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# Safety Evaluation of Continuous Green T Intersections

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This document is a technical summary of the Federal Highway Administration report, *Safety Evaluation of Continuous Green T Intersections* (FHWA-HRT-16-036).[1]

## Objective

The Federal Highway Administration (FHWA) organized 40 States to participate in the FHWA Evaluation of Low-Cost Safety Improvements Pooled Fund Study as part of its strategic highway safety plan support effort. The purpose of the study was to evaluate the safety effectiveness of low-cost safety improvement strategies through scientifically rigorous crash-based studies. One of the strategies evaluated for this study is the use of continuous green T (CGT) intersections at three-leg locations. This treatment allows for a continuous through movement on the major street with a channelized left-turn movement from the minor street onto the major street.

Past research has shown that environmental and operational benefits of CGT intersections, when compared with conventional signalized intersections, include reductions in delay, fuel consumption, and emissions.[2,3] Research on the safety effects of CGT intersections has been limited in scope and statistical significance.

This study sought to fill this knowledge gap by examining the safety effectiveness of CGT intersections in terms of crash frequency using the propensity scores-potential outcomes framework. A benefit–cost (B/C) analysis compared the safety benefits to the construction costs of a CGT relative to a conventional signalized three-leg intersection.

## Introduction

Intersection safety is a priority for transportation agencies in the United States since at-grade intersections are inherent conflict locations on highway and street networks. Alternative intersection designs have emerged in recent years to improve traffic operations and safety. CGT intersections are an alternative to conventional signalized intersections with three approach legs.

CGT intersections are characterized by a channelized left-turn movement from the minor street approach onto the mainline (major street), along with a continuous mainline through movement that occurs at the same time.[4] The continuous-moving through lanes are not controlled by a traffic signal phase, while the other intersection movements are controlled by a three-phase signal. The through lanes on the mainline that have continuous flow typically contain a green through arrow signal indicator to inform drivers that they do not have to stop. The continuous through lanes are often separated from the left-turn and merge lanes with delineators, curbed islands, pavement markings, or other separations.

A literature review found that research on the safety and operational effects of CGT intersections has been relatively limited. With regard to safety, crash-type proportion analyses have indicated that continuous flow movements at CGT intersections do not differ from the through lanes in the opposing direction. Additionally, published literature suggests that the proportion of sideswipe crashes on continuous flow lanes on a major road are higher relative to opposing through lanes, but there were not significant differences in other crash types.[5] No statistically significant differences among severity outcomes have been reported when comparing CGT continuous flow lanes to lanes in the opposing direction. With regard to operations, published research indicates that vehicle delay, emissions, and fuel consumption are lower at CGT intersections relative to traditional signalized T intersections.[5]

This study builds on the existing research by examining the safety effectiveness of CGT intersections in terms of crash frequency using the propensity scores-potential outcomes framework and data from multiple States.

## Methodology

This study used data from Florida and South Carolina, two States with multiple CGT intersections that have existed for several years. The sample was composed of 30 CGT and 38 comparison intersections in Florida and 16 CGT and 21 comparison intersections in South Carolina. The Florida Department of Transportation and the South Carolina Department of Transportation supplied the traffic volume and crash data. Where traffic volume data were not available, the missing data were either obtained from local jurisdictions or estimated using the Institute of Transportation Engineers' *Trip Generation Manual* based on the land use near the intersections.[6]

### Propensity Scores-Potential Outcomes Framework

To examine the safety effectiveness of CGT intersections in terms of crash frequency, the propensity scores-potential outcomes framework described by Sasidharan and Donnell was used.[7] In this analysis, the CGT intersections were compared with the safety performance of traditional, signalized T intersections. The following target crashes were included in the evaluation:

- Total crashes within 250 ft of the intersection.
- Fatal and injury crashes within 250 ft of the intersection.
- Rear-end, angle, and sideswipe crashes within 250 ft of the intersection.

Harwood et al. defined the 250-ft measure as the boundary for intersection-related crashes when assessing the safety performance of left- and right-turn lanes at three- and four-leg stop- and signal-controlled intersections.[8] It should be noted that, in some instances, crashes located within 260 ft of the intersection were included in the South Carolina analysis because the data were codified such that the 250-ft boundary could not be identified.

