Assessing Different Freeway Interchange Design Impacts on Traffic Emissions and Fuel Consumption Through Microsimulation

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Abstract

When evaluating different roadway design alternatives, environmental impacts attributed to vehicular emissions should be considered as significant as their traffic safety and operational performances. In today's world we are aware of the impacts of climate change and global warming. As freight and passenger travel demands increase, so does congestion and emissions from transportation vehicles, which have drawn a significant attention in recent years. Transportation is the highest contributor to U.S. greenhouse gas (GHG) emissions by economic sectors. Vissim emission calculator provides an opportunity to perform a comparative emissions analysis. This paper summarizes a case study of an existing service interchange, a conventional diamond interchange (CDI) at Austin Blvd on I-75 located 12 miles south of downtown Dayton, Ohio with other two alternative designs, a diverging diamond interchange (DDI) and a single point urban interchange (SPUI), in terms of fuel consumptions, emissions, and traffic operations for similar traffic conditions, and roadway characteristics through microsimulation. In this study we focused on three critical pollutant gases emitted from vehicles' exhaust pipes, i.e., carbon dioxide, carbon monoxide and nitrogen oxides, including fuel consumption. In addition, the study selected average stopped delay and average queue length for traffic operations measures of effectiveness (MOEs) because these two reflect all others in terms of the expected trends and expectations. The signal optimization for each interchange was conducted utilizing PTV Vistro and traffic simulation and emissions analysis using PTV Vissim. The results indicate that the existing CDI design results in much higher emission rates than the SPUI and the DDI for each traffic level condition considered. Although the SPUI's and DDI's performances were very close, a significant difference was observed at higher traffic volumes. Generally, emissions at the DDI design were lower compared to the SPUI design.

Keywords: Emissions, Microsimulation, Vissim, Interchange, Fuel consumption.

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1. Introduction

Intersections and interchanges are places with an elevated probability of crash incidences and traffic congestion sources as they turn out to be bottlenecks due to increased traffic interactions due to potential vehicles' paths crossing each other as compared to segments in the roadway networks. When designing intersections or interchanges, attention is usually on two major measures of effectiveness (MOEs) to assess the feasibility of different design alternatives, which are safety and operational performances as the main criteria. Since limited access facilities, such as freeways and expressways, are generally designed to the highest standards, thus they are expected to experience significantly lower crash frequency, injury, and fatality rates than other roadway facility types, but these rates are generally higher in the locale of interchanges due to increased traffic conflicts [1].

The foregoing discussion outlines that intersections or interchanges are the main focus of attention. Therefore, various interchange design alternatives are compared based on their expected traffic operational and safety impacts [1]. However, intersections (including interchanges) are also critical elements of road networks in terms of air quality impact, and their control type and geometric configurations can significantly affect vehicular emissions [2-6]. In recent years, air pollution produced by vehicular traffic has received increasing attention in traffic management and control. On-road vehicles are a significant source of transportation carbon dioxide (CO_2) greenhouse gas emissions.

Traffic congestion, delays, costs, and lost productivity have become epidemic in most countries with large urban overpopulated cities. Generally, intersections can be grouped into two major types, i.e., at-grade and grade separated intersections. At-grade intersections are mainly used to control arterials, collectors and other minor roadways and the most common ones include traffic signals, two-way stops (TWSC), yield controls, all-way stops (AWSC), and roundabouts. On the other end, grade-separated intersections, also known as interchanges, are used to provide controls between freeways, i.e., facilities with limited access and arterials (known as service interchanges) or freeway to freeway (known as system interchanges). Several service interchanges used in the United States include conventional diamond interchanges (CDIs), single-point urban interchanges (SPUIs) and diverging diamond interchanges (DDIs). The CDIs are the most common types of interchanges in the United States. The SPUIs are relatively new as the first one built in the United States was in 1974, and the innovative DDIs are very recent as the first one in the United States was built in 2008.

Since intersections are locations with the highest probability of crash occurrences and traffic congestion and consequently, these are the main reasons why much of the research on intersections focus on their impacts on safety and traffic flow and there are widely used and well-established standard manuals that provide guidance on how to analyze and compare intersections' performances in terms of traffic operations [7,8] and safety analyses [8]. The Federal Highway Administration [9] acknowledges that motorists, pedestrians, and bicyclists face greater mobility challenges and safety risks at interchanges as traffic volumes grow and congestion worsens [9]. The FHWA [9] further asserts that the DDI is a simple design innovation that improves safety and mobility as compared to conventional interchange designs (i.e., CDI and SPUI).

