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Environmental impact of modern roundabouts

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Abstract

In United States (US) vehicular emissions have increased considerably over the years and have attracted the attention of environmental and transportation researchers. Traditional intersections force vehicular traffic to slow down and stop in varying patterns and contribute to the increase in vehicular emissions. Modern roundabouts in US have enhanced the performance and safety of many intersections. There are numerous studies conducted by IIHS and various researchers, which support this fact. These modern roundabouts are not only capable of improving traffic flow but they can as well cut down vehicular emissions and fuel consumption by reducing the vehicle idle time at intersections and thereby creating a positive impact on the environment. The primary focus of this research was to study the impact of modern roundabouts in cutting down vehicular emissions. Six sites with different traffic volume ranges, where a modern roundabout has replaced stop-controlled intersection, have been chosen for the study. The operation of the roadways at the intersection was videotaped and the traffic flow data was extracted from these tapes and analyzed using SIDRA (signalized and un-signalized intersection design and research aid) software. The version used was aaSIDRA 2.0. The software produces many Measures of Effectiveness (MOEs) of which four were chosen for analyzing the environmental impact of roundabouts. The chosen four outputs give rate of emission of HC, CO, NO_X, and CO_2 in (kg/h).

All the MOEs were statistically compared to determine which intersection control performed better. After comparing all the MOEs at all locations for the before and after traffic volumes, it was found that the modern roundabout performed better than the existing intersection control (i.e. stop signs) in cutting down vehicular emissions therefore creating a positive impact on the environment. The research concludes that a modern roundabout can be used as a viable alternative to cut down vehicular emissions, making intersections more environmentally friendly.

Keywords: Modern roundabouts; Vehicular emissions; Reducing air pollution

1. Introduction

With the increase in traffic over the years, one of the major threats to clean air in many of the developed countries like the USA is vehicular emissions. Problems posed by the environmental impact of traffic are growing and are a challenge for traffic engineers. Vehicular emissions are dependent on the total amount of traffic, intersection control type, driving patterns and vehicular characteristics.

Vehicular emissions contain a wide variety of pollutants, principally carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_X), particulate matter (PM_{10}) and hydrocarbons (HC) or volatile organic compounds (VOC), which have a major long-term impact on air quality. These emissions vary with the engine design, the air-to-fuel ratio, and vehicle operating characteristics. With increasing vehicle speed there is an increase in NO_X emissions and decrease in CO, PM_{10} and HC or VOC emissions. The emissions of (CO_2) and oxides of sulfur (SO_x) vary directly with fuel consumption and for any given vehicle and fuel combination, aggregate emission levels vary according to the distance traveled and the driving patterns (Federal Highway Administration, 2000).

Road and street intersections force vehicular traffic to slow down and stop in varying patterns of interruption of ideal, constant traffic flow at an ideal speed. The longer the

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stops, the more fuel that is consumed and vehicular emissions increase. With the vehicular emissions problems worsening, it has become prudent to choose effective traffic control devices that can improve traffic flow on the roads and, reduce emissions per vehicle kilometer traveled while enhancing mobility.

Modern roundabouts in the USA, which are functioning as one of the safest and most efficient forms of intersection control (Russell et al., 2000, 2002a, b) and improving traffic flow at intersections, have the additional advantage of cutting down vehicular emissions and fuel consumption by reducing vehicle idling time at the intersections thereby having a positive affect on the environment.

The primary focus of this research was to study the impact of modern roundabouts in reducing vehicular emissions at intersections. The research focused on six sites with different traffic volume ranges where a modern roundabout has replaced stop-controlled intersection. The emissions at these intersections were compared for the before (stop controlled) and after (modern roundabout) conditions to assess the impact of a modern roundabout.

