Environmental Impact of Kansas Roundabouts

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Abstract

With the increase in traffic over the years there has also been a considerable increase in vehicular emissions. Problems posed by environmental impact of traffic are growing and are posing a challenge to traffic engineers. Modern roundabouts can improve traffic flow as well as 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 is to study the impact of modern roundabouts in Kansas in cutting down vehicular emissions. Three locations in Kansas; namely, Olathe, Lawrence, and Paola, where a modern roundabout has replaced a stop controlled intersection, have been chosen for the study. The operation of the roadways at the intersection was videotaped and traffic flow data was extracted from these tapes and analyzed using aaSIDRA (Signalized and Un-signalized Intersection Design and Research Aid) software, version 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 MOEs give rate of emission of HC, CO, NOX, and CO_2 in (kg/hr).

All the MOEs were statistically compared to determine which intersection control performed better. After observing 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, thereby resulting in a positive impact on the environment. The research concludes that a modern roundabout can be considered, a viable alternative to cut down vehicular emissions and thereby making intersections more environment friendly.

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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 NOx emissions and decrease in CO, PM_{10} and HC or VOC emissions. The emissions of carbon dioxide (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. [1]

Other affects of vehicular emissions include formation of ozone and acid rains which have a long term detrimental effects. At ground level, ozone is a severe irritant and the primary component of “smog”. In urban areas, at least half of the ozone producing components comes from transportation sources such as automobiles. Ozone exposure is linked to respiratory illnesses such as asthma and lung inflammation. The particulate matter from vehicular emissions consists of airborne solid particles and liquid droplets. Fine particles can easily reach remote lung areas, and their presence in the lungs is linked to serious respiratory ailments such as asthma, chronic bronchitis and aggravated coughing. Exposure to these particles may aggravate other medical conditions such as heart disease and emphysema and may cause premature death. In the environment, particulate matter contributes to diminished visibility and particle deposition (soiling). [1]

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 stops, more fuel is consumed and the 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 forms of intersection control and improving traffic flow at intersections, have the additional advantage of cutting down vehicular emissions and fuel consumption by reducing the vehicle idling time intersections and thereby having a positive affect on the environment.

Objective of this research

The primary focus of this research is to study the effect that modern roundabouts in Kansas have in cutting down vehicular emissions at intersections. This research focuses on three locations in Kansas; namely, Olathe, Lawrence, and Paola where a modern roundabout replaced a stop controlled intersection. The emissions at the intersections were compared for the before (Stop Controlled) and after conditions (Roundabout) to assess the impact of roundabouts.

Literature Review

Vehicle exhaust fumes played a major role in the deterioration of air quality in urban areas since 1950's 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. Figure 1 shows the emission trends in USA from 1970. Though the figure shows a decrease in emissions, the impact of mobile emissions continues to be large. The EPA estimates that over 5,000 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. [1]

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 TCD's, and, in some cases, complex freeway interchanges. The safety record, of well designed modern roundabouts is excellent. A major US study by Persaud, et.al., [2001] concluded that modern roundabouts decrease all crashes about 39%, injury crashes about 76%, and the study projected a 90% decrease in fatal crashes. [2] In particular, single-lane roundabouts may perform better than two-way stop-controlled (TWSC) intersections in the U.S. under some conditions. [3]

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 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 aesthetics of the place and create visual gateways to communities or neighborhoods. In commercial areas they can improve access to adjacent properties. [4]

As stated by Jaquemart [5]:

> "The high capacity and fluidity achieved by the modern roundabout are two main reasons for its success. The substantial reduction in injury accidents has been the primary reason for great success of modern roundabouts in France, Germany, Australia and UK The fact that drivers do not have to wait as long at roundabouts as at signalized intersections makes the roundabouts friendlier to both the driver and to the environment"

In a study conducted by Kansas State researchers it is found that the roundabouts reduced delays, proportion of vehicles stopped and queues at the intersections for all the roundabouts that are included in this study. The results of the study are given below: [6]

Table 1: Kansas Roundabouts Operational Performance Results

Measures Of Effectiveness	AM Results			PM Results			
	AWSC	R.A	% Diff.	AWSC	R.A	% Diff.	Statistically Different
Average Intersection Delay (Seconds/veh)	28.4	8.4	-70%	48	8.8	-82%	Yes
Maximum Approach Delay (Seconds/veh)	44.5	10.4	-77%	87.4	11	-87%	Yes
95% Queue Length (Feet)	212	66	-69%	481	86	-82%	Yes
Degree Of Saturation V/C (Intersection)	0.7	0.2	-71%	0.88	0.3	-66%	Yes
Proportion Of Vehicles Stopped (%) (Intersection)	93	35	-62%	93	40	-57%	Yes
Max.Proportion Of Vehicles Stopped (%) (Approach)	92	35	-62%	92	42	-54%	Yes