As mentioned above, when assessing the feasibility of different intersection/interchange design alternatives we typically use their safety and operational performances as the main criteria. Vehicular emissions depend on traffic, road and vehicle characteristics, atmospheric conditions and driving behavior. At intersections vehicles usually slow down and often stop, thus interrupting traffic flow in varying patterns. This is true to all at-grade intersections and service interchanges. Several studies on vehicular emissions and fuel consumption in the literature have mainly focused on at-grade intersections especially evaluating roundabouts versus traffic signals or other unsignalized intersections such as TWSCs, AWSCs, and yield controls [e.g., 5,6,10]. Based on our literature search, no study was found that focused on service interchanges, which typically end up having either a signal control or unsignalized control (TWSC) on the arterial end, which cause traffic exiting from freeway or expressway to stop, crawl down and decelerate and accelerate similar to typical at-grade intersections. However, a few studies of traffic emissions for freeway segments were found but did not focus on the interchanges [e.g., 11,12].

The U.S. Environmental Protection Agency (EPA) provides a breakdown of the total U.S. greenhouse emissions by economic sector for 2019 where it is estimated that a total of 6,558 million metric tons of CO_2 equivalent were accumulated nationwide [13]. Vehicular emissions are more harmful with substantial impacts to communities adjacent to roadway facilities because, unlike emissions from industry, they are produced at low levels near the ground [14]. Emissions of greenhouse gases (GHGs), primarily carbon dioxide (CO_2), are contributing to global (warming) climate change, which is believed to be one of the most critical environmental issues facing our planet this century [11,13]. The transportation sector is one of the biggest contributors to anthropogenic (chiefly of environmental pollution and pollutants originating in human activity) U.S. greenhouse gas emissions [11,13]. Figure 1 [13] shows the main sources of total U.S. greenhouse gas emissions in 2019 global warming potential (GWP).

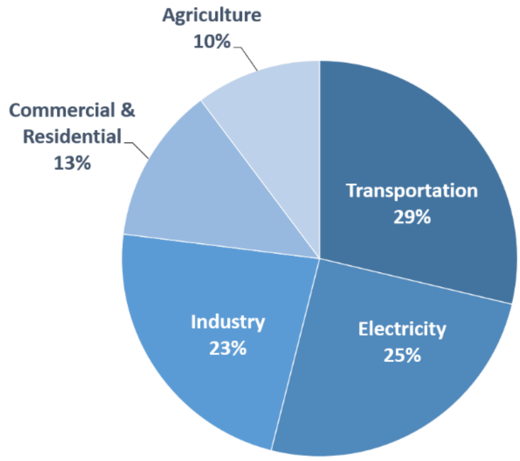

Figure 1: The Total U.S. greenhouse gas emissions by economic sectors in 2019.

Most greenhouse gas emissions from transportation are carbon dioxide (CO_2) emissions resulting from the burning of petroleum-based products such as petrol used in internal combustion engines [13]. According to EPA [13], passenger vehicles (i.e., passenger cars, sports utility vehicles, pickup trucks, and minivans) and light-duty trucks are the major sources of transportation-related greenhouse gas emissions and they contribute more than 50% of the transportation sector-based emissions. The other portion of the transportation sector-based greenhouse gas emissions originate from other transportation modes such as goods trucks, boats, ships, commercial aircraft, trains, pipelines and lubricants [13]. Therefore, traffic entering and leaving freeways and expressways via service interchanges in urbanized areas that are heavily congested contribute a significant share of emissions.

The objective of the current study was to compare the environmental performance of three service interchange designs using traffic microsimulation. This comparative analysis involded an existing conventional diamond interchange (CDI) and two relatively newer but popular interchange types, i.e., a single point urban interchange (SPUI) and a diverging diamond interchange (DDI). More specifically, a real existing service interchange was modeled in Vissim with the three different alternative designs, signal design optimized in PTV Vistro, and they were analyzed in terms of traffic operations (vehicle performances) within the three designs of service interchange controls and were compared in terms of emissions of three major pollutants (CO_2, CO, and NO_X) based on simulated traffic analysis. Additionally, this study selected only two traffic operations MOEs: average stopped delay and average queue length because these two also reflect all other MOEs in terms of the expected trends and expectations.

