Developing Efficiency Attributes for Right-Turn Flashing Yellow Arrow on Impeding Through and Opposing Left Phases Using a Multinomial Logit Model

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Submitted: September 21st, 2020
Revised: Jan 21st, 2021
2nd Revision: Feb 7th, 2021
3rd Revision: Mar 31st, 2021

ABSTRACT

The right-turn flashing yellow arrow (FYA) signal display is still considered a new signal practice in the United States. The Manual on Uniform Traffic Control Devices MUTCD (2009) allocates a signal phasing section for the right-turn FYA, which requires a four-section configuration. It supports multiple phase indications that guide the motorists through permissive, protected, and/or permissive/protected phases. However, there are no right-turn FYA or protected permissive right turn (PPRT) guidelines in place with a focus on operational efficiency. In this paper, we investigated two permissive right-turn FYA phases in various traffic conditions and signal timing plans. The first permissive right-turn FYA phase is the right-turn on impeding through (RTOIT) taking place during the cross-street through movement. The second permissive right-turn FYA phase occurs during the opposing left-turn movement and is thus called the right-turn on impeding left (RTOIL). We aimed to develop warrants leading to the efficient implementation of permissive right-turn FYA phases based on a microsimulation analysis. The response; the average maximum right-turn throughput (MRTT) per cycle, was categorized into three categorical variables represented as the non-efficient (NE), low efficient (LE), and efficient (E) categories depending on the number of executed right turns per cycle. A multinomial logit model was developed to establish a decision support system that predicts the efficiency attributes of the permissive RTOIT and RTOIL FYA phases which can help traffic management center operators in planning and operational-level applications.

Keywords: Right-turn FYA, Permissive Right-turn Phases, Blank out Signs, Right-turn on Red, Right-turn on Circular Green, Multinomial Logit Models.

INTRODUCTION

The flashing yellow arrow (FYA) is a new signal phasing standard for the left and the right turning movements that is seeing widespread use throughout the United States and is fast evolving in the central Florida area. However, the right-turn FYA signal is not commonly used as the left turn FYA. Few States are implementing this new practice as recommended in the 2009 Manual on Uniform Traffic Control Devices (MUTCD) like the state of Oregon and Utah. The protected/permissive FYA phasing allows the use of a protected only mode (PO), permissive only mode (Per), or protected/permissive mode (PPRT). A protected right turn has the right of way (ROW) to proceed through an intersection where conflicting vehicles or pedestrians are prohibited. A permissive right-turn relies only on finding an acceptable gap in the impeding traffic in order to make a safe turn, including bicycles and pedestrians (FHWA 2015; Hurwitz et al. 2018). Factors such as sight distance restriction, approach crash rate, percentage of heavy traffic, acceptable stopped delay, and operating speed of an approach affect the signal indication mode selection (HCM, 2010). This study was developed to investigate the proper use of right-turn FYA signal under certain operational factors such the impeding traffic volume, pedestrian volumes and impeding signal intervals.

The right-turn FYA phase is implemented only on a four-section configuration, which can tolerate the four phasing modes described in the MUTCD. The four indications change depending on which intersection approach has the right-of-way movement. For instance, when the cross-street through traffic or the opposing left-turn traffic has the right of way to proceed through the intersection, the right-turn shall be permitted to display FYA signal indication. Right-turn traffic has to yield to pedestrians crossing the side street or the main street during the adjacent through green movement. It is also standard practice for the right-turn phase to display a protected right-turn green arrow simultaneously with the movement of the crossing left-turn approach movement known as an overlap while prohibiting the U-turn to prevent conflicts with the right turning traffic.

The current research investigates two permissive right-turn FYA phases in different traffic approaches, signal timing plans, and pedestrian circumstances using microsimulation. The first right-turn on red phase is impeded by the cross-street through traffic and any pedestrian crossing the main street described as right turn on impeding through (RTOIT). The second right-turn on red phase is impeded only by the opposing left-turn traffic, defined as right turn on impeding left (TROIL). There is a third type of RTOR, termed as right-turn on adjacent through (RTOAT) which occurs simultaneously with the adjacent lane’s green phase and is impeded only by pedestrian activity crossing the cross-street. However, the focus of this paper is on the first two patterns; RTOIT and RTOIL FYA phases only. The experiment included a multi-level factorial design that evaluated the permissive phase attributes at multiple traffic volumes and signal timing plans. The guidelines and models obtained from the statistical design of experiment (DOE) helped in assessing the efficient implementation of a permissive protected right-turn (PPRT) FYA signal for a single exclusive right-turn lane.

We used the outcome of the microsimulation and the DOE to establish a decision support system. The response, average maximum right-turn throughput (MRTT) per cycle, was categorized into categorical variables representing the efficiency attributes of the two FYA signal phases. The observations were extracted from the DOE’s scenarios in a set of random seed replications. We took this step to develop a discreet choice model that can allow decision makers to assess the efficient application of a permissive FYA signal during RTOIT, and RTOIL phases using a set of significant parameters.