Vehicles stopping at traffic signals and stop signs emit more carbon dioxide (CO_2) when compared to 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 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. [7, 8]

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 stop vehicles even during off-peak hours and thereby experience higher delays and emissions. United Kingdom (UK) engineers believe that traffic signals have lower emissions only in exceptional cases. [7, 8]

As stated by Barry Crown, a roundabout expert from the UK: [7]

> "When vehicles are idle in a queue they emit about 7 times as much carbon monoxide (CO) as vehicles traveling at 10 mph. The emissions from a stopped vehicle are about 4.5 times greater than a vehicle moving at 5mph"

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 per cent. The roundabouts also steadied the driving patterns. [9]

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 hydrocarbons (HC) in 5 studies by an average of 33 percent, carbon monoxide (CO) in 6 studies by an average of 36 percent, and nitric oxides (NOx) in 6 studies by an average of 21 percent. The regional scale air quality benefits of roundabouts would depend on their percent contribution to regional mobile source emissions. [10, 11]

In a study conducted by Mustafa et.al [1993] they 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. [12]

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 NOx emissions by 21% and fuel consumption by 28% per car within the influence of the junction. [13]

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. [14]

Methodology

Description of Study Sites

Four locations in Kansas were studied for this research. Two sites were studied in Olathe, one site in Lawrence, and one in Paola. 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.

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 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 Paola is 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.

All the sites 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 this type of intersection control is that the presence of vehicles on all the approaches of an AWSC intersection will result in longer departure headways and longer driver decision times that reduce the capacity of the intersection. 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. See Table 2 for the intersection hourly traffic volume ranges and the percentage of left turn for the intersections studied.

Table 2: Intersection hourly Trafffic Volume Ranges and percentages of left turns

PAOLA DATA			
AM (AWSC)	**AM (Roundabout)**	**PM (AWSC)**	**PM (Roundabout)**
257-594 (veh/hr)	235-559 (veh/hr)	192-690 (veh/hr)	156-663 (veh/hr)
28% Left turns	29% Left turns	38% Left turns	40% Left turns
LAWRENCE DATA			
AM (AWSC)	**AM (Roundabout)**	**PM (AWSC)**	**PM (Roundabout)**
227-536 (veh/hr)	263-447 (veh/hr)	412-733 (veh/hr)	442-692 (veh/hr)
30% Left turns	17% Left turns	26% Left turns	21% Left turns
OLATHE:ROGERS/SHERIDAN DATA			
AM (AWSC)	**AM (Roundabout)**	**PM (AWSC)**	**PM (Roundabout)**
926-1625 (veh/hr)	931-1738 (veh/hr)	1220-1994 (veh/hr)	1244-2024 (veh/hr)
28% Left turns	28% Left turns	21% Left turns	22% Left turns
OLATHE:RIDGEVIEW/SHERIDAN DATA			
AM (AWSC)	**AM (Roundabout)**	**PM (AWSC)**	**PM (Roundabout)**
708-1110 (veh/hr)	776-1124 (veh/hr)	1140-1626 (veh/hr)	1119-1784 (veh/hr)
33% Left turns	33% Left turns	35% Left turns	38% Left turns

Data Collection

The data collection consisted of two phases. The first phase was data collection on videotapes with a video camera and the second phase was obtaining traffic counts visually from the videotapes.

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 degrees 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 cameras were 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 meters (20 feet) above the ground. This mounting height provides a focal plane of approximately 40.5 meters by 54.0 meters (133 feet by 177 feet). 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. [15, 16]

Data from the intersection was collected in the before condition (when the intersection was controlled by stop signs) and in the after condition (after a modern roundabout was built at the intersection). The traffic counts from the intersection were video taped for two six-hour sessions from 7:00AM-1:00PM and from 1:00PM-7:00PM 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.

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 student graduate 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 fifteen (15) minutes was recorded on pre-prepared data collection sheets. Hourly counts were used as input data for analysis using the computer program aaSIDRA (Signalized and Un-signalized Intersection Design and Research Aid). [17].

During the process of visual data extraction from the videotapes, it was observed that pedestrian and bicyclists' traffic was low, and they were ignored in the analysis. Heavy vehicle traffic going through the intersection was also light and, was not counted separately. Instead, heavy vehicle traffic was assumed to be 3% of the total traffic volumes on each of the approaches, for purpose of analysis.