An observational before-after evaluation (e.g., using the empirical Bayes (EB) method) could not be used in this study because of a lack of available before-period crash data, either because the CGT intersections were constructed as such or because the conversion from a traditional intersection took place before crash data were recorded electronically. Recent research has shown that the propensity scores-potential outcomes framework produces safety effect estimates (i.e., crash modification factors (CMFs)) that are nearly identical to EB observational before-after and cross-sectional statistical models when treatments are deployed at locations that were not selected for countermeasure implementation based on high crash frequencies.[9] Because the CGT intersections used in this study were likely constructed to provide operational efficiencies at three-leg intersections, it was assumed that the propensity scores-potential outcomes framework would produce results equivalent to the EB method.

The propensity scores-potential outcomes methodology used in the study considered the following:

- Comparability of the comparison intersections (traditional signalized T intersection).
- Missing traffic volume data.
- The need to pool data from multiple States to improve the sample size.

## Propensity Scores

The propensity scores for the CGT treatment were estimated in this study using the binary logit model. Propensity score analysis is a method that can be applied to mimic randomized experiments by using observed covariates to estimate the probability that an observation received a treatment (i.e., the propensity score).[10] The estimated propensity scores are then used to match treated and untreated observations.[11,12] This process removes correlation between the treatment and observed covariates. When propensity score matching is paired with regression analysis (performed after matching), selection bias is reduced.

## Matching

Numerous algorithms exist for propensity score matching. The optimal method for matching is dependent on the available data. This study used the following three matching methods:

- **Nearest-neighbor (NN) matching:** Involves randomly ordering the data to reduce bias in the matching results. Either 1:1 (one treated to one untreated) matching or 1:*n* (one treated to *n* untreated) matching can be done using NN matching. Specifying a caliper width ensures that all matched observations will have a maximum propensity score difference within the range of the caliper width. Once the matching criteria have been established, the treated observations are matched to the untreated observations with the most similar propensity score (within the caliper width or confidence interval (CI)).[7,10,11]
- **Mahalanobis matching:** Uses the same algorithm as NN matching with one difference: the treated observations are matched to the untreated observations with the closest match based on multiple variables, not just the propensity score.[11] The closest match based on multiple variables uses the Mahalanobis distance. As with NN matching, the data should be randomly ordered prior to matching.
- **Genetic matching:** Is a sequential process that finds the best matches for each treated entity that results in the best overall covariate balance.[12] The genetic matching process minimizes imbalance across the covariates; covariate balance is assessed using Kolmogorov-Smirnov (K-S) statistics in addition to standardized bias measures.[13]

Since the intersections in Florida and South Carolina likely differ with regard to unobservable variables (e.g., crash reporting thresholds and driver demographics), matching was done separately for each State.

### *Cross-Sectional Modeling Comparison*

Because traffic safety evaluations often use cross-sectional regression models to estimate CMFs, this study also used this approach to estimate CMFs. The cross-sectional model did not use any matched data and was estimated using a mixed effects negative binomial regression model. In the model, an indicator variable (i.e., CGT versus conventional signalized T intersection) was included in the specification to assess the safety performance of the CGT relative to the conventional signalized T intersection.

### Potential Outcome Estimation

After matching treated (CGT) and untreated (conventional signalized T intersections) sites, the potential outcomes (crash frequency) were estimated using count regression models.

### CMF Estimation

Mixed effects negative binomial or Poisson regression was used to estimate the CMFs whenever possible. Due to the small sample sizes of the two datasets, the data from both States were combined to estimate CMFs for CGT intersections. The resulting CMFs indicate the average safety effect of the CGT intersections for Florida and South Carolina.

## Results

Variable selection and model specification were based on the crash prediction model forms found in the *Highway Safety Manual*.[14] In addition, matching was used to remove the correlation between the treatment (CGT) and other variables in the model. The potential outcomes models considered these same variable forms, as well as the standardized bias, to further minimize the correlation between the treatment and other variables in the model.

As discussed in the Methodology section, mixed effects negative binomial or Poisson regression was used to estimate the CMFs whenever possible. The optimal weights found using genetic matching could not be accommodated using mixed effects regression, so weighted standard negative binomial regression with robust standard errors was used with the genetic matching results. The regression models for estimating the CMFs, along with the CMFs and 95-percent CIs, are shown in table 1 for genetic matching. Only the CMFs from the genetic matching method are shown here because this procedure produced the best covariate balance in the sample.