BACKGROUND

The right-turn treatment is defined by three main factors for each approach; Lane usage (shared, exclusive, or channelized), the right turn on red acceptance (allowed or prohibited), and right-turn movement mode type (permissive, protected, or both). Dedicated right turn lane phasing is operated the same way as the left-turn phasing when there is an exclusive right-turn lane. It can operate as Per, PO or PPRT. The traditional PPRT has been a five-section configuration until the 2009 MUTCD recommended the use of four-section configuration as shown in Figure 1 due to its safety benefits (Casola 2018, Hurwitz, D., Monsere, C., Kothuri, S., Jashami, H., Buker, K., & Kading, A. 2018, Noyce and Knodler 2017).

The PPRT signal allows four permissive right-turn movements: the circular red that involve right-turn on impeding through (RTOIT) phase and the right-turn on impeding left (RTOIL) phase. Moreover, a permissive right turn is also allowed during the adjacent through lane's circular green and a protected right-turn green arrow during the overlap phase with the crossing left turn while the U-turn is prohibited. The overlap phasing also requires a five or four section head signal. The right-turn on adjacent through (RTOAT) phase occurs during the adjacent through lanes' circular green signal and is impeded only by pedestrians crossing the side street. It is permitted to display FYA indications for a permissive right-turn movement while the signal for the adjacent through movement displays steady circular green indications (MUTCD 2009). The right-turn on impeding through (RTOIT) is impeded by the cross-street through traffic and any pedestrian crossing the main street. The right turn on impeding left (TROIL) is impeded only by the opposing left-turn traffic. Figure 2 illustrates the four permissive right turn movements including protected overlap, permissive RTOIT, permissive RTOIL, and the permissive RTOAT phases.

A protected right turn requires an exclusive right-turn lane that separates the right-turn movement from an adjacent through movement (FHWA 2015 a; Hurwitz et al. 2018). According to the National Cooperative Highway Research Program (NCHRP) Report 279, Neuman (1985) conducted a study on right-turn treatments and found that right-turn volumes, right-turning rear end crashes, and/or pedestrian crossing volumes were significant factors that justified the need for exclusive right-turn lanes at signalized intersections. Additionally, the existence of an exclusive right-turn lane was found to efficiently improve the overall operation and safety of intersections (Hurwitz et al., 2018; ODOT, 2012). (Dixon, Hibbard et al. 1999, Rodegerdts, Nevers et al. 2004) observed that the use of exclusive right-turn lanes, islands, and traffic control devices at signalized intersections improved the traffic operationssand safety of right-turning traffic.

Pedestrian crossing at signalized intersections conflicts with many traffic maneuvers. A permissive right-turn relies only on an acceptable gap in the impeding incoming traffic to maneuver, including bicycles and pedestrians (FHWA 2015, Hurwitz, Monsere et al. 2018). Motorists turning right on circular green must yield to pedestrians crossing on a walk signal from side streets (Herman 2002). Therefore, "Yield to Pedestrians" or "Pedestrians Watch for Turning Vehicle" signs are commonly used to mitigate pedestrian related risks in conjunction with turning traffic (Zegeer, Opiela et al. 1982). Pedestrians are usually assigned to cross simultaneously with the through-traffic movement whereas vehicles and bicycles are expected to yield before turning right (FHWA 2015 b). The literature review showed that drivers have a strong understanding of the right-turn FYA and found that the addition of the proposed FYA message led to lower levels of confusion upon full implementation (Casola 2018, Hurwitz, D., Monsere, C., Kothuri, S., Jashami, H., Buker, K., & Kading, A. 2018, Noyce and Knodler 2017).

Right turn on red (RTOR) allows right-turn traffic to make a right-turn movement after yielding to pedestrians and impeding traffic. In general, vehicular traffic may turn right on red after a full stop and yield to pedestrians and impeding traffic (FHWA 2015, Herman 2002). Many studies have researched the RTOR and found that allowing right turns on red leads to operational delay reduction, positive environmental effect, and energy consumption reduction (Herman, 2002; McGee, H. W., Stimpson, W. A., Cohen, J., King, G. F., & Morris, R. F 1976). Hurwitz, et al. (2018) studied the implementation of the flashing yellow indication on a permissive right turn to investigate the safety and operational effectiveness of implementing FYA at exclusive right-turn lanes. The objective was to examine the operational performance of several PPRT phasing alternatives under multiple volume levels. The study shows the percent difference in delay for six scenarios by increasing the EB left-turns and WB right-turns up to 25% and the pedestrian volumes to 100%, compares to the base scenario. Moreover, the various PPRT phasing alternatives during the impeding through and impeding left phases showed little to no change in delays with an increase of right-turn volumes and impeding volume of pedestrians. It was found that drivers turning right on the FYA display significantly showed higher visual attention compared to when they are turning on a permissive circular green indication (Hurwitz, Monsere et al. 2018, Noyce and Knodler 2017).

The Technical Council Committee 4M-20 was established by the Institute of Transportation Engineers to investigate driver behavior on RTOR. The RTOR movements accrues on CIRCULAR RED signal indications during the movement of the impeding through and left-turns. The committee found that 1) RTOR maneuvers equal up to 39.2% of all right-turn movements, 2) 40.4% of drivers on RTOR do not come to a full stop before proceeding to the intersection and 3) 95% of right turners on red who had the opportunity to right-turn on red did so (Wagoner, 1992). The RTOR indication signal uses three or five section head signal systems that could be replaced by a four section head signal that support the right-turn FYA indication signal. The MUTCD stated that "It shall be permitted to display a flashing right-turn yellow arrow signal indication for a permissive right-turn movement while the signal faces for the adjacent through movement display steady CIRCULAR RED signal indications" (MUTCD 2009).