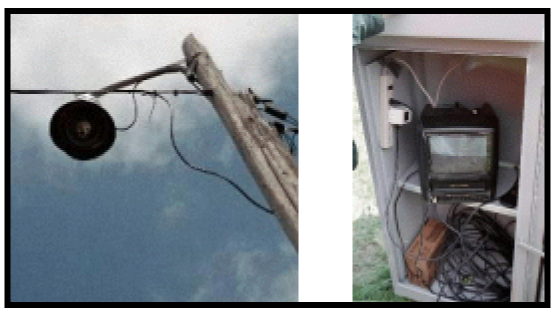

Figure 1: Camera and TV/VCR units used in data collection

Software Selection

The software used for data analysis is a.a.SIDRA. Version 2.0. The Australian Road Research Board (ARRB), Transport Research Ltd., has 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.

> *"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." [18].

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 four of them were considered relevant to the project. The four measures of effectiveness (MOEs) used in evaluating the performance are:

- Carbon Monoxide (CO)
- Carbon Dioxide (CO_2)
- Nitrogen Oxides (NOx)
- Hydrocarbons (HC) or Volatile Organic Compounds (VOC)

The characteristics and effects of chosen (MOEs) are: [1, 19]

"Carbon Monoxide (CO): *Carbon monoxide is a colorless, odorless gas produced whenever incomplete fuel combustion occurs. In the United States, more than two-thirds of the carbon monoxide emissions come from transportation sources. In urban areas, motor vehicle contributions to carbon monoxide pollution can exceed ninety percent. When inhaled, the gas forms carboxyhemoglobin, a compound that disrupts normal respiration by inhibiting the transfer of oxygen to specialized blood cells that transport the oxygen throughout the body. Symptoms from exposure include impairments in visual perception, manual dexterity, learning functions and the ability to perform complex tasks. Sensitive individuals, such as infants, the elderly or respiratory patients may be highly susceptible to acute symptoms of carbon monoxide poisoning.*

Carbon Dioxide (CO2): *Carbon dioxide is the by product of complete fuel combustion. Although it does not impair human health, the accumulation of carbon dioxide in the atmosphere is believed to contribute to global climate changes by trapping the earth's heat.*

Nitrogen Oxides (NOx): *Nitrogen oxides form when nitrogen and oxygen atoms chemically react inside the high pressure and temperature conditions in an engine. Nitrogen oxides are precursors for ozone, and in the environment, they contribute to the formation of acidic rain.*

Hydrocarbons (HC) or Volatile Organic Compounds (VOC): *Hydrocarbon emissions are a product of partial fuel combustion, fuel evaporation and refueling losses caused by spillage and vapor leakage. Hydrocarbons react with nitrogen oxides and sunlight to form ozone. Some hydrocarbons are toxic and may be carcinogenic."*

Unless otherwise stated, most of this section is paraphrased from aaSIDRA 2.0 User Guide and Manual: [20]

SIDRA uses a four-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.

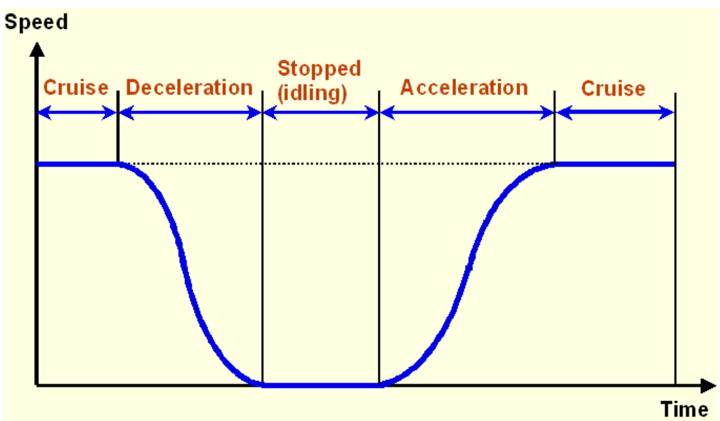

Figure 2: Graphical representation of Drive-cycle model used by SIDRA

For each lane of traffic, aaSIDRA constructs vehicle movements through the intersection as a series of cruise, acceleration, deceleration and idling elements (see below), distinguishing between stopped and unstopped vehicles as well as light and heavy vehicle characteristics. Since traffic performance is different in each lane of traffic at intersections, the fuel consumption, cost and pollutant emissions are calculated for each of the four modes of driving, for each lane of traffic separately and the results are added together for the entire driving maneuver. In each lane, the model is applied to queued and unqueued vehicles separately according to the proportion queued estimated by aaSIDRA. For unqueued vehicles, only the cruise and geometric stop components apply. For queued vehicles, aaSIDRA determines the "drive cycles" distinguishing between major stops, queue move-ups (stops in queue) and geometric stops (slow-down or full stop in the absence of any other vehicle).