2. Methodology

2.1 Data

This study used actual and most current traffic data for a CDI located in Montgomery County in Ohio. Data was provided by the Ohio Department of Transportation (ODOT). This interchange is located at the intersection of I-75 and Austin Blvd, about 12 miles south of Downtown Dayton. The latest classified turning traffic data counted on December 5, 2019 and signal timing data were obtained.

2.2 Methods

2.2.1 Signal Optimization

PTV Vistro 2020, were utilized to optimize the intersections on each model. As a transportation analysis software, Vistro uses HCM 6th edition analysis method for signalized intersections. These two intersections are fully actuated with four coordination patterns which the PM peak hour pattern was selected for this study. The pedestrian phases were not introduced in these simulations considering that very low volumes of pedestrian crossing were reported during peak hours. According to the Google map, a speed limit of 45 mi/h is posted on both approaches of the Austin Blvd arterial and thus the 45 mi/h speed limit was used in all three models. The Bing Aerial map embedded in Vistro helped shape the geometry and other characteristics of the intersections. Figures 2 to 4 show the basic geometry of each interchange, the existing CDI, the SPUI, and the DDI as modeled in Vistro 2020.

All the interchanges' characteristics, such as the number of lanes, lane width, and gradient, assumed the same throughout the models. For the DDI and SPUI adjustments were made in turning movements to allow through movements on both north and south bounds. Thus, the through movement volumes were added to the right turn movements in those directions.

Figure 2: The existing conventional diamond interchange design in Vistro.

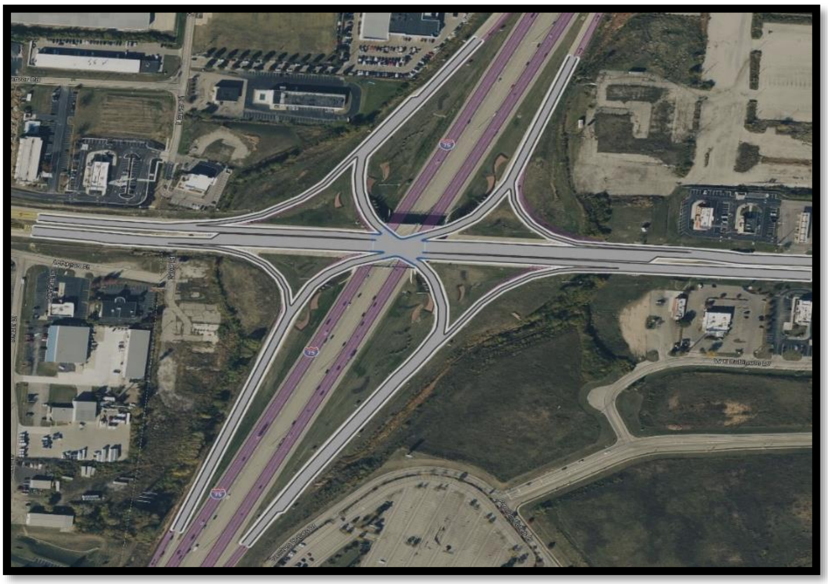

Figure 3: The proposed single point urban interchange design in Vistro.

Figure 4: The proposed diverging diamond interchange design in Vistro.

Vistro software's integration with PTV Vissim enabled us to transfer the geometry, signal timing, and other intersections' characteristics. The Vissim previewer option in Vistro is a great feature to visualize the network before exporting it to Vissim. After finalizing the network, we exported the network and signal data to an ANM file, which we imported to Vissim to complete the simulation analysis.

2.2.2 Traffic Simulation

PTV Vissim is a microscopic tool that models various transport operations in rural and urban areas, based on second-by-second, behavior-based simulation. Wiedemann's 74 car-following models, suitable for urban traffic, were adopted in these simulations. The simulated model is 100% stochastic and constrained with some network parameters, signal controls, and vehicle records. Which also considers different driving behavior to account for day-to-day variable traffic conditions. Ring Barrier Controllers were used for signal lights as per the existing intersection and in compliance with the NEMA standards. The existing CDI's signal timing with two controllers were set to the values obtained from ODOT with minor adjustments. The traffic lights are fully actuated and the detectors' locations in the virtual model were placed as closely as possible to their real locations on the ground. However, for the other two models, the DDI and SPUI, the optimized version of the signal timing with two controllers for DDI and one Controller for SPUI were considered in this study. All other parameters such as vehicle type, vehicle composition, vehicle classes, driving behavior, vehicle route decision, and vehicle inputs were introduced according to the ODOT data and network geometry and were nominally adjusted while calibrating the model to fit the existing scenario. Even though slope affects emissions, given that this case study is a comparative analysis, the slopes were set to zero for the entire network for all scenarios.