The literature review revealed that there are a lot of studies related to the safety aspects and comprehension of the four-section configuration. Most previous studies confirmed that the FYA indication performs as well as or outperforms the circular green (CG) indication in terms of driver comprehension and safety. However, there are no right-turn FYA or PPRT guidelines in place with a focus on operational efficiency. There is a crucial need to conduct research for permissive right-turn FYA and to develop operational warrants for the efficient implementation of the permissive phase as demonstrated in the recent NCHRP 03-136 call to evaluate the performance of RTOR operation at signalized intersections with single and dual right-turn lanes. This paper is dedicated to develop warrants for the efficient implementation of the permissive right-turn FYA phase.

METHODOLOGY

We extensively researched the measures of effectiveness that properly assess a permissive right-turn phase. We applied the number of sneakers frequency to appropriately predict the efficiency attribute of a permissive right-turn FYA signal phase. A sneaker is defined as a vehicle that waits before the stop line of an intersection and departs after the green time ends (Wu 2011). The Highway Capacity Manual (HCM 2010) defined sneaker as a number of left turns per cycle that departed at the end of a permissive phase. It is an accepted practice in the traffic field to assume two sneakers per cycle during permissive phases (Martin et al., 1998). Wu (2011) proposed a mathematical model to predict the probability that the share lane is blocked by a permitted turning vehicles and adopted two sneakers per cycle according to the approximation formulas (Harders 1968). The model was applied to permissive shared left-turn and right-turn lanes.

As mentioned earlier, the focus of this paper is RTOIT and RTOIL. Each permissive right-turn phase was investigated in a separate systemic stochastic analysis using a set of impeding traffic flows, impeding phase intervals, and/or impeding pedestrian volumes. The average maximum right-turn throughput (MRTT) per cycle was the main measure of effectiveness (MOE) used to assess the efficiency of a permissive right-turn FYA phase. The sneakers usually find no gaps during the impeding green interval and use only the amber and/or clearance intervals to depart. Therefore, the research methodology assumed that a permissive right-turn FYA phase is not considered feasible and accordingly not warranted, if the number of right turn vehicles is less than two per cycle on an impeding phase. The average MRTT per cycle results obtained from the design of experiment were categorized into three efficient attributes. Firstly, the non-efficient (NE) attribute, which highlights all MRTT results that have an average MRTT per cycle less than or equal to two right-turns. Secondly, the low efficient (LE) attribute, which represents results with an average MRTT ranging from 2.0 to 3.0 throughputs per cycle. And thirdly, the efficient (E) attribute, which was represented by an average MRTT per cycle of three throughputs or more per cycle.

Microsimulation is a tool used to perform reliable traffic operations assessments. It is capable of simulating roadway segments and intersections in a network , traffic signals and vehicular and pedestrian operations. The reliability and the applicability of microsimulation applications vary in terms of imitating the new designs, ability of simulating signal control practices and/or import signal plans from other tools, and the capability of the operation of the simulation for different replications and random seeds (El Esawey & Sayed 2013). VISSIM Version 10.02, a stochastic microsimulation tool developed by the PTV group was used to simulate the PPRT signal phasing scenarios. It produces a set of traffic measurements as well as simulate movement, approach, link, route, area, and other pedestrian operations (Siromaskul & Speth 2008).

Study Intersection

There are few signalized intersections in Central Florida implementing the four-section configuration for right-turns.thereforethe study intersection utilized an existing five-section signal head with a protected permissive right-turn display in lieu of the FYA. Three candidate locations with a five-section signal display were proposed. The research team selected the Alafaya Trail at Lake Underhill Road intersection to be the main signalized intersection in this study due to its heavy traffic and geometry qualification overview. The signal timing plan for this intersection was obtained from Orange County Traffic Engineering Division. It runs as an 8-phase operation, with four protected left-turn phases and a protected/permissive right-turn phase in the westbound approach. The studied PPRT phase (westbound to northbound movement) displayed three signal indications. 1) A protected green arrow indication appeared during the non-conflicting southbound left turn phase overlap with prohibited U-turns. 2) A circular green indication was displayed during the adjacent westbound through movement. 3) A circular red indication was displayed during the northbound through movement. Turning movement count (TMC) data along with vehicle speed profiles and pedestrian volume counts were provided for this intersection from the maintaining agency.