The results showed that there was a small but not statistically significant benefit associated with the CGT intersection relative to the conventional signalized T intersection. The CMFs associated with total, fatal and injury, and target crashes were 0.958 (*p*-value = 0.699 and 95-percent CI = 0.772 to 1.189), 0.846 (*p*-value = 0.211 and 95-percent CI = 0.651 to 1.099), and 0.920 (*p*-value = 0.519 and 95-percent CI = 0.714 to 1.185), respectively. Because the propensity scores-potential outcomes framework involves matching, some treated and untreated intersections in the database were not included in the analysis sample. For purposes of comparison, cross-sectional regression models using all available data were estimated, and the results were similar to the propensity scores-potential outcomes results. In these models (see table 2), the CMFs associated with total, fatal and injury, and target crashes were 0.937 (*p*-value = 0.389), 0.882 (*p*-value = 0.230), and 0.830 (*p*-value = 0.187), respectively.

The CMFs estimated using the unmatched data are more likely to be biased than the estimates using the matched data, so the CMFs from the matched data should be regarded as more robust. It is encouraging that the CMFs estimated using the unmatched data are similar to the CMFs from the matched data, although the

Table 1. Genetic matched regression models and CMF estimates using weighted standard negative binomial model (with robust standard errors).

| Crash Type | CMF | CMF 95 Percent Upper Bound | CMF 95 Percent Lower Bound |
|---|---|---|---|
| Total | 0.958 | 1.189 | 0.772 |
| Fatal and injury | 0.846 | 1.099 | 0.651 |
| Target (rear-end, angle, and sideswipe) | 0.920 | 1.185 | 0.714 |

Table 2. CMF models for unmatched cross-sectional data.

| Crash Type | Model Type | CMF | CMF 95 Percent Upper Bound | CMF 95 Percent Lower Bound |
|---|---|---|---|---|
| Total | Mixed effects negative binomial | 0.937 | 1.245 | 0.705 |
| Fatal and injury | Mixed effects Poisson | 0.882 | 1.176 | 0.661 |
| Target (rear-end, angle, and sideswipe) | Mixed effects negative binomial | 0.830 | 1.146 | 0.602 |

safety benefit estimated with both sets of models is not statistically significant. Based on the K-S test results, the genetic matching resulted in the best covariate balance. Thus, the CMFs estimated from the genetic matching are preferred over the cross-sectional model.

## Economic Analysis

The B/C analysis confirmed that the CGT is a cost-effective intersection design alternative to the conventional signalized T intersection. Because this study was unable to use an observational before-after study methodology, the B/C analysis presented in this study compares two different intersection forms (i.e., CGT versus conventional signalized T intersection).

The CMFs used for the economic analysis were those estimated using the propensity scores-potential outcomes framework (i.e., genetic matching results). The difference in the cost to construct a CGT relative to a conventional signalized T intersection is based on the difference in the area between the two intersection forms. A CGT will have added pavement costs, which are dependent on the posted speed limit of the intersecting roadways (this influences the length of auxiliary lanes at the CGT intersections) and the type of pavement used to construct the intersection.

For a posted speed limit of 35 mi/h, the added pavement area to construct a CGT relative to a conventional signalized T intersection was 363.3 yd$^2$. For a posted speed limit of 55 mi/h, the additional pavement area was 940 yd$^2$. Using \$28/yd$^2$ as the cost for asphalt pavement and \$70/yd$^2$ as the cost for concrete pavement, the cost for 35 mi/h was \$10,173.33 for asphalt and \$25,433.33 for concrete. The cost for 55 mi/h was \$26,320 for asphalt and \$65,800 for concrete.[15]

The annual costs (based on the initial paving costs and no maintenance over the 20-year project life), discounted at 7 percent over the 20-year project life, are \$956.30 for asphalt and \$2,390.70 for concrete pavements at 35 mi/h intersections and \$2,474.10 for asphalt and \$6,185.20 for concrete at 55 mi/h intersections, respectively.