2. Literature review

Vehicle exhaust fumes have played a major role in the deterioration of air quality in urban areas since 1950s and as a result the Clean Air Act (CAA) was passed in 1970. The CAA gives the Environmental Protection Agency (EPA) the authority to set limits on emission standards. The EPA estimates that over 5000 tons of VOCs from transportation sources were emitted in 1999 and that approximately 62 million people living in areas that do not meet health-based standards. EPA also estimated that in 1999 the transportation sector, including on-road and non-road vehicles, contributed to 47% of HC emissions, 55% of NO_X emissions, 77% of CO emissions, and 25% of PM emissions (National Air Quality and Emissions Trends Report, 2001).

Roundabouts are being implemented throughout the US in a variety of situations. Many states and cities are considering roundabouts as a viable alternative to other traffic control devices (TCDs), and, in some cases, complex freeway interchanges. Modern roundabouts are becoming popular in the US for more than just safety reasons. As stated in an article by the Insurance Institute for Highway Safety (IIHS) they reduce fuel consumption and vehicular emissions by reducing stopping at intersections, and also reduce noise levels by making the traffic flow orderly. Modern roundabouts can enhance the esthetics of the place and create visual gateways to communities or neighborhoods. In commercial areas they can improve access to adjacent properties (Insurance Institute of Highway Safety, 2001).

Vehicles stopping at traffic signals and stop signs emit more CO_2 when compared to vehicles at roundabouts as the delay and queuing are greater. Even if the delays are similar to that of roundabout, traffic signals always queue traffic at a red light and hence emissions are usually greater. The average delays at roundabouts have to be significantly larger than at traffic signals for the emissions to be equal. When traffic volumes are low, traffic rarely stops at a roundabout and the emissions are very small (Barry, 2001; Mutasem et al., 2000).

When roundabouts become very congested with large queues, the emissions equal those at traffic signals. During off-peak hours roundabouts do not experience long queues and delays and the emissions are low. Traffic signals and stop signs halt vehicles even during off-peak hours creating higher delays and emissions. United Kingdom (UK) engineers believe that traffic signals have lower emissions only in exceptional cases (Barry, 2001; Mutasem et al., 2000).

As stated by Barry Crown, a roundabout expert from the UK: "When vehicles are idle in a queue they emit about 7 times as much CO as vehicles traveling at 10 mph. The emissions from a stopped vehicle are about 4.5 times greater than a vehicle moving at 5 mph" (Barry, 2001).

The Bärenkreuzung/Zollikofen project undertaken in Bern, Switzerland, replaced two important signalized intersections by roundabouts and the result was a reduction of emissions and fuel savings by about 17%. The roundabouts also steadied the driving patterns (Bern).

On a microscale there have been studies conducted on the effect that different traffic flows have on emissions at an intersection. Of the studies that reported quantitative results, roundabouts reduced vehicle emissions for HC in 5 studies by an average of 33%, CO in 6 studies by an average of 36%, and NO_X in 6 studies by an average of 21%. The regional scale air quality benefits of roundabouts would depend on their percent contribution to regional mobile source emissions (Wayne; Hyden and Varhelyi, 2000).

In a study conducted by (Mustafa et al., 1993), the authors concluded that there exists a direct relationship between vehicle emissions and traffic volumes at urban intersections regardless of traffic control. Their simulation results showed that traffic signals generate more emissions (almost 50% higher) than a roundabout. In case of higher traffic volumes the HC generated by traffic signals is twice as high as that generated at roundabouts (Mustafa et al., 1993).

In another study conducted by Varhelyi in Sweden, he found that replacing a signalized intersection with a roundabout resulted in an average decrease in CO emissions by 29% and NO_X emissions by 21% and fuel consumption by 28% per car within the influence of the junction (Varhelyi, 2002).

Results of a study conducted by Jarkko Niittymaki show fuel consumption reductions of 30% in an intersection designed as a roundabout instead of using traffic signals and environmentally optimized traffic control systems have proved an energy saving potential of 10–20% in different cases (Niittymäki and Höglund, 1999).