The intersection under study, Alafaya Trail at Lake Underhill Road, is located in Orlando, Florida, on two major urban arterials that serve heavy traffic volumes along several signalized intersections in East Orlando. The southbound direction along Alafaya Trial has double through lanes, an exclusive right-turn lane, and exclusive double left-turn lanes. The northbound direction has double through lanes, one shared through/right lane, and double exclusive left-turn lanes. Lake Underhill Road serves double through lanes, an exclusive right-turn lane, and exclusive double left-turn lanes in the eastbound direction. The westbound approach has double through lanes, an exclusive right-turn lane (WBR), and an exclusive left-turn lane. Figure 3 shows an aerial as well as a modeled view in VISSIM with the highlighted WBR in red box. The movement under study is the exclusive westbound right turn with five-section head display which allowed a protected permissive right turn operation. The studied intersection is considered a high-demand traffic intersection and saturated at all approaches, especially during peak hours. Vehicle composition included 98% passenger cars and 2% heavy vehicles, based on the data obtained from Orange County, Florida. The morning and evening peak hour turning movement volumes along with the signal timings were obtained from Orange County Traffic Engineering Department. The intersection was modeled in VISSIM and calibrated and validated based on field observations related to delay and queuing using Jamar equipment to replicate local driving conditions. Field observations were conducted for the evening peak hour and broken down into 5 minute-interval for a total of 12 input data which were used in the calibration process. The morning data was used in the validation process. The final model was used in the Design of Experiment (DOE) scenarios.

The VISSIM software utilized the car-following model based on Wiedemann and Fellendorf (Wiedemann & Reiter, 1991). The Wiedemann model involves 10 driver behavior parameters. the car-following model parameters controls an aspect of the car following model (Woody 2006). To achieve an accurate model that replicates the existing condition, we had to identify a proper set of driver parameters. The default parameters set in VISSIM obtained an accurate model that matched the model outputs and the field Turning Movement Counts (TMCs) at less than 3% error. Moreover, the outputs of the VISSIM model implementing the driving parameters were replicated at 97% of the field traffic conditions for all the approach movements' volumes.

Design of Experiment

The experiment included a multi-level factorial design that assessed the permissive phase attributes at multiple traffic and signal timing levels. Four main parameters were considered in the design of experiment based on the previous studies that demonstrated their effect on the permissive right-turn maximum throughput (Tarko 2001, HCM 2010, Creasey, Stamatiadis et al. 2011). The parameters included the impeding vehicular flow at the rightmost lane in the northbound direction, impeding green interval (IGI), expected signal cycle, and impeding pedestrian volume during the impeding through phase only.

VISSIM software cannot be used to allocate volume per lane for an exact lane, rather it can be used for the whole movement volume. The intersection under study, Alafaya Trail at Lake Underhill Road is designed with shared through/right lane in the northbound. Therefore, to maintain a uniform traffic volume distribution in the impeding through traffic lanes in the northbound direction due to the third shared through movement, the through lane was converted in VISSIM to an exclusive right-turn bay. Furthermore, the methodology assumed that the number of impeding inbound left-turn lanes equals the number of lanes of the outbound approach. Thus, RTOIL motorists rely only on the gaps generated between the impeding eastbound opposing left traffic at the rightmost lane. For example, if an impeding left inbound approach was designed with double lanes but the outbound approach was designed with triple through lanes, the additional lane would motivate the right-turn traffic in VISSIM to use it to turn right without yielding to the impeding left traffic which is not a realistic situation that’s why the third northbound through lane was eliminated in this scenario and converted to an exclusive right turn lane. This situation served both scenarios.

It was deemed necessary to design two experiments that encompass the proper measure of effectiveness. To appropriately obtain accurate maximum right-turn throughputs results, the exclusive studied right-turn input volumes were increased enough in each scenario in order to ensure a continuous right-turn demand throughout the experiment. The right turn volume levels ranged between 450 and 650 which was exceeding the capacity of the right lane.

Right-Turn on Impeding through (RTOIT) DOE

The RTOIT DOE included four main parameters; impeding flows, Impeding Green Interval (IGI), cycle length, and pedestrian volumes each with different number of levelsas shown in Table 1. The measures of effectiveness (MOE) were obtained for the various vehicular flows and pedestrian volumes at several signal timing plans to assess the efficiency of a permissive RTOIT FYA phase. The DOE resulted in 3*3*4*3=108 different scenarios in random replication runs. The signal timing plan involved three levels of hypothetical pedestrian volumes in pedestrians per hour (pph) and four levels of hypothetical impeding flow volumes in vehicles per hour per lane (vph/ln), each at a fixed IGI interval. The pedestrian volume levels ranged from 50 to 300 pph . The impeding through flows to capacity ratios for the four incremental impeding volumes were designed to range from 0.70 and not to exceed 1.10.

The pedestrian phases during the RTOIT were designed as a concurrent pedestrian phase that allows pedestrians to simultaneously walk parallel to the green-indication-receiving vehicular traffic. Specifically, the impeding pedestrian phase was optimized to receive the walking phase display immediately as the northbound through lanes received the green indication. Synchro version 9.0 software was used to optimize the signal timing plans proposed in the DOEs. Pretimed control was adopted in this research with fixed green times to fulfill the DOE’s signal timing plans.

RTOIT Results and Analysis

Table 1 lists the design of experiment parameters and levels as well as the RTOIT MRTT results obtained from the microsimulation in vehicle per hour (vph) using a random set of 10 replication runs for each scenario. The right-turn throughput was collected on a second-by-second basis for 1 hour. We used Excel spreadsheets to accumulate the right-turn throughputs occurring simultaneously with the impeding through phase based on the signal display outputs provided in VISSIM. Table 2 summarizes the MRTT in vehicles per cycle to determine the efficiency category for the right turn FYA phase. The average MRTT per cycle was obtained by averaging the MRTT per hour (vph) to the number of cycles.

Based on the efficiency categorical score, Category 1, highlighted in red, represents all non-efficient scenarios with an average MRTT per cycle equal or less than 2.0 throughputs per cycle. Category 2, highlighted in orange, is all the low efficient scenarios with a range of an average MRTT per cycle from 2.1 to 2.9. Category 3, highlighted in green, is all efficient scenarios that were equal to or more than 3.0 average throughputs per cycle. This step was considered to achieve efficiency-based scores that were derived from the number of sneakers per cycle methodology.

Tables 1 and 2 illustrate the decreasing trend in the MRTT at the same cycle length and IGI with the increase in pedestrian and vehicular flow rate. Figure 4 shows the MRTT per cycle at the lowest cycle length (c=120 sec) and g/C ratio of 1/6 which translates into IGI of 20 seconds. It also demonstrates a non-efficient scenario when pedestrian flow is heavy. The results also revealed that the effect of pedestrian flow on MRTT vanishes with the increase in IGI interval as seen in the case of IGI=60 seconds.

In conclusion, a RTOIT FYA signal is highly recommended during an efficient FYA phase complimented with a yield to pedestrian blank out sign (BOS) to alert the right-turn motorists to yield for pedestrians walking concurrent with the impeding through traffic. A red indication complimented with BOS of NO-TURN ON RED on the impeding interval is strongly recommended during non-efficient and low-efficient FYA phases.

Right Turn on Impeding Left-turn (RTOIL) DOE

The RTOIL DOE included three main parameters, each with different number of levels. They included cycle length (3 levels) and g/C ratio (4 levels) which resulted in twelve different impeding green interval (IGI) levels, and the impeding left-turn flow rates (4 levels) to assess a permissive RTOIL FYA phase as shown in Table 3. MOE was obtained for the various vehicular flows at the twelve signal timing plans to assess the efficiency of a permissive RTOIL FYA phase. The experimental design resulted in 3*4*4=48 different scenarios in random replication runs. The signal timing plan involved four levels of hypothetical impeding flow volumes in vehicle per hour per lane (vph/ln), each at a fixed IGI interval. The impeding through flows to capacity ratios for the rightmost left lane were designed to range from 0.75 to 1.3.

RTOIL Results and Analysis

The research aimed to develop warrants for the efficient implementation of a right-turn FYA phase during the opposing left phases. Similar to the RTOIT, the average MRTT per cycle (vpc) was used to categorize the results from the experiment into three categories based on an efficiency categorical score. Category 1, highlighted in red, illustrates all non-efficient scenarios with an average MRTT per cycle equal or less than 2.0 throughputs per cycle. Category 2, highlighted in orange, shows all the low efficient scenarios with a range of an average MRTT per cycle from 2.1 to 2.9 and Category 3, highlighted in green, is for all efficient scenarios that were equal to or more than 3.0 average throughputs per cycle as shown in Table 4. This step was considered to achieve efficiency-based scores that were derived from the number of sneakers per cycle methodology.

The average MRTT per cycle was obtained by averaging the MRTT per hour (vph) to the number of cycles.

Tables 3 and 4 illustrate the decreasing trend in the MRTT at the same cycle length and IGI with the increase in vehicular left-turn flow rate. Figure 5 shows the MRTT per cycle at two different cycle lengths but with a relatively high IGI (30 seconds) which is showing almost the same throughput per cycle in the low efficiency category (2.9<MRTT<2.1). The results also revealed that the MRTT reaches the efficient category only when IGI exceeds 40 seconds. To conclude, a red indication complimented with a BOS of NO TURN ON RED on the impeding interval is strongly recommended during a non-efficient RTOIL phase.

PERMISSIVE RIGHT-TURN FYA EFFICIENCY MODELING

The right-turn throughputs were collected on a second-by-second basis for one hour during the permissive RTOIT and RTOIL from the two DOEs. Specifically, the RTOIT MRTT results were obtained by accumulating all the right-turn throughputs that occurred simultaneously with the impeding through during the northbound through phase. Moreover, the RTOIL MRTT results were obtained by accumulating all the right-turn throughputs that occurred simultaneously with the impeding opposing left during the eastbound left phase. The signal display outputs provided by VISSIM were used to determine the RTOIT and RTOIL phases for all cycles. Finally, Excel spreadsheets were used to count the MRTT for all the scenarios.

The stochastic results collected from the RTOIT and RTOIL DOEs were listed in one dataset that involved about 800 observations in a set of random seed replications. The dataset included six independent variables and three categorical response variables. The pedestrian volume per cycle was assumed to be zero for all the RTOIL scenarios because the RTOIL DOE was designed without considering pedestrian volume as an independent variable. Furthermore, the dataset was built with a new categorical binary independent variable representing the impeding approach type to properly assess the potential performance difference between the RTOIT and the RTOIL FYA phases. The response; the average MRTT per cycle, was categorized into three dummy variables represented as the non-efficient (NE), low efficient (LE), and efficient (E) categories. A multinomial logit model was developed to predict the efficiency attributes of a permissive RTOIT or RTOIL FYA signal phase using the aforementioned parametric variables.

The RTOIT and RTOIL efficiency attributes were predicted using a set of continuous and categorical binary predictors. The impeding flows were replaced by the impeding flow to capacity ratios (IFTCR) to accurately measure the impact of the impeding flow for any G/C signal plan. The impeding green interval, cycle length, pedestrian volume per cycle, and IFTCR were used as continuous variables. The impeding approach was listed as a categorical binary variable that represents the RTOIL FYA phase relative to the base category (RTOIT FYA phase). The MNL model results showed that the cycle length variable was statistically insignificant and correlated with other variables. Thus, it was dropped from the model's variables and consequently the pedestrian volume variable was listed in pedestrian per cycle instead of hour. The model initially included all variables and then excluded the statistically insignificant variables based on 95% confidence level.

Model Estimation Results

The coefficients listed in Table 5 and Table 6 demonstrate the statistically significant effect of the listed variables on the RTOIT and RTOIL FYA efficiency attributes relative to the base category (NE).

It should be noted that a pooled system was developed using datasets from both phases (RTOIT and RTOIL) together to improve the estimation efficiency. To elaborate, a base effect was estimated for each exogeneous variable that is common across the two datasets and then estimate deviations for different FYA phases (Bhowmik et al., 2019). As we have two FYA phases to model, we can typically estimate one base effect and one deviation term within each alternative (2 in this case). The t-statistics of the deviation variable will offer insights on the significance of the deviation term from the base effect. If the deviation term is insignificant for one variable, it concludes that particular variable does not offer different impacts across the two FYA phases. For example, in the current analysis, we tried one base effect (common across the datasets) of impeding green interval (IGI) and one deviation term with the RTOIT phase only within each alternative (LE and E). However, we did not find the deviation term to be significant which highlights that this variable does not have differential sensitivity across RTOIT and RTOIL phases. Therefore, the coefficient of IGI will be same (in magnitude) in both efficiency models. Similarly, we did not find any significant differential effect of the constant and IFTCR term across the two models as indicated by the same magnitude of these variables in Table 5 and 6.

In terms of the goodness of fit measure for the model, we computed ρ_c^2[1] which represents the improvement (value 0 means no improvement and 1 means perfect) from the constant only model. In our analysis, we find the value of ρ_c^2 to be 0.75. The parameters' results and estimates are discussed in the following section:

Impeding green interval (IGI). The impact of impeding green on the RTOIT and RTOIL FYA phases indicates that longer impeding green intervals improve the likelihood of achieving an efficient FYA during the RTOIT and RTOIL phases. The impeding green intervals were statistically significant when predicting the maximum right turn throughput on red phases. The positive sign for the impeding green interval parameter increases the likelihood of reaching an efficient or low efficient FYA phase.

Impeding flow-to-capacity ratio (IFTCR). The effect of the impeding saturation flow ratio demonstrates that the RTOIT and RTOIL FYA phases are less likely to be efficient during a saturated impeding flow movement. Moreover, the model results indicate that the negative sign of the IFTCR parameter contributes to reducing the likelihood of achieving an efficient or low efficient RTOIT or RTOIL FYA signal phases as the IFTCR increases.

Impeding pedestrian volume per cycle. The impact of the impeding pedestrian volume per cycle indicates that the probability of efficient or low-efficient RTOIT FYA signal phases reduces with increased pedestrian volume per cycle, especially at short impeding green intervals which was reflected in the negative sign parameter. It was also found that pedestrian activity impeded the right-turn movement and increased the total delay at the intersection.

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[1] $\rho_c^2 = 1 - (\frac{L(B)}{L(C)})$; where $L(B)$ = log-likelihood at convergence and $L(c)$ = log-likelihood for constant only model (sample share model).

Impeding left-turn approach. The effect of the impeding left-turn approach indicates that the implementation of an efficient RTOIL FYA signal phase is less likely. The right-turn traffic was found more conservative in making a right turn on the RTOIL than the RTOIT. To conclude, the model outputs indicate that the left-turn approach decreases the probability of implementing an efficient FYA signal phase during the impeding left phase.

CONCLUSIONS

The developed DOEs investigated two permissive right-turn patterns; RTOIT, and RTOIL under a set of parameters. The permissive right-turn FYA phases were investigated in separate models to warrant an efficient right-turn FYA phase. The DOEs were developed using a set of parametric variables including an impeding flow, an impeding green interval, a cycle length, and a pedestrian volume.

The maximum right turn throughput was the main and only MOE used in the DOEs to assess the efficiency attributes for the permissive right turn FYA phases. The MRTT vph was used in many studies to predict the right turn capacity on a permissive right turn phase (Tarko 2001, Creasey, Stamatiadis et al. 2011). The microsimulation analytical procedures were conducted using VISSIM version 10.02 software. VISSIM models were developed using validated networks to investigate the two permissive right-turn FYA patterns.