The number of crashes (total, fatal and injury, and property damage only (PDO)) with and without the CGT was predicted for the 20-year service life. The comprehensive crash costs used for this analysis were derived using 2001 dollar values from Council et al.[16] As suggested by the authors, the crash cost values were multiplied by the ratio of the Consumer Price Index for 2001 and 2014 (ratio was 2.425) to produce a 2014 estimate of comprehensive crash costs.[17]

The 2001 comprehensive crash costs were \$129,418 for fatal and injury crashes and \$10,249 for PDO crashes on roads with posted speed limits below 50 mi/h. The 2001 comprehensive crash costs were \$146,281 for fatal and injury crashes and \$4,015 for PDO crashes on roads with posted speed limits equal to or above 50 mi/h. This produced crash cost savings of \$1,536,250 for the 35 mi/h posted speed limit and \$2,427,752 for the 55 mi/h posted speed limit for the 20-year project life. The annual benefits (from crash costs) were \$76,813 for the 35 mi/h posted speed limit major roads and \$121,388 for the 55 mi/h posted speed limit major roads. Table 3 compares the annual benefits and costs for 35 and 55 mi/h posted speed limits treated with asphalt and concrete pavement.

The B/C ratio is calculated as the ratio of the annual benefits to the annual costs for each pavement type and posted speed limit. Annual benefits are equal for asphalt and concrete pavements. These results, as shown in table 3, suggest that the CGT is cost effective relative to the conventional signalized T intersection.

## Summary and Conclusions

The objective of this study was to evaluate the safety impacts of CGT intersections. Total, fatal and injury, and target (rear-end, angle, and sideswipe) crash types were considered. Data from Florida and South Carolina were used for this study to estimate CMFs for CGT intersections relative to conventional signalized T intersections. The propensity scores-potential outcomes framework was used to estimate the CMFs. Genetic matching provided better matching results than other matching methods. The CMFs were estimated using weighted negative binomial regression with the genetic matched data.

Data from 30 CGT (treated) and 38 conventional signalized T (untreated) intersections from Florida were used in the evaluation, as were 16 treated and 21 untreated sites from South Carolina. In the propensity scores-potential outcomes framework, a propensity scores model was estimated using a binary logistic regression model, where the dependent variable was codified as a binary variable based on the presence of the CGT or the conventional signalized intersection form. The independent variables in the propensity scores model included safety-influencing features present at the intersections, including the average annual daily traffic on the major and minor street approaches, posted speed limit, cross-sectional widths, and type of intersection channelization.

The propensity scores were then used to match treated (CGT) to untreated (conventional signalized T) intersections, mimicking a randomized experiment. After matching, the potential outcomes were estimated using weighted negative binomial regression with robust standard errors. The expected total, fatal and injury, and target crash frequencies were used as the dependent variables in the count models, while the intersection safety-influencing variables were used as independent variables. In addition, an indicator variable was used in the potential outcomes model to assess the safety performance of the CGT relative to a conventional signalized intersection.

The CMF point estimates suggest that there is a potential reduction in crash frequency associated with the CGT intersection relative to the conventional signalized T intersection. Although the results were not statistically significant, it was likely due to the small sample size rather than the lack of an effect. Because the CGT is not expected to compromise safety performance relative to a conventional signalized T intersection and affords improved traffic operational performance and fewer environmental impacts (i.e., lower vehicle emissions), it should be considered as a potential alternative intersection form when conditions exist to effectively implement it.

Based on the findings of this research and the literature review, CGT intersections are likely to be favorable over traditional signalized T intersections when the following conditions exist:

- High through traffic volumes on the major street approach on the far side of the intersection (this approach could function as the continuous flow lane).

Table 3. B/C ratios for different speed limits and pavement types.

| Posted Speed Limit (mi/h) | Annual Benefits | Annual Cost of Asphalt | Annual Cost of Concrete | B/C Ratio for Asphalt | B/C Ratio for Concrete |
|---|---|---|---|---|---|
| 35 | $76,813 | $956.30 | $2,390.70 | 80.3 | 32.1 |
| 55 | $121,388 | $2,474.10 | $6,185.20 | 49.1 | 19.6 |

- Low cyclist demand.
- No pedestrian demand or an alternative pedestrian crossing nearby.

Anecdotal feedback from Florida indicated that non-motorized users have expressed concern with the high-speed, continuous flow lanes on the major approaches of CGT intersections. Pedestrians and bicyclists wishing to cross from the minor street approach onto the far side of the high-speed continuous flow lanes may have difficulty identifying gaps or adequate gap sizes. As such, implementation of CGT intersections at locations with anticipated pedestrian and bicycle users should be weighed against the operational and environmental benefits.

The B/C analysis confirmed that the CGT is a cost-effective intersection design alternative to the conventional signalized T intersection (based on the point estimates of the CMFs). The B/C ratios for both asphalt and concrete pavements, as well as 35 and 55 mi/h posted speed limits on the major road, significantly exceed 1.0.