3. Methodology

3.1. Description of study sites

Six study sites were selected for this research. Five of the sites are in Kansas and one in Nevada. Of the sites studied in Kansas two were in Olathe, one in Lawrence, one in Hutchinson and one in Paola. Data from these sites was available from previous roundabout studies at Kansas State University (KSU) (Russell et al., 2000, 2002a, b).

The sites in Olathe are:

1. The intersection of the Ridgeview Road and Sheridan Avenue; and
2. The intersection of Rogers Road and Sheridan Avenue (See Fig. 1).

Sheridan Road runs in the East–West direction while the Ridgeview and Rogers roads run in the North–South direction, roughly parallel to Interstate 35 (*I*-35).

The site in Lawrence (Fig. 2) is the T-intersection of the Harvard Road and Monterey Way. Harvard Road runs in the East–West direction while and ends at Monterey Way, which runs in the North–South direction.

The site in Hutchinson is the intersection of 23rd Street and Severance Avenue. Severance Avenue runs in the North–South direction and 23rd street runs in the East–West direction.

The site in Paola is the intersection of the Old KC Road, State Route K68 and Hedge Lane. The Old KC Road runs in the North–South direction. And the K68 runs in the East–West direction. Hedge Lane runs in South–East-North–West direction, and intersects K-68 just east of the K-68 and Old KC Road intersection.

The site in Nevada is the intersection of the Wedekind Road and ClearAcre Lane. Wedekind Road runs in the East–West direction while ClearAcre Lane runs in the North–South direction.

All the sites except Hutchinson and Nevada (which had a two-way stop control—TWSC) were controlled by stop signs on all approaches (all way stop control—AWSC) prior to the installation of the modern roundabout. The major drawback of AWSC is that the presence of vehicles on all the approaches of the intersection will result in longer departure headways and longer driver decision times that reduce the capacity of the intersection. The major drawback of TWSC is congestion on the minor street caused by a demand that exceeds capacity, and queues that form on the major street because of inadequate capacity for left turning vehicles yielding to opposing traffic. In the after condition, a single-lane modern roundabout was built at all sites. The Paola roundabout is different from the others because it has five legs, and is an intersection on the state highway (Russell et al., 2002a). See Table 1 for the intersection hourly traffic volume ranges and the percentage of left turn for the intersections studied.

Fig. 1. Rogers/Sheridan Roundabout.

Fig. 2. Lawrence Roundabout.

Table 1
Intersection hourly traffic volume ranges and percentages of left turns

AM (AWSC[a])	AM (roundabout)	PM (AWSC)	PM (roundabout)
Paola data			
257–594 (veh/h) 28% left turns	235–559 (veh/h) 29% left turns	192–690 (veh/h) 38% left turns	156–663 (veh/h) 40% left turns
Lawrence data			
227–536 (veh/h) 30% left turns	263–447 (veh/h) 17% left turns	412–733 (veh/h) 26% left turns	442–692 (veh/h) 21% left turns
Olathe: rogers/sheridan data			
926–1625 (veh/h) 28% left turns	931–1738 (veh/h) 28% left turns	1220–1994 (veh/h) 21% left turns	1244–2024 (veh/h) 22% left turns
Olathe: ridgeview/sheridan data			
708–1110 (veh/h) 33% left turns	776–1124 (veh/h) 33% left turns	1140–1626 (veh/h) 35% left turns	1119–1784 (veh/h) 38% left turns
AM (TWSC[b])	AM (roundabout)	PM (TWSC)	PM (roundabout)
Hutchinson data			
449–983 (veh/h) 13% left turns	415–864 (veh/h) 12% left turns	514–1204 (veh/h) 13% left turns	501–1110 (veh/h) 15% left turns
Nevada data			
423–718 (veh/h) 31% left turns	372–691 (veh/h) 32% left turns	619–893 (veh/h) 28% left turns	547–881 (veh/h) 27% left turns

[a]Stop control can be all way stop control (AWSC).
[b]Two-way stop control (TWSC).