Discrete choice modeling procedures were established to develop a decision support system. The response, average MRTT per cycle, was categorized into a couple of dummy variables representing the efficiency attributes for the permissive right-turn FYA signal phases. Almost 800 observations were extracted from the DOE scenarios to develop the MNL model. The developed models should help traffic operators determine the efficiency attributes of permissive right-turn FYA on the RTOIT and the RTOIL phases.

The RTOIT and RTOIL experiments outcomes were unique and appropriately predicted the efficient implementation of a right-turn FYA signal phase during the impeding through and opposing left phases. The impeding green interval and IFTCR, pedestrian per cycle and the impeding left approach were significant parameters and recommended to be used in predicting the efficiency of the RTOIL and RTOIT FYA phases.

A right-turn FYA is highly recommended during an efficient FYA phase with a blank out sign (BOS) of “Yield to Pedestrian” to alert right-turning motorists to yield for pedestrians walking concurrently with the impeding through traffic. A red indication complimented with a BOS of “No Turn on Red” on the impeding interval is recommended during the non-efficient and low-efficient FYA phases because the FYA efficiency attribute is unlikely feasible through all cycles.

RESERACH PRACTICALITY AND IMPLEMETATION

It is worth noting that the results of this research can be generalized for implementation purposes. Table 2 (with impeding through) and Table 4 (with impeding left) are used to determine the number of right turns per cycle under specific operating conditions and whether it will be efficient or not given that less than 2 vehicles per cycle is considered inefficient. The value can then be multiplied by the number of cycles per hour to calculate the threshold of the total hourly volume of right turns. If the hourly volume is fulfilled, then a FYA phase is warranted. If it is exceeded, then a protected phase is needed, or it could be a combination between a protected phase and a FYA phase. It should be noted that Tables 1 and 3 directly display the hourly volume thresholds. However, the results in Tables 2 and 4 were utilized in modeling the efficiency attributes per cycle.

Figures 4 and 5 are graphical representation of the results and can be used to calculate the hourly thresholds in conjunction with the tables. The graph is entered from the X-axis with the number of impeding flow (through flow in Figure 4 or left turn flow in Figure 5 and by selecting the specific graph representing a cycle length to determine the number of right turns per cycle). Figures 4 and 5 also display the thresholds that define the 3 efficiency levels; below threshold 1 is inefficient (less than 2 vehicles per cycle), between thresholds 1 and 2 is low efficiency (from 2-3 veh/cycle) and above threshold 2 is efficient (more than 3 veh/cycle).

The design of experiment developed in this study solved the problem of extraneous variables such as the driver behavior by using a volume to capacity ratio exceeding one for right turning traffic during the peak hour in a heavily congested intersection. The analysis was based on the amount of traffic that was able to sneak in available gaps in the impeding flow to make the right turn. In general, these conditions include both aggressive drivers as well as conservative drivers.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Hatem Abou-Senna, Essam Radwan, Mohammed Alfawzan; data collection: Mohammed Alfawzan; analysis and interpretation of results: Tanmoy Bowhmik, Naveen Eluru, Mohammed Alfawzan; draft manuscript preparation: Mohammed Alfawzan, Salma El Zayat, Hatem Abou-Senna and Muneer saeed. All authors reviewed the results and approved the final version of the manuscript.

DATA AVAILABILITY STATEMENT

Some or all data, models, or a third party provided code used during the study. Direct requests for these materials may be made to the provider as indicated in the Acknowledgements.

ACKNOWLEDGEMENT

The authors would like to thank Orange County Traffic Engineering Division for their help in providing the data needed for this research. The data included turning movement counts during the pm peak hour, pedestrian counts and signal timing.

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FIGURES CAPTIONS

Figure 1. Five-section and four-section head displays for right turns (source: MUTCD 2009).

Figure 2. Four permissive right turn movements (source: FHWA 2015).

Figure 3. Study intersection at Alafaya Trail and Lake Underhill Road

Figure 4. Effect of vehicular and pedestrian flow on RTOIT MRTT (C=120, IGI=20 Sec)

Figure 5. Effect of vehicular flow and Cycle Length on MRTT (IGI=30 Sec)

Table 1 RTOIT Design of Experiment and MRTT Results in VPH

Impeding phase G/C Ratio	Impeding Flow (vph/ln)	Cycle Length =120 s				Cycle Length =150 s				Cycle length =180 s			
		IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph	IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph	IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph
$1/6$	L1= 200	IGI= 20 s	73	65	59	IGI= 25 s	61	50	44	IGI= 30 s	62	56	52
	L2= 220		66	61	51		54	50	41		60	54	54
	L3= 240		62	58	49		51	46	38		55	52	49
	L4= 260		58	53	46		48	43	36		52	50	45
$1/4$	L1= 300	IGI= 30s	105	96	86	IGI= 38 s	88	81	79	IGI= 45 s	90	86	85
	L2= 330		93	87	79		82	78	73		84	82	80
	L3=360		88	82	73		76	73	70		76	75	74
	L4= 390		82	79	71		68	66	65		72	68	66
$1/3$	L1= 400	IGI= 40 s	126	119	112	IGI= 50 s	124	121	117	IGI= 60 s	122	121	122
	L2= 440		119	115	109		120	109	109		113	107	109
	L3= 480		108	103	104		104	101	100		101	101	100
	L4= 520		98	95	92		99	91	90		93	93	93

Table 2 RTOIT MRTT in Vehicles per Cycle (VPC)

Impeding phase G/C Ratio	Impeding Flow (vph/ln)	Cycle Length =120 s				Cycle Length =150 s				Cycle length =180 s			
		IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph	IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph	IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph
1/6	L1= 200	IGI= 20	2.4	2.2	2.0	IGI= 25	2.5	2.1	1.8	IGI= 30	3.1	2.8	2.6
	L2= 220		2.2	2.0	1.7		2.3	2.1	1.7		3.0	2.7	2.7
	L3= 240		2.1	1.9	1.6		2.1	1.9	1.6		2.7	2.6	2.4
	L4= 260		1.9	1.8	1.5		2.0	1.8	1.5		2.6	2.5	2.2
1/4	L1= 300	IGI= 30s	3.5	3.2	2.9	IGI= 38 s	3.7	3.4	3.3	IGI= 45 s	4.5	4.3	4.3
	L2= 330		3.1	2.9	2.6		3.4	3.2	3.1		4.2	4.1	4.0
	L3=360		2.9	2.7	2.4		3.2	3.0	2.9		3.8	3.8	3.7
	L4= 390		2.7	2.6	2.4		2.9	2.8	2.7		3.6	3.4	3.3
1/3	L1= 400	IGI= 40 s	4.2	4.0	3.7	IGI= 50 s	5.2	5.0	4.9	IGI= 60 s	6.1	6.1	6.1
	L2= 440		4.0	3.8	3.6		5.0	4.5	4.5		5.6	5.4	5.5
	L3= 480		3.6	3.4	3.5		4.3	4.2	4.2		5.1	5.1	5.0
	L4= 520		3.3	3.2	3.1		4.1	3.8	3.8		4.6	4.7	4.7

Table 3 RTOIL Design of Experiment and MRTT Results in VPH

Impeding G/C Ratio	Impeding Flow (vph)	IGI (s)	C=120 s	IGI (s)	C=150 s	IGI (s)	C=180 s
1/10	L1= 110	IGI=12 s	56	IGI=15 s	51	IGI=18 s	46
	L2= 130		51		41		40
	L3=150		43		37		35
	L4= 160		42		33		33
1/8	L1= 140	IGI=15 s	58	IGI=19 s	52	IGI=22 s	52
	L2= 170		52		44		42
	L3=180		45		39		40
	L4= 190		42		37		38
1/6	L1=200	IGI=20 s	63	IGI=25 s	65	IGI=30 s	57
	L2= 220		58		54		52
	L3= 240		53		52		47
	L4= 260		44		45		43
1/4	L1= 300	IGI=30 s	84	IGI=37 s	78	IGI=45 s	79
	L2= 330		78		68		68
	L3=360		72		61		61
	L4= 390		61		51		54

Table 4 RTOIL MRTT in Vehicles per Cycle (VPC)

Impeding G/C Ratio	Impeding Flow (vph/ln)	IGI (s)	C=120 s	IGI (s)	C=150 s	IGI (s)	C=180 s
1/10	L1= 110	IGI=12 s	1.9	IGI=15 s	2.1	IGI=18 s	2.3
	L2= 130		1.7		1.7		2.0
	L3=150		1.4		1.5		1.8
	L4= 160		1.4		1.4		1.6
1/8	L1= 140	IGI=15 s	1.9	IGI=19 s	2.2	IGI=22 s	2.6
	L2= 170		1.7		1.8		2.1
	L3=180		1.5		1.6		2.0
	L4= 190		1.4		1.5		1.9
1/6	L1=200	IGI=20 s	2.1	IGI=25 s	2.7	IGI=30 s	2.9
	L2= 220		1.9		2.3		2.6
	L3= 240		1.8		2.2		2.4
	L4= 260		1.5		1.9		2.2
1/4	L1= 300	IGI=30 s	2.8	IGI=37 s	3.2	IGI=45 s	3.9
	L2= 330		2.6		2.8		3.4
	L3=360		2.4		2.5		3.0
	L4= 390		2.0		2.1		2.7

TABLE 5 RTOIT Efficiency MNL Model Estimates

	Non-efficient (NE)	Low-Efficient (LE)		Efficient (E)	
Variables	—	Estimate	T-stat	Estimate	T-stat
Constant	—	10.9629	5.122	13.4152	4.456
IGI	—	0.3765	8.755	1.0532	11.816
Pedestrian Per cycle	—	-0.3899	-6.725	-0.7021	-8.446
IFTCR	—	-17.7709	-7.892	-44.2408	-10.442

TABLE 6 RTOIL Efficiency MNL Model Estimates

	Non-efficient (NE)	Low-Efficient (LE)		Efficient (E)	
Variables	—	Estimate	T-stat	Estimate	T-stat
Constant	—	10.9629	5.122	13.4152	4.456
IGI	—	0.3765	8.755	1.0532	11.816
IFTCR	—	-17.7709	-7.892	-44.2408	-10.442
Left-turn Approach	—	-1.6735	-3.487	-8.8657	-7.892