The drive cycles are defined by the initial and final speeds in each element of the driving maneuver. The drive cycle information is used to calculate acceleration and deceleration times and distances for each element of the drive cycle individually. The fuel consumption, emission rates and operating cost values are calculated for each element of the drive cycle individually and the results are added together for the entire queued vehicle maneuver, and then the results for queued and unqueued vehicles are aggregated.

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).

Data Analysis

The data collected from videotapes for the AM and PM periods was recorded manually in 15-minute periods, and hourly data was then input to the SIDRA software for analysis. All the Measures of Effectiveness (MOEs) were statistically compared using the standard statistical procedures as shown in the summary table below. 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 3: Summary of Statistical Tests: [17]

Statistical Test	**Inference**
NORMALITY TEST	
a. – IQR/S □ 1.3.	Sample is normally distributed if 1.3.
b. – Shapiro Wilk P-Value	H_o: "Sample is normally distributed", á=0.01
EQUAL VARIANCES	
Levene's Test	H_o: ó$^{2}_{4\text{-Lane}}$= ó$^{2}_{3\text{-Lane}}$
NORMAL W/EQUAL VARIANCES	
Analysis Of Variance (ANOVA) F-Test	H_o: $\mu_{4\text{-Lane}} = \mu_{3\text{-Lane}}$
	-Fail to reject H_o, Analysis Stops.
	-Reject H_o, Perform Multiple Comparisons (Tukey's and Duncan's Tests)
NORMAL W/UNEQUAL VARIANCES	
Welch's Test	H_o: $\mu_{4\text{-Lane}} = \mu_{3\text{-Lane}}$
	-Fail to reject H_o, Analysis Stops.
	-Reject H_o, Perform Multiple Comparisons (Fisher Least Difference Test)
NOT NORMAL	
Kruskal-Wallis Test	H_o: Population distributions are same, á=0.05
	-Fail to reject H_o, Analysis Stops.
	-Reject H_o, Observe data plots to determine rank order.

IQR: Inter Quartile Range, S: Standard Deviation

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 after statistical testing are then averaged and the overall results for Kansas Roundabouts are given in Table 4. The results for individual sites are given in Table 5.

Table 4: Kansas Emission Results

KANSAS ROUNDABOUTS-EMISSIONS : AM RESULTS				
POLLUTANT	AWSC	RA	% Diff.	Statistically Different
Carbon Monoxide (CO) Kg/Hr	9.745	6.03	-38	Yes
Carbon Dioxide (CO2) Kg/Hr	272.6	122.1	-55	Yes
Oxides Of Nitrogen (NOX) Kg/Hr	0.318	0.177	-44	Yes
HydroCarbons (HC) Kg/Hr	0.53875	0.207	-62	Yes
KANSAS ROUNDABOUTS-EMISSIONS : PM RESULTS				
POLLUTANT	AWSC	RA	% Diff.	Statistically Different
Carbon Monoxide (CO) Kg/Hr	13.90	7.68	-45	Yes
Carbon Dioxide (CO2) Kg/Hr	398.8	153.9	-61	Yes
Oxides Of Nitrogen (NOX) Kg/Hr	0.457	0.226	-51	Yes
HydroCarbons (HC) Kg/Hr	0.786	0.253	-68	Yes

Table 5: Emission Results for all sites

OLATHE:RIDGEVIEW/SHERIDAN : AM RESULTS				
POLLUTANT	AWSC	RA	% Diff.	Statistically Different
Carbon Monoxide (CO) Kg/Hr	14.22	8.28	-42	Yes
Carbon Dioxide (CO2) Kg/Hr	428.9	158.1	-63	Yes
Oxides Of Nitrogen (NOX) Kg/Hr	0.474	0.238	-50	Yes
HydroCarbons (HC) Kg/Hr	0.847	0.264	-69	Yes
OLATHE:RIDGEVIEW/SHERIDAN : PM RESULTS				
POLLUTANT	AWSC	RA	% Diff.	Statistically Different
Carbon Monoxide (CO) Kg/Hr	19.99	11.64	-42	Yes
Carbon Dioxide (CO2) Kg/Hr	614.1	221.6	-64	Yes
Oxides Of Nitrogen (NOX) Kg/Hr	0.67	0.33	-51	Yes
HydroCarbons (HC) Kg/Hr	1.222	0.366	-70	Yes