3.2. Data collection

The available data had been collected in two phases. The first phase was videotaping intersection traffic movements with a video camera and the second phase was obtaining traffic counts visually from the videotapes (Russell et al., 2000, 2002a, b).

3.2.1. Phase 1: video data collection

The benefit of using this method for data collection is that all the data is recorded on videotapes and can be accessed and retrieved at a later time. In this method, all the information recorded on the tapes can be accessed for evaluation at any time and serves as a permanent record for re-verification of data, or reuse for other purposes. A specially designed 360°-omni directional, video camera and videocassette recorder were used for data collection at each location. The camera was designed to provide a full 360° view when mounted above the intersection. The camera was placed near the intersection to see the traffic flow coming toward and leaving the intersection. The camera was installed on existing poles and mounted perpendicular to the ground. The perpendicular mounting allowed the video image to be relatively distortion free to the horizon in all directions. The camera was mounted approximately 6 m (20 ft) above the ground. This mounting height provides a focal plane of approximately 40.5 m × 54.0 m (133 ft × 177 ft). The camera feed went in to a TV/VCR unit placed in a recycled traffic signal controller cabinet. All the equipment was mounted on a single pole. The video images were recorded on standard VHS videotapes. See Fig. 3 for details (Mandavilli, 2002; Russell et al., 2002b). The traffic counts from the intersection were video-taped for two 6-h sessions from 7:00 AM to 1:00 PM and from 1:00 PM to 7:00 PM on normal week days for the before and after conditions. A normal day in this study refers to a day with no adverse environmental/weather or any external factor(s), such as special events in the nearby locality of the study intersection that would impact the flow of traffic through the study intersection.

Fig. 3. Camera and TV/VCR units used in data collection.

3.2.2. Phase 2: visual data collection

In this phase, the data was visually collected from the videotapes. All the videotapes were studied visually to extract the traffic volumes and turning movements for the analysis. Various graduate student research assistants in the Department of Civil Engineering at KSU did the data extraction from the videotapes. Every vehicle coming from all the approaches for a period of 15 min (Russell et al., 2000) was recorded on pre-prepared data collection sheets. Hourly counts were used as input data for analysis using the computer program aaSIDRA (signalized and unsignalized intersection design and research aid) (Russell et al., 2000).

3.2.3. Software selection

The software used for data analysis is aaSIDRA, Version 2.0. The Australian Road Research Board (ARRB), Transport Research Ltd., originally developed the SIDRA package as an aid for design and evaluation of intersections such as signalized intersections, roundabouts, two-way stop control, and yield-sign control intersections. SIDRA was taken over by a private company, which now supports the software. aaSIDRA 2.0 is the latest version.

> In evaluating and computing the performance of intersection controls there are some advantages that the SIDRA model has over any other software model. The SIDRA method emphasizes the consistency of capacity and performance analysis methods for roundabouts, sign-controlled, and signalized intersections through the use of an integrated modeling framework. Another strength of SIDRA is that it is based on the US Highway Capacity Manual (HCM) as well as Australian Road Research Board (ARRB) research results (Sisiopiku et al., 2001).

The input to the software includes the road geometry, traffic counts, turning movements, and speed of the vehicles. The SIDRA software analyzes the data and the output provides measures of effectiveness from which the performance of the roadway can be determined. There are 19 measures of effectiveness given in SIDRA output but only 4 of them were considered relevant to the project. The 4 measures of effectiveness (MOEs) used in evaluating the performance are:

- CO;
- CO_2;
- NO_X; and
- HC or VOC.

SIDRA uses a 4-mode elemental model for estimating fuel consumption, operating cost and pollutant emissions for all types of traffic facilities. This helps with estimation of air quality, energy and cost implications of alternative intersection design. For this purpose, a unique vehicle drive-cycle model (acceleration, deceleration, idling, cruise) is used. See Fig. 4 for details (Akcelik and Besley, 2002).