Visualization color scheme in Vissim were used to calibrate the existing CDI. The Heatmap was created based on the network's current speed attribute and compared with live Google Maps traffic and OHGO for the evening peak hour period (4:45-5:45 pm) for which our traffic counts are based on. There were similarities in the congested areas where the speed was the lowest, with higher queue lengths. We concluded that by editing the desired speed distribution and some minor adjustments to driving behavior, the simulated model was closer enough to the actual traffic conditions. Also, introducing four data collection points helped to check the throughput volume at each exit, which within 15% reduction, the traffic counts were acceptable.

2.2.3 Simulation of Emissions and Fuel Consumption

Emission simulation studies can be done in various ways. In this study, we chose Vissim to calculate vehicles' exhaust emissions to assess the environmental impact. For emissions calculation, EmissionModel.dll as an external emission model was introduced to each vehicle type, which in this modeling we only have two vehicle types: (1) car and (2) heavy vehicle. Following parameters were transferred for all vehicles: accelerations, speeds, weights, ID numbers, vehicle types, and gradients.

We chose the emission values to display in Vehicle Network Performance Evaluation and Node Results by adding each emission attribute to the list. One node was defined for each model, and for each interchange design three levels of traffic volumes were analyzed to create a sensitivity analysis of traffic volume: the first scenario being analyzed for 20% higher volume, the second scenario for 20% lower volume; and the third scenario being analyzed using the actual traffic counts (i.e., the base condition). The analysis was performed for a one-hour simulation period with 15 minutes of warming time, different random seeds, and ten runs for each scenario. Thus, we ended up with nine different scenarios based on three traffic demand levels and three interchange design types.

3. Analysis and Results

This section presents the study results. The comparative results from Vissim output that are used in the performance assessment of the three interchange design alternatives, which are discussed in this section are divided into two parts. The first part discusses the operational measures of effectiveness (MOEs) in terms of average stopped delay and average queue length. The second part discusses the emissions measures of effectiveness in terms of CO_2, CO, NO_x, and fuel consumption.

3.1 Traffic Operations Assessment

PTV Vissim's output results include several measures of effectiveness that reflect the operational performance of the modeled node. Vissim simulation produces several operational performance measures including queue length, queue delay, vehicle delay, stopped delay, vehicle length, travel speeds, LOS, etc. Data collected from Vissim to assess the operational performance included all these mentioned performance measures. Node feature in Vissim was used for data collection. Nodes, are the network sections at intersections but can also be introduced at section elements to collect data. In this case, the evaluation data collection node included both on-ramp and off-ramp traffic using the node evaluation where you record data from the nodes of microscopic simulation as outputs. We only selected to discuss two of these MOEs, that is, average stopped delay and average queue length as already explained above. Average stopped delay is defined as the average stopped delay in seconds of vehicles in the network within the node and the average queue length is defined as the average distance in feet detected by queue counters in a node [14].

Figure 5 shows a comparison of predicted average stopped delays (in seconds) results between the existing CDI and the two alternative designs (SPUI and DDI) for the same PM peak hour traffic volume scenarios (i.e., actual volume, ±20% volumes). The results in Figure 5 show that the average stopped delays were substantially much higher for a CDI as compared to a SPUI and a DDI. A SPUI has slightly better performance in terms of stopped delays at lower traffic volumes than a DDI but at a higher volume, a DDI slightly edged the SPUI. As expected, all interchange design types had their stopped delays increasing by increasing traffic demand (increased congestion and without signal retiming).