OLATHE:ROGERS/SHERIDAN : AM RESULTS				
POLLUTANT	AWSC	RA	% Diff.	Statistically Different
Carbon Monoxide (CO) Kg/Hr	16.98	9.85	-42	Yes
Carbon Dioxide (CO2) Kg/Hr	513.8	200.5	-61	Yes
Oxides Of Nitrogen (NOX) Kg/Hr	0.573	0.29	-49	Yes
HydroCarbons (HC) Kg/Hr	1.012	0.331	-67	Yes
OLATHE:ROGERS/SHERIDAN : PM RESULTS				
POLLUTANT	AWSC	RA	% Diff.	Statistically Different
Carbon Monoxide (CO) Kg/Hr	25.84	11.84	-54	Yes
Carbon Dioxide (CO2) Kg/Hr	789.5	239.8	-70	Yes
Oxides Of Nitrogen (NOX) Kg/Hr	0.854	0.344	-60	Yes
HydroCarbons (HC) Kg/Hr	1.588	0.395	-75	Yes

LAWRENCE : AM RESULTS				
POLLUTANT	AWSC	RA	% Diff.	Statistically Different
Carbon Monoxide (CO) Kg/Hr	3.91	3.12	-20	Yes
Carbon Dioxide (CO2) Kg/Hr	78.91	65.72	-17	Yes
Oxides Of Nitrogen (NOX) Kg/Hr	0.11	0.09	-18	Yes
HydroCarbons (HC) Kg/Hr	0.14	0.11	-21	Yes
LAWRENCE : PM RESULTS				
POLLUTANT	AWSC	RA	% Diff.	Statistically Different
Carbon Monoxide (CO) Kg/Hr	5.2	4.03	-23	Yes
Carbon Dioxide (CO2) Kg/Hr	107.02	83.14	-22	Yes
Oxides Of Nitrogen (NOX) Kg/Hr	0.15	0.12	-20	Yes
HydroCarbons (HC) Kg/Hr	0.19	0.14	-26	Yes

PAOLA : AM RESULTS				
POLLUTANT	AWSC	RA	% Diff.	Statistically Different
Carbon Monoxide (CO) Kg/Hr	3.87	2.86	-26	Yes
Carbon Dioxide (CO2) Kg/Hr	68.9	64.1	-7	No
Oxides Of Nitrogen (NOX) Kg/Hr	0.115	0.088	-23	Yes
HydroCarbons (HC) Kg/Hr	0.156	0.123	-21	No
PAOLA : PM RESULTS				
POLLUTANT	AWSC	RA	% Diff.	Statistically Different
Carbon Monoxide (CO) Kg/Hr	4.56	3.22	-29	Yes
Carbon Dioxide (CO2) Kg/Hr	84.5	71.2	-16	Yes
Oxides Of Nitrogen (NOX) Kg/Hr	0.152	0.109	-28	Yes
HydroCarbons (HC) Kg/Hr	0.145	0.111	-23	Yes

Discussion of Results

- The average Carbon Monoxide (CO) emissions (Kg/hr) for the intersection locations studied are 38% and 45% 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 Carbon Dioxide (CO_2) emissions (Kg/hr) for the intersection locations studied are 55% and 61% 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 Oxides of Nitrogen (Nox) emissions (Kg/hr) for the intersection locations studied are 44% and 51% less for the AM period and PM periods respectively for the case of a modern roundabout. Statistical tests showed that the decrease in NOx 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 Hydrocarbons (HC) emissions (Kg/hr) for the intersection locations studied are 62% and 68% less for the AM period and PM periods respectively for the case of a 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, All Way Stop Control (AWSC) because, as previous studies have concluded, the modern roundabouts have less delay, queuing and stopping than an AWSC. This is reflected in the decrease in vehicular emissions shown above.

Conclusions

- The modern roundabouts in Kansas operated more effectively than the before intersection control (AWSC) in reducing vehicular emissions at all locations studied.
- There was a (38%-45%) decrease in the Carbon Monoxide (CO) emissions (Kg/hr) 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 (55%-61%) decrease in the Carbon Dioxide (CO_2) emissions (Kg/hr) 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 (44%-51%) decrease in the Oxides of Nitrogen (Nox) emissions (Kg/hr) 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 (62%-68%) decrease in the Hydrocarbons (HC) emissions (Kg/hr) 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 intersection 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.

Overall Conclusion

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

Further Study

Further studies should be conducted in other locations in Kansas 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.

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