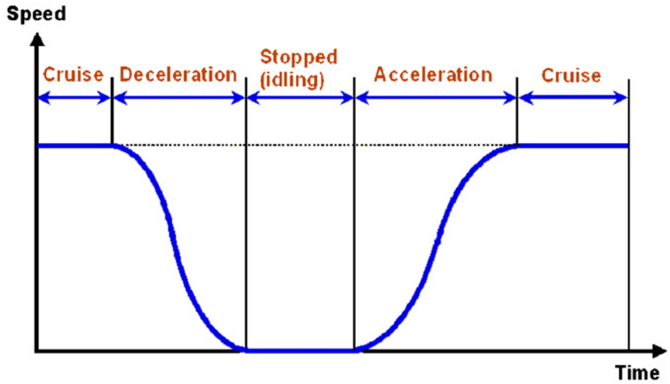

Fig. 4. Graphical representation of drive-cycle model used by SIDRA (Akcelik and Besley, 2002).

Fuel consumption and emission rates are calculated from a set of equations which use such vehicle parameters as mass and fuel emission efficiency rates, as well as road grade and relevant speeds (cruise, initial, final).

3.3. Data analysis

The data collected from videotapes for the AM and PM periods was recorded manually in 15-min periods, and hourly data was then input to the SIDRA software for analysis. All the Measures of Effectiveness (MOEs) were statistically compared using standard statistical procedures. Minitab 13 was the software used to perform the statistical tests. The data analysis was done separately for the AM and PM hourly volumes but the procedure followed was the same for both sets of data. This was done to see whether the results differed due to the differences in before and after traffic volumes for both AM and PM traffic counts, as there was more traffic during the PM period than during the AM period. Table 2 shows a summary of the statistical tests performed.

Table 2
Summary of statistical tests

Statistical test	Inference
I. *Normality*	
(a) IQR/S$\approx$1.3	Sample is normally distributed if $\approx$1.3
(b) Shapiro Wilk P-value	H_0: "Sample is normally distributed", $\alpha = 0.01$
II. *Equal variances*	
Levene's test	H_0: $\sigma^2_{SC} = \sigma^2_{RA}$, $\alpha = 0.01$
III. A. *Normal w/equal variances*	
Analysis of variance (ANOVA) F-test	H_0: $\mu_{SC} = \mu_{RA}$, $\alpha = 0.05$
	Fail to reject H_0, means equal, analysis stops
	Reject H_0, perform multiple comparisons (Tukey's and/or Duncan's tests)
III. B. *Normal w/unequal variances*	
Welch's test	H_0: $\mu_{SC} = \mu_{RA}$, $\alpha = 0.05$
	Fail to reject H_0, means equal, analysis stops
	Reject H_0, perform multiple comparisons (Fisher Least significant difference test)
III. C. *Not normal*	
Kruskal–Wallis test	H_0: Population distributions are the same, $\alpha = 0.05$
	Fail to reject H_0, analysis stops
	Reject H_0, Observe data plots to determine rank order

IQR: inter quartile range; S: standard deviation; SC: stop control can be all way stop control (AWSC) or two-way stop control (TWSC); RA: modern roundabout.

4. Results

The statistical analysis of the MOEs helps determine if and how the stop-controlled intersections and the roundabout-controlled intersections differed in cutting down vehicular emissions. The analysis provides information to assess characteristics of the stop controls and the roundabout. The statistical testing was done separately for the AM and PM periods for all the locations in order to evaluate the operation of the intersection during these separate periods. The results obtained for each site are then averaged and the overall results are given in Table 3.