## References


1. Donnell, E., Wood, J., and Eccles, K. (2016). *Safety Evaluation of Continuous Green T Intersections*, Report No. FHWA-HRT-16-036, Federal Highway Administration, Washington, DC.
2. Jarem, E.S. (2004). *Safety and Operational Characteristics of Continuous Green Through Lanes at Signalized Intersections in Florida*, Presented at ITE Annual Meeting and Exhibit, Lake Buena Vista, FL.
3. Litsas, S. and Rakha, H. (2013). "Evaluation of Continuous Green T-Intersections on Isolated Undersaturated Four-Lane Highways." *Transportation Research Record: Journal of the Transportation Research Board*, *2348*, pp. 19–29, Transportation Research Board, Washington, DC.
4. Hughes, W., Jagannathan, R., Sengupta, D., and Hummer, J. (2010). *Alternative Intersections/Interchanges: Informational Report*, Report No. FHWA-HRT-09-060, Federal Highway Administration, Washington, DC.
5. Sando, T., Chimba, D., Kwigizile, V., and Walker, H. (2011). "Safety Analysis of Continuous Green Through Lane Intersections." *Journal of the Transportation Research Forum*, *50*(1), pp. 5–17, Transportation Research Forum, Fargo, ND.
6. ITE. (2012). *Trip Generation Manual*, Ninth Edition, Institute of Transportation Engineers, Washington, DC.
7. Sasidharan, L. and Donnell, E.T. (2013). "Application of Propensity Scores and Potential Outcomes to Estimate Effectiveness of Traffic Safety Countermeasures: Exploratory Analysis Using Intersection Lighting Data." *Accident Analysis & Prevention*, *50*, pp. 539–553, Elsevier, Amsterdam, Netherlands.
8. Harwood, D.W., Bauer, K.M., Potts, I.B., Torbic, D.J., Richard, K.R., Kohlman Rabbini, E.R., Hauer, E., and Elefteriadou, L. (2002). *Safety Effectiveness of Intersection Left-and Right-Turn Lanes*, Report No. FHWA-RD-02-089, Federal Highway Administration, Washington, DC.
9. Wood, J.S., Donnell, E.T., and Porter, R.J. (2014). "Comparison of Safety Effect Estimates Obtained from Empirical Bayes Before-After Study, Propensity Scores-Potential Outcomes Framework, and Regression Model with Cross Sectional Data." *Accident Analysis & Prevention*, *75*, pp. 144–154, Elsevier, Amsterdam, Netherlands.
10. Rosenbaum, P.R. and Rubin, D.B. (1983). "The Central Role of the Propensity Score in Observational Studies for Causal Effects." *Biometrika*, *70*(1), pp. 41–55, Oxford University Press, Oxford, United Kingdom.
11. Guo, C. and Fraser, M.W. (2010). *Propensity Score Analysis*, Sage Publications, Inc., Washington, DC.
12. Holmes, W.M. (2013). *Using Propensity Scores in Quasi-Experimental Designs*, Sage Publications, Inc., Washington, DC.
13. Diamond, A. and Sekhon, J.S. (2013). "Genetic Matching for Estimating Causal

Effects: A General Multivariate Matching Method for Achieving Balance in Observational Studies." The Review of Economics and Statistics, 95(3), pp. 932–945, The MIT Press, Cambridge, MA.

14. AASHTO. (2010). Highway Safety Manual, American Association of State Highway and Transportation Officials, Washington, DC.

15. 15. Pennsylvania Department of Transportation. (2015). Publication 287—Item Price History for Projects Let From 4/4/2013 to 4/16/2015, Pennsylvania Department of Transportation, Harrisburg, PA. Available online: https://www.dot14.state.pa.us/ECMS/, last accessed June 17, 2019.

16. Council, F., Zolashnja, E., Miller, T., and Persaud, B. (2005). Crash Cost Estimates by Maximum Police-Reported Injury Severity Within Selected Crash Geometrics, Report No. FHWA-HRT-05-051, Federal Highway Administration, Washington, DC.

17. U.S. Department of Labor, Bureau of Labor Statistics. (2015). "Consumer Price Index." (website) Washington, DC. Available online: https://www.bls.gov/cpi/home.htm, last accessed May 2015.

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