration of yellow signals, all-red periods, and minimum and maximum green times.
(4) Operation periods of coordination plans. Typically, several signal coordination plans are executed on an arterial system. The time-of-the-day periods of all the timing plans were obtained from the INDOT districts to identify the coordination plan executed during each 15-minute interval.
(5) Crash data. These data included the date, time, geographic coordinates of the crash location, type of crash, crash severity level, and other pieces of information found in the records of relevant crashes.

Traffic Arrival Pattern

The primary postulate about the manner in which signal coordination affects safety involves the so-called *traffic arrival pattern*. The arrival pattern is typically characterized as a cyclic traffic rate profile of vehicles arriving at an intersection. Such a profile is affected by coordinated upstream signals and may exhibit high rates during red signals (poor progression) or during green signals (good progression).

We decided to incorporate arrival patterns in our investigation of the safety impact of signal coordination. We represent a traffic flow leaving a traffic signal with two distinct flow rates: primary rate V_p during an arterial green signal and secondary rate V_s during an arterial red signal (turning movements). The primary and secondary volume rates measured in vehicle per hour per lane (vphpl) at the upstream intersection are:

$$V_p = \frac{4 \cdot Q_p \cdot C}{n \cdot g} \text{ and } V_s = \frac{4 \cdot Q_s \cdot C}{n \cdot r}. \qquad \text{1. Eq.1}$$

where Q_p is 15-minute traffic count of arterial through movement at the upstream intersection, Qs is 15-minute traffic count of movements turning at the upstream intersection towards the downstream intersection, n is number of arterial lanes, g is arterial green phase including the green and change periods (second), r is arterial red phase, and C is signal cycle (second).

The cyclic traffic pattern produced by traffic signals gradually flattens along the road and after traveling T seconds it becomes flat at a uniform rate $V_T = \frac{4 \cdot Q_p + 4 \cdot Q_s}{n}$. The initial flow rate V_0 (V_p or V_s) after traveling t <T seconds converts to V_t according to the following linear transformation:

$$V_t = V_0 + \frac{t}{T} \cdot (V_T - V_0) \qquad \text{Eq.3}$$

Hook and Albers (1999) suggested that for intersections located more than 5,000 feet from each other, coordination probably has no impact on the downstream cyclical traffic profile. In this study, we similarly assumed that traffic moves at the posted speed limit and the vehicle platoon is fully dispersed after 120 seconds of travel.

In general, the number of vehicles arriving at the downstream intersection during a certain portion of a cycle ΔC (such as the second half of a red signal or the first two seconds of a green signal) expressed in veh/h/lane can be calculated as:

$$V_{\Delta C} = \frac{1}{C} \sum_{i \in \Delta C} V_{ti} \qquad \text{Eq.4}$$

where $V_{\Delta C}$ is the number of vehicles arriving at the downstream intersection during the ΔC time window (veh/h/lane), $\{\Delta C\}$ are the seconds included in the considered part of cycle, V_{ti} is the arriving hourly volume rate in second i, and C is the cycle length (second).

The traffic arrival pattern on arterial approaches is constantly changing due to the inherent variation of traffic conditions, the various coordination plans used, and the adaptive nature of modern signals. Second-by-second traffic arrival data are certainly desirable for real-time traffic control but were not available to us to investigate the safety impacts in long periods. Therefore, we had to rely on historical traffic counts available in 15-minute intervals and use the traffic progression and dispersion model described earlier in this section to be able to determine the likely traffic arrival patterns in the investigated intervals. We decided to present the traffic pattern in a way that takes into account the limited precision of data, the randomness of vehicle arrivals, and the ability to include the pattern representation into the statistical modeling framework. The chosen representation is less precise then the second-by-second traffic cyclic profiles sometimes used, but it is more elaborated than the platoon ratio used in HCM *(TRB, 2000).*