4.1. Discussion of results

- The average CO emissions (kg/h) for the intersection locations studied are 21% and 42% less for the AM period and PM periods, respectively for the case of a modern roundabout. Statistical tests showed that the decrease in CO emissions after a roundabout was installed is statistically different from the emissions that occurred in case of AWSC for both AM and PM conditions.
- The average CO_2 emissions (kg/h) for the intersection locations studied are 16% and 59% less for the AM period and PM periods, respectively for the case of a modern roundabout. Statistical tests showed that the decrease in CO_2 emissions after a roundabout was installed is statistically different from the emissions that occurred in case of AWSC for both AM and PM conditions.
- The average NO_X emissions (kg/h) for the intersection locations studied are 20% and 48% less for the AM period and PM periods respectively for the case of a modern roundabout. Statistical tests showed that the decrease in NO_X emissions after a roundabout was installed is statistically different from the emissions that occurred in case of AWSC for both AM and PM conditions.
- The average HC emissions (kg/h) for the intersection locations studied are 18% and 65% less for the AM period and PM periods respectively for the case of a

Table 3
Overall emissions results

Emissions results Measures of effectiveness	SC[a]	RA[b]	% Diff.	Statistically different
AM results				
Carbon monoxide (CO) kg/h	9.77	7.67	−21	Yes
Carbon dioxide (CO_2) kg/h	138.91	117.18	−16	Yes
Oxides of nitrogen (NO_X) kg/h	0.31	0.25	−20	Yes
Hydrocarbons (HC) kg/h	0.23	0.19	−17	Yes
PM results				
Carbon monoxide (CO) kg/h	11.8225	6.855	−42	Yes
Carbon dioxide (CO_2) kg/h	335.7	138	−59	Yes
Oxides of nitrogen (NO_X) kg/h	0.3875	0.2015	−48	Yes
Hydrocarbons (HC) kg/h	0.66237	0.23	−65	Yes

[a]Stop control can be all way stop control (AWSC) or two-way stop control (TWSC).
[b]Modern roundabout.

modern roundabout. Statistical tests showed that the decrease in HC emissions after a roundabout was installed is statistically different from the emissions that occurred in case of AWSC for both AM and PM conditions.

- The results from SDIRA analysis also showed that there was a statistically significant decrease in delay, queuing and stopping after the modern roundabout was installed when compared to the before, (AWSC/TWSC) because, as previous studies have concluded, the modern roundabouts have less delay, queuing and stopping than an AWSC/TWSC. This is reflected in the decrease in vehicular emissions shown above.

5. Conclusions

- The modern roundabouts in Kansas operated more effectively than the before intersection control (AWSC/TWSC) in reducing vehicular emissions at all locations studied.
- There was a (21–42%) decrease in the carbon monoxide (CO) emissions (kg/h) for the AM and PM periods after the installation of modern roundabout. The decrease was observed to be statistically significant for both periods.
- There was a (16–59%) decrease in the carbon dioxide (CO_2) emissions (kg/h) for the AM and PM periods after the installation of modern roundabout. The decrease was observed to be statistically significant for both periods.
- There was a (20–48%) decrease in the Oxides of Nitrogen (NO_X) emissions (kg/h) for the AM and PM periods after the installation of modern roundabout. The decrease was observed to be statistically significant for both periods.
- There was a (17–65%) decrease in the hydrocarbons (HC) emissions (kg/h) for the AM and PM periods after the installation of modern roundabout. The decrease was observed to be statistically significant for both periods.
- Reduction in delays, queues and proportion of vehicle stopped at the intersection in the case of roundabouts suggest that roundabouts enhanced the operational performance of the intersections and account for the reduction in vehicular emissions.
- Since all the locations had a range of different traffic conditions, it is reasonable to suggest that a modern roundabout may be the best intersection alternative to reduce vehicular emissions for several other locations in Kansas with similar ranges of traffic volumes.

5.1. Overall conclusion

Considering the above summary, it is concluded that at the intersections studied the modern roundabouts significantly reduced the vehicular emissions of the intersections studied by making the traffic flow orderly.

5.2. Further study

Further studies should be conducted in other locations in United States with different traffic conditions, particularly those where volumes are high enough that a multi-lane roundabout is required, in order to get a much clearer picture. Also, field studies should be conducted using emissions detection equipment to further verify the results obtained from SIDRA.

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