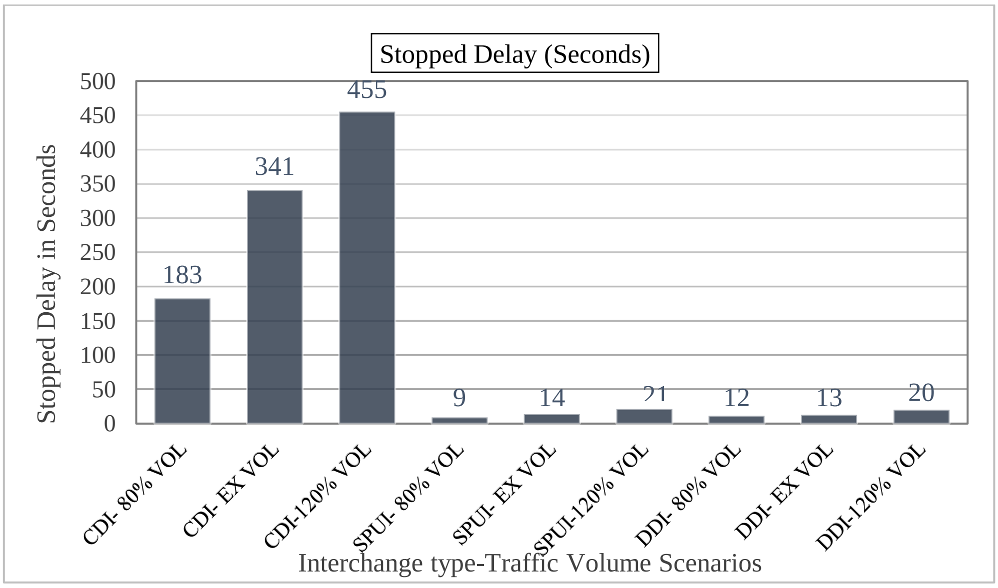

Figure 5: Average stop delay results.

Figure 6 depicts the average queue length results in feet for the three interchange designs and the three traffic demand level alternatives considered in this study. Again, the CDI had the largest queue length, and it became much higher with increased traffic volumes. The SPUI experienced the lowest queue lengths at higher volume (at 100% and 120% traffic volumes). However, the DDI had a little bit less than half of the queue experienced at the SPUI when the traffic volume was at 80% of the existing volume.

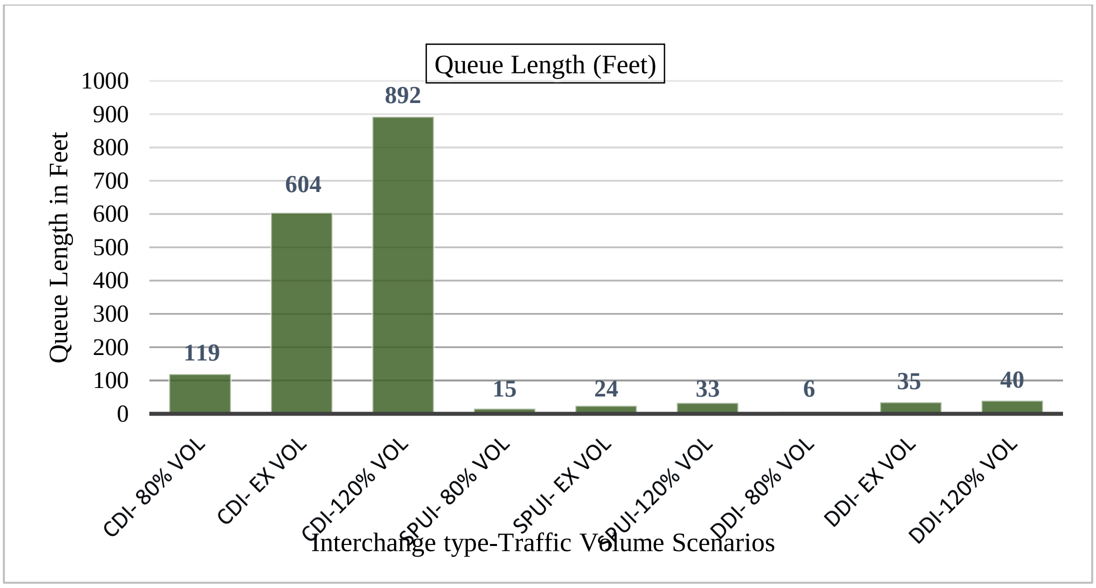

Figure 6: Average queue length results.

3.2 Emissions and Fuel Consumption Assessment

Although Vissim emissions output results include many environmental pollutants including some little-known ones, in this study, we concentrated on more known major pollutants that EPA and previous studies have mentioned to come from motor vehicle exhaust pipes and believed to be the main sources of environmental degradation [13]. The emission result tables in Vissim were directly exported from Vissim as node results, and each table contained the value of emissions that were initially given in gram units. From these results, then each emission was normalized by dividing the emission value by total vehicle miles traveled (VMT) for each interchange design for all scenarios considered in this study. This normalization makes it better to understand the relationships between the emission rates and the individual design alternatives. In addition, a comparative result of fuel consumption by all vehicles that traversed through the defined node that captures the interchange ramps including interconnected links throughout the entire simulated hour of Vissim microscopic analysis is provided. Figure 7 shows the comparison of total carbon dioxide emissions given in grams per miles traveled. The CDI produced much higher carbon dioxide per miles travel than the two other design alternatives for all three traffic demand levels. At the 80% traffic volume, both the SPUI and DDI produced almost equal amounts of carbon dioxide per miles traveled, but at 100% and 120% traffic demand, the DDI performed better than the SPUI by producing less pollution in terms of CO_2 emission for each vehicle mile of travel.