The following description of coding traffic patterns was applied to arterial traffic flows and coordinated signal phases. We divided a signal cycle into four parts: the first half of arterial red (R1), the second half of arterial red (R2), the first half of arterial green (G1), and the second half of arterial green (G2), where end-of-yellow is the end of the arterial green phase. The coordinated signal phase may vary between the maximum and minimum values. Thus, we defined 12 traffic indicator variables: R1_max, R2_max, G1_max, G2_max, R1_mid, R2_mid, G1_mid, G2_mid, R1_min, R2_min, G1_min, and G2_min. The indicator is equal to 1 if more than 25% of the volume arrives during the cycle part stated by the variable; otherwise, the indicator is equal to 0. The prefix indicates which green signal is assumed: maximum, midpoint between minimum and maximum, and minimum. For instance, G2_max is 1 when more than 25% of the volume arrives in the second half of maximum green. Thus, each approach in each time interval has an associated four-digit code, such as 0011 or 1001, representing the traffic arrival pattern. In summary, 12 traffic indicator values representing three traffic arrival patterns were calculated for each coordinated approach and each 15-minute interval.

A case study was conducted to evaluate the validity of the traffic pattern characterization method. The actual patterns observed on the arterial approaches of the US 52 systems were compared to the pattern calculated with the proposed model. The results are summarized in Table 4. Each row corresponds to an arterial approach under a certain coordination plan. The shaded cells include more than 25% of the traffic flow in the cycle. The maximum-based pattern codes were found to be the most accurate and hence we expected that the maximum- based variables might be most useful in investigating safety.

MODELS AND THEIR DISCUSSION

In this research, we model the likelihood of a crash on an arterial approach to a signalized intersection in a 15-minute interval. The likelihood of multiple crashes in a 15-minute interval is negligible. A logit model is the natural choice (*Ben-Akiva and Lerman 1985; Greene 2000*). Two logit models were developed: (1) a multinomial logit model to estimate the rear-end (RE) crash likelihood, the right-angle (RA) crash likelihood, and the no crash or other crash likelihood; and (2) a binary logit model to estimate the injury-fatal (IF) crash likelihood given a crash and the property-damage-only (PDO) crash likelihood. The three likelihood values estimated in the first

Table 4 Evaluation of the proposed model of traffic pattern

Calculated from the proposed model for Max Green				Observed			
R1	R2	G1	G2	R1	R2	G1	G2
22.5%	16.5%	21.5%	39.5%	17.6%	14.7%	33.9%	33.9%
32.4%	17.6%	15.0%	35.0%	24.2%	10.0%	26.2%	39.6%
32.3%	17.7%	15.1%	34.8%	30.2%	11.0%	14.4%	44.4%
23.2%	23.2%	26.8%	26.8%	21.0%	25.7%	35.7%	17.6%
23.2%	23.2%	26.8%	26.8%	21.5%	16.5%	35.8%	26.2%
23.2%	23.2%	26.8%	26.8%	14.8%	13.4%	43.0%	28.9%
26.4%	10.6%	19.4%	43.6%	2.2%	1.9%	57.9%	38.0%
27.0%	8.7%	18.1%	46.2%	3.3%	2.7%	60.0%	34.0%
27.1%	8.4%	17.9%	46.6%	4.7%	2.9%	35.9%	56.5%
9.4%	26.7%	38.8%	25.1%	8.4%	13.3%	58.9%	19.3%
8.9%	26.8%	39.3%	25.0%	4.0%	7.7%	58.8%	29.4%
11.8%	26.0%	36.7%	25.5%	22.3%	13.6%	40.9%	23.1%
8.4%	26.9%	39.7%	25.0%	6.2%	9.5%	56.9%	27.5%
22.5%	10.3%	29.2%	38.0%	12.4%	17.9%	41.3%	28.4%
22.8%	11.6%	28.7%	36.9%	15.7%	25.0%	27.3%	32.0%
22.0%	20.8%	27.7%	29.5%	13.9%	13.3%	42.8%	30.1%
22.2%	21.1%	27.4%	29.3%	11.9%	20.8%	31.5%	35.7%
22.0%	20.8%	27.7%	29.5%	9.7%	23.4%	50.3%	16.6%
14.5%	15.0%	33.0%	37.4%	10.1%	5.6%	49.4%	34.8%
16.3%	16.9%	31.5%	35.3%	6.0%	13.9%	40.8%	39.3%
18.0%	18.6%	30.1%	33.3%	15.0%	6.8%	41.7%	36.4%
11.5%	59.2%	24.9%	4.4%	42.3%	25.7%	16.2%	15.8%
12.6%	57.7%	24.5%	5.2%	30.8%	24.1%	22.4%	22.7%
12.6%	57.7%	24.6%	5.2%	30.4%	30.4%	19.0%	20.2%
12.2%	58.2%	24.7%	4.9%	29.6%	25.6%	17.0%	27.8%

model are absolute while the two likelihood values estimated in the second model are conditioned on a crash occurrence. Combining the probabilities from the two models, we estimated the probabilities of five possible outcomes (RE-PDO, RE-IF, RA-PDO, RA-IF, no crash). An attractive property of these probabilities is that they can be aggregated over a road network and/or time to obtain the expected number of crashes.

Crash Likelihood

The large size of the dataset posed a serious difficulty for this research. The complete dataset includes 202,981 no crash intervals, 356 rear-end crash intervals, and 67 right-angle crash intervals. The estimation process became a formidable computational task given the available computing capacity. A similar situation is described in King and Zeng (2001) where the authors found a solution to the problem by noticing that a positive observation (crash) carries much more information than a null observation (no crash). Following King and Zeng, a sampling strategy was utilized of keeping all the crash observations and randomly selecting a portion of

the no-crash observations. This strategy is a special case of the choice-based random sampling strategy (Ben-Akiva and Lerman 1985). The maximum likelihood estimators of such a sample are still consistent, except for the choice-specific constant terms. In the multinomial logit model setting, the correction for the constant terms should be $-\log(SF_i / PF_i)$ (Washington et al. 2003), where SF_i is the fraction of observations with outcome i in the sub-sample and PF_i is the fraction of observations with outcome i in the entire population.

Table 5 lists the variables considered in the models development. We have checked not only individual traffic concentration indicators (R1, R2, G1, G2) determined for all the three coordination phase values (minimum, midpoint, and maximum), but also the individual four-digit traffic patterns and their combinations. Furthermore, geometry variables not directly related to the signal coordination (but possibly correlated with some other variables) where added to the model to reduce the estimation bias of the model coefficients. Table 6 presents the obtained likelihood model for RE and RA crashes.

The presence of an exclusive right-turn lane (RightLane=1) is associated with an exceptionally low frequency of rear-end and right-angle crashes. Removing vehicles turning right from the platoon of vehicles eliminates or at least reduces the braking and lane-changing maneuvers that may be surprising to drivers who are currently focused on traffic signal indications. We have discussed other possible scenarios in the light of available data to identify other characteristics that could be represented by the right-turn lane variable and couldn't find such. According to our best judgment, adding exclusive right-turn lanes to urban arterial streets should improve safety considerably.

The long distance from an upstream intersection represented by the travel time longer than 40 seconds (TrTimeGt40 = 1) is associated with an increased risk of rear-end crashes. The possible explanations are as follows.

1 Long distance between intersections may be associated with higher travel speeds reached near the downstream intersection.
2 Long travel time may relax drivers who lose the alertness caused by passing the upstream intersection. This relaxation increases the reaction time and may contribute to unsuccessful collision avoidance at the downstream intersection.
3 Longer distances create an opportunity for vehicles queues to grow long posing a source of surprise to drivers who may not expect the back of the queue far away from the downstream intersection.

The risk reduction effect of short distances from upstream approaches (TrTimeLt15=1) can be explained similarly.

1. A shorter distance is associated with a shorter queue at the downstream intersection.
2. Drivers have a better view of the downstream intersection and thus are better prepared.
3. Arterial systems engineers usually try to time the signals such that back-to-back stops are minimized (Li and Tarko 2006). This goal is easier to achieve for closely spaced intersections. The fewer number of stops is associated with a lower risk of rear-end crashes.
4. Drivers are usually more alert right after they leave the upstream intersections.

The speed limit (SpeedLmt) effect is another pronounced safety impact. The mechanism seems to be quite obvious since the ability to stop a car to avoid a rear-end crash or violation of a red signal is highly dependent on the speed.

Short cycle lengths are typically associated with lower traffic volumes and shorter red signals along the arterial streets. As a result, vehicle queues tend to be shorter and, together with lower traffic volumes, reduce the drivers' exposure to read-end crashes. It has to be

Table 5 Description of investigated variables

Variable Codes	**Variable description**
SR28, SR135, SR431, US41, US30	Indicator variables of arterial system
PrimVol / SecVol	Primary/secondary volume rate on approach (vphpl)
TotalVol	Total approach volume rate (vphpl)
CrossVol	Total crossing street volume rate (vphpl)
BRVol / BGVol	Arterial traffic at the beginning of red / green in 2 second time window (veh)
AccCrossVol	Volume accumulated on the crossing street during arterial green (veh)
Winter	Indicator of winter (Jan, Feb, Nov, Dec)
AM	Morning indicator (intervals before 12:00 PM)
ArtWidth / CrossWidth	Width of the arterial/crossing street (ft)
SpeedLmt	Posted speed limit (mph)
TravelTime	Travel time = Distance from upstream intersection / Speed limit (seconds)
TrTimeGt40 / TrTimeLt15	Indicator of travel time from upstream intersection longer than 40 seconds / shorter than 15 seconds
LeftLane / RightLane	Indicator of exclusive left / right turning lane
CyclePerHour	Number of cycles per hour
Yellow / AR / ChangeInt	Duration of the yellow / all-red / entire change interval (s)
ProgRatio	Platoon ratio determined for 15-min intervals
AT12 / AT34 / AT56	Arrival type 1 or 2 / 3 or 4 / 5 or 6
R1 / R2 / G1 / G2	Indicator of traffic concentration (more than 25 % of approach traffic) in arterial first half of red / second half of red / first half of green / second half of green
R1R2G1G2	Four-digit traffic arrival pattern determined; for example, 1001 indicates traffic concentration in the first half of red and the second half of green
TAP*n*	Indicator of combined traffic arrival pattern including selected individual patterns; for example, TAP1 includes 0011, 1001, and 0001 patterns, while TAP2 includes 0110, 0100, and 0010 patterns
R1xBRVol	Product of R1 and BRVol
G1xBGVol	Product of G1 and ArtVol
_max / _mid / _min	Suffix added to previously defined traffic and signal variables indicates if these variables apply to maximum / midpoint / minimum arterial greens; for example, 0011_max indicated that the 0011 pattern assumes the maximum arterial greens, while ProgR_min is the progression ratio calculated for minimum arterial greens.

Table 6 Estimated Multinomial Model of Crash Likelihoods

Variable	Rear-end (RE)			Right-angle (RA)		
	Coef.	Std. Err.	t-stat	Coef.	Std. Err.	t-stat
SR135	-2.53	0.345	-7.34	-0.831	0.407	-2.04
SR431	0.864	0.359	2.41	-1.261	0.460	-2.74
R1xBRVol_max	0.0280	0.00813	3.45	0.0334	0.0197	1.69
BGVol_max	0.0384	0.0110	3.50	0.0370	0.0258	1.44
Winter	-0.290	0.121	-2.41	-	-	-
AM	-0.291	0.122	-2.39	-0.559	0.279	-0.559
RightLane	-2.75	0.321	-8.56	-1.15	0.339	-1.145
SpeedLmt	0.158	0.0305	5.17	0.159	0.0394	0.159
TrTimeLt15	-0.764	0.202	-3.78	-0.668	0.381	-0.668
TrTimeGt40	0.861	0.163	5.27	-	-	-
G2_max	-0.215	0.122	-1.77	-0.471	0.301	-1.57
CyclePerHour	-0.0444	0.0157	-2.82	-	-	-
Intercept	-11.2	1.61	-6.94	-14.00	1.82	-7.70
Fitness Statistics						
d.f.	23			observations	203,404	
r^2	0.0949			BIC	6109.45	

emphasized that the detailed inspection of a large number of crash reports described previously indicates that the main source of rear-end collisions is the presence of vehicle queues and slowly moving vehicles on the approach to an intersection. Longer cycle lengths are usually selected when the demand for capacity is higher and the queues are longer. In other words, we think that the obtained model may justify reduction of the cycle length only if there is sufficient capacity and the new traffic patterns promote safety.

A high value of R1xBRVol_max indicates a concentration of the arriving traffic in the first half of the arterial red signal including the first two seconds of red. It is associated with increased likelihood of both rear-end and right-angle crashes. This situation creates conditions for a dilemma zone, rapid braking maneuvers (precursor event of RE crash), and violation of the red signal (precursor event for RA crash) on the arterial road.

A high value of BGVol_max means that considerable arterial traffic arrives during the first two seconds of green (when the green is at maximum on the coordinated intersections). This value is associated with a higher risk of rear-end and right-angle crashes. There are several possible explanations for this effect. (1) Vehicles arriving at the beginning of green are most susceptible to the initial queue shockwave. (2) Another possible cause is related to the operation logic of the actuated signal controller. The beginning of the green phase of the arterial movement fluctuates according to the traffic demand. Therefore, vehicles arriving around this time window face a greater variation of signal status. This elevates the degree of uncertainty and surprise to drivers along the arterial street. (3) A high value of BGVol_max is also strongly associated with the increased risk of right-angle collisions. The vehicles arriving at the beginning of the green (BGVol_max) are susceptible to the red-light runners from the side street.

The concentration of traffic arriving during the second half of the arterial green signal (G2_max=1) is associated with a lower risk of rear-end crashes. These vehicles are the ones least likely to encounter a vehicle queue stopped during the preceding red signal. This result confirms that the presence of a queue is a frequent cause of rear-end crashes.

Another crash likelihood factor is the morning effect, represented by the AM variable. It was found that in the morning that both rear-end and right-angle crashes are less likely, which can be attributed to the lower fatigue level of drivers. In the morning, drivers are generally well rested and make fewer mistakes (Bunn et al. 2005). The effect, however, is not controllable for traffic engineers and thus is not discussed further in this study.

Winter reduces the likelihood of rear-end crashes which may be attributed to the lower level of traffic on arterial roads. It should be noted that our traffic data, although a good representation of traffic variability within a day, they do not reflect the seasonal variability and the effect of the winter season.

The exclusive right-turn lane (RightLane) is associated with significantly lower likelihood of both rear-end and right-angle crashes. The impact level of this factor is surprisingly high. It reduces both the likelihood of rear-end and right-angle crashes to around 5% as before. In other words, the risk reduction factor of the existence of a right turn lane is greater than 95%. It should be noted that the arterial effects are already controlled. The mechanism of a right-turn lane for reducing rear-end crashes is obvious. If there is no exclusive right turn lane, the right-turning vehicle slows down when approaching the intersection. This causes extra disturbance to the traffic flow and forces the following vehicles to change maneuver in a short time. Particularly, this scenario is highly risky if a high density vehicle platoon is approaching an intersection when the green signal is shown. If an exclusive right turn lane is present, the right-turning vehicles will change to the lane when approaching the intersection. The following vehicles pass through the intersection with much less chance of being forced to slow down abruptly.

The mechanism of the right-turn lane on right-angle crashes can be partially explained by better assessment of the conflicting traffic flows. Vehicles staying in the through lane will proceed through the intersection. Vehicles coming from a conflicting movement, for example, right-turning vehicles from crossing streets have a reliable way to judge the behavior of the vehicle. The through vehicles will not be misunderstood as turning vehicles and thus reduce the risk of right-angle crashes. However, these explanations seem to be inadequate. Future studies should investigate this issue further.

Crash Severity

Table 7 shows the estimated crash severity model results. Two additional binary variables were added to allow a type of crash to be among the model inputs; Re represents the RE crash, and RA represents the RE crash. The model includes less statistically significant variables than the crash likelihood model due to a smaller number of observations. Also, interpretation of the results is more difficult due to a larger number of potential variables not available for the modeling.

The impact of the arterial traffic pattern on crash severity is represented by variable G2_max. G2_max=1 means that more than 25% of vehicles arrived at the approach during the second half of the green signal, calculated based on the maximum green. It is possible that drivers arriving in the second half of green tend to maintain higher speeds than drivers who see a red signal ahead when approaching the intersection, thus a RE collision during the second half of green is more likely to bring a severe outcome.

Insufficient duration of the arterial yellow signal, represented by ShortY = 1, is associated with a higher likelihood of a severe outcome from a right-angle crash. The yellow signal was checked using the MUTCD standard (FHWA, 2003). The plausible explanation of this impact is based on consideration of two RA scenarios: (1) a collision between an arterial vehicle clearing the intersection and a slowly moving vehicle accelerating from queue on the crossing street; or (2) a collision between a vehicle clearing the intersection from the crossing street and a slowly moving arterial vehicle accelerating from a queue. The first scenario is potentially more severe because arterial vehicles clear the intersection at higher speed than crossing vehicles. The risk of a potentially more severe scenario increases when a yellow signal on the arterial road is too short.

The reducing effect of traffic volume (VolTotal) on the severity of rear-end crashes can be explained with the reduction of speed during the congested period and on congested arterial streets. Also, drivers may proceed with enhanced caution during such conditions. Other variables present in the severity model have less appealing interpretations; thus, no discussion of their meaning is provided. They were used to together with other variables and their corresponding coefficients to predict crash severity.

Reduction in severe crashes during the winter season can be explained by the degradation of driving conditions which typically results in additional crashes with an increased proportion of less severe crashes due to slower driving speeds.

The effect which cannot be easily explained is the reducing effect of the traffic concentration in the second half of the arterial green on the severity of RA crashes. One possible explanation is a multiplicity of severity factors omitted in the model (vehicles, occupants, drivers, use of safety restraints, etc.). It is possible that some of these important factors not included in the model might be partially represented by the G2_max x Ra variable. Obviously, other variables included in the model may be affected by the same problem, thus interpretation of this model should be done with caution.

Table 7 Integrated logit model of crash severity

		Coef.	Std. Err.	t-stat	P-value
Overall	Intercept	-0.538	0.305	-1.76	0.078
Rear-end	SR431 x Re	-0.726	0.270	-2.69	0.007
	TotalVol x Re	-0.00129	0.0005	-2.65	0.008
	G2_max x Re	0.520	0.273	1.90	0.057
Right-angle	ShortY x Ra	1.720	0.562	3.06	0.002
	Winter x Ra	-1.250	0.634	-1.97	0.049
	G2_max x Ra	-1.485	0.660	-2.25	0.024
Model Fitness Statistics					
Observations	423				
pseudo R^2	0.0883				
df	7				

CONCLUSIONS

In this study, we developed models of crash likelihood and severity on coordinated arterial systems. The statistical modeling results were consistent with the crash pattern analysis of the numerous corresponding detailed police reports. First, it was confirmed that arterial signal coordination can significantly affect the safety performance. Second, rear-end crashes are caused by the queue-forming and discharging process at the beginning of the green. Third, the results also confirm that the traffic volume rate at the beginning of the red (plus the end of the green) is most susceptible to right-angle crashes. The crash frequency reduction effect of longer yellow was not confirmed, but the severity reduction effect of a sufficient change period was confirmed.

Modern signal controllers adjust signals to traffic fluctuation. This is one of the most difficult aspects of traffic signals to represent in statistical models such as the ones developed in the presented study. We have addressed this issues in two ways: (1) by considering short time intervals with determined traffic arrival patterns reflecting the current traffic volume and signal coordination plan, and (2) determining these traffic arrival patterns for three arterial green signal scenarios: minimum, midpoint, and maximum. The signal and traffic variables derived for the maximum arterial green signals as allowed by the coordination plans were found to carry the most safety-related information, which may indicate that the arterial signal phases that reach maximum value and terminate regardless of the traffic demand may cause additional risk of rear-end and right-angle collisions.

The traffic pattern representation proposed in this study outperformed the traditional measure of coordination quality, such as arrival type and platoon ratio. It means that the proposed characterization contains more safety information than the traditional measures used in traffic operations analysis.

The findings of this research can serve as a guide for traffic system engineers. A traffic system engineer and a highway designer can lower the risk of both rear-end and right-angle crashes and can lower the crash severity in several ways:

- Install right-turn turning bays on arterial approaches
- Design signal offsets that promote traffic arrivals at the stop-line in the second part of the green signal and reduce the possibility of traffic arriving during the second part of red
- Apply shorter cycle lengths if they are allowed by demand and capacity
- Reduce the number of vehicles arriving shortly after the phase changes
- Use sufficiently long yellow signals
- Consider lower posted speed limits if consistent with the geometric design of the arterial
- Avoid solutions with frequent timeouts of arterial signal phases (green signal reaches the limit imposed by the coordination plan).

It should be noted that these recommendations may be difficult to attain simultaneously along the entire arterial street. Also, the traffic mobility must be taken into account. Therefore, a prototype software tool based on the developed models has been developed by the authors to evaluate and select the safest solution among those alternative solutions that satisfactory meet the traffic mobility criterion.

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