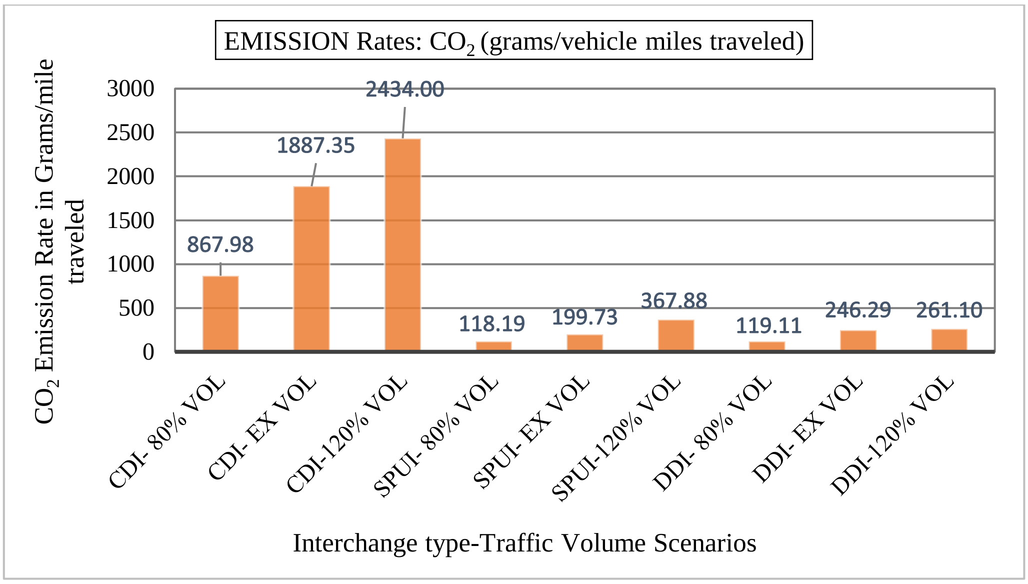

Figure 7: Total CO_2 emissions in grams/vehicle miles traveled results.

Figure 8 shows the comparative results for the carbon monoxide emissions predicted from the Vissim microsimulation analysis of the three interchange design alternatives and three traffic demand scenarios considered in this study. These results are also given as the normalized results in terms of grams per vehicle miles traveled. The carbon monoxide results closely mirror those of carbon dioxide results. The CDI emitted much more carbon monoxide pollutants per vehicle miles traveled compared to the other two designs. Again, the DDI and SPUI emitted equal amounts of CO pollutants at 80% of the traffic volume considered, but the DDI did better for the two higher volumes, that is, at 100% and 120 traffic volumes as compared to the SPUI's performance. As expected, all interchange design alternatives produced higher rates of CO_2 than CO across all the traffic demands considered.

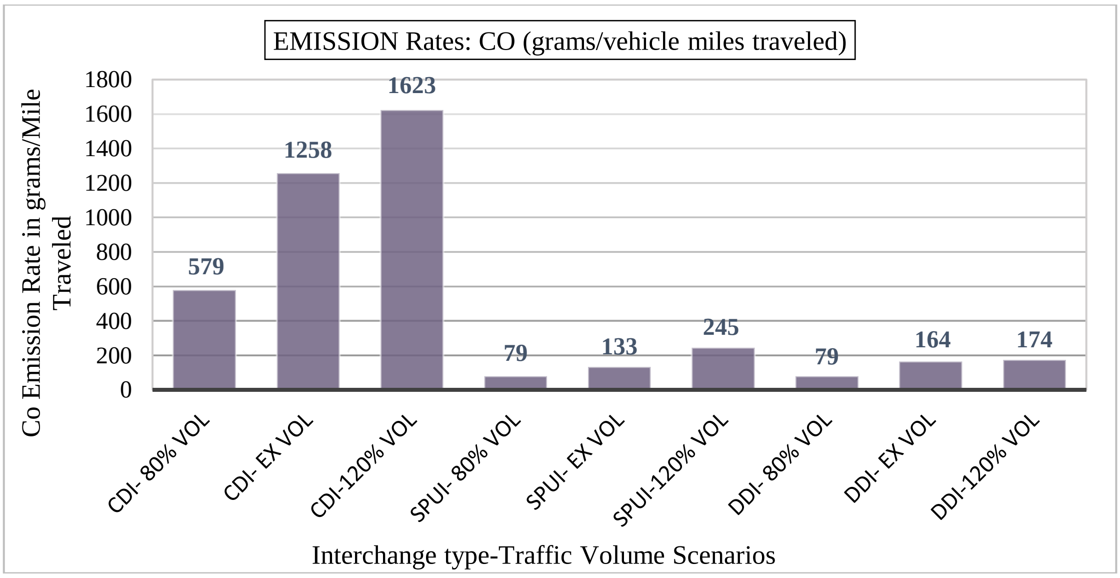

Figure 8: Total CO emissions in grams/vehicle miles traveled results.

Figure 9 shows the results of nitrogen oxides (NO_x) emission rates by vehicles for the different traffic demand levels over the different interchange design types considered in this study. The nitrogen oxides emission results show similar trends shown by the carbon dioxide and carbon monoxide emissions. In all cases, emissions increase with an increase in traffic volume, i.e., with increased congestion.

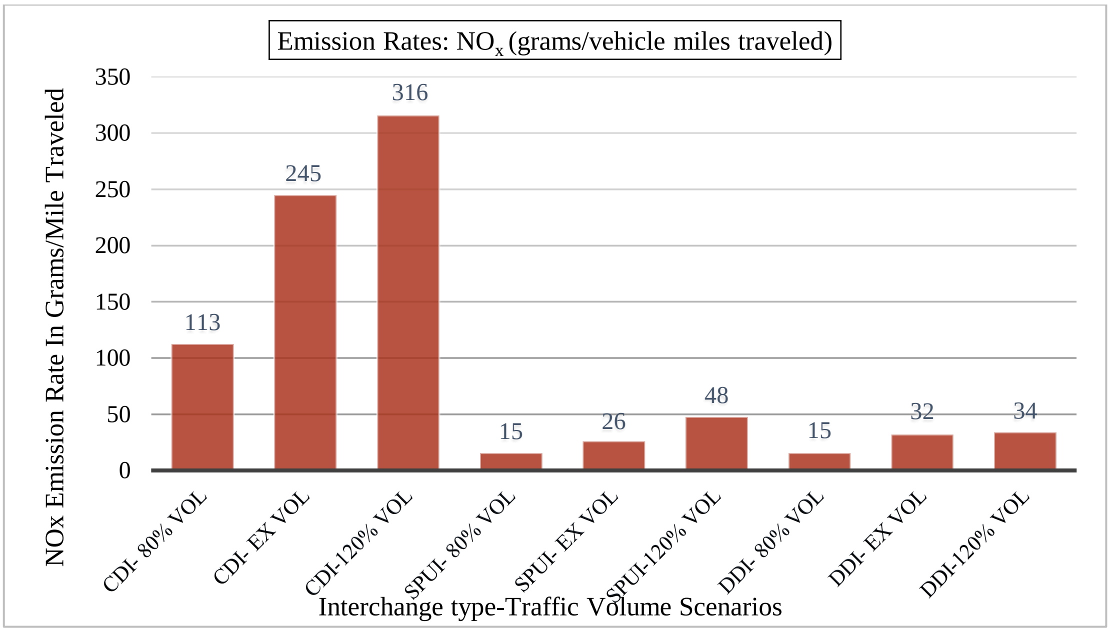

Figure 9: Total NO_x emissions in grams/vehicle miles traveled results.

Figure 10 depicts the results of total fuel consumption in gallons for each interchange design type and traffic loading scenario considered in this study. This is the total gallons of fuel estimated to be consumed by all vehicles over the hour of analysis when traveling over all the roadway links within the Vissim's defined node. The fuel consumption rates follow a similar trend as those shown by the three pollutant emissions discussed above. The interchange design type that caused vehicles to consume more fuel for the same traffic demand, produced more pollutant emissions. It was also expected that total fuel consumption increased with an increase in traffic volumes for all three interchange design types because each vehicle in the traffic stream consumed fuel and collectively you expect to get more fuel consumed cumulatively.

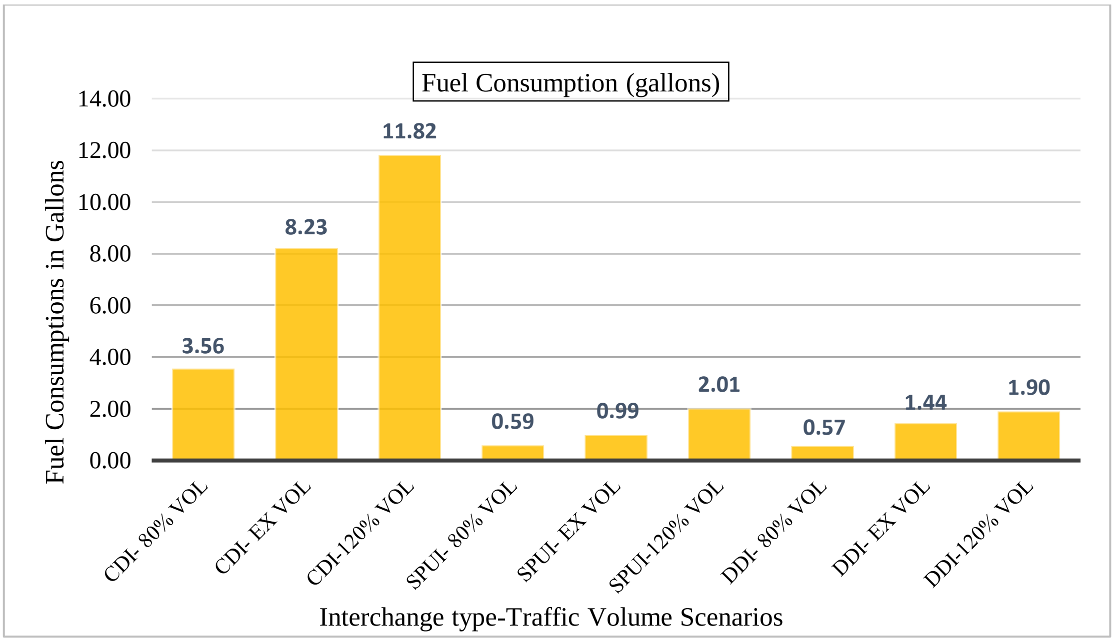

Figure 10: Total fuel consumption in gallons for each interchange design type and traffic scenario.

4. Discussion

The results indicate that the existing CDI design results in much higher emission rates and higher fuel consumption than the other two alternative designs, SPUI and DDI, for each traffic level conditions (traffic characteristics). A reduction of 85% on average for both alternative designs compared to the existing CDI was calculated. The three different traffic volume levels (80%, 100%, and 120%) were developed to perform a sensitivity analysis to assess their impact on traffic operations and pollutants emissions for each interchange design type under study. In terms of operations analysis assessment by using the average queue length as a measure of effectiveness, we found that for a CDI design, lowering the traffic volume by 20% lowered the average queue length by 80% and a 20% increase in traffic volume increased an average queue length by 48%. For a SPUI design, lowering the traffic volume by 20% lowered the average queue length by 37% and a 20% increase in traffic volume increased an average queue length by 35%. For a DDI design, lowering the traffic volume by 20% lowered the average queue length by 83% and a 20% increase in traffic volume increased an average queue length by 15%. This sensitivity analysis of queue length shows that a DDI still performs well at a higher traffic volume because it is the one that experienced the lowest increase (which is less than 20%) when traffic volume was increased by 20%. In other words, we expected a DDI to perform better with congested traffic demand than the other two alternatives compared in this study.

When looking at the average stop delay as a measure of traffic operations analysis assessment, we saw that for a CDI design, lowering the traffic volume by 20% lowered the average stop delay by 46% and a 20% increase in traffic volume increased an average stop delay by 34%. For a SPUI design, lowering the traffic volume by 20% lowered the average stop delay by 37% and a 20% increase in traffic volume increased the average stop delay by 53%. For a DDI design, lowering the traffic volume by 20% lowered the stop delay by 10% and a 20% increase in traffic volume increased the stop delay by 57%. This sensitivity analysis of stop delay shows that a CDI experienced the lowest stop delay increase when the traffic volume was increased by 20% However, this is highly overshadowed by the fact that the actual stop delay at CDI was already way higher than the other two design alternative, which means that change in delay, does not even bring it closer to what the DDI and SPUI experience. Please note that the actual stop delays at CDI, SPUI, and DDI were 455, 21, and 20 seconds, respectively.

In terms of emissions sensitivity analysis assessment by using the total average grams emitted per vehicle miles traveled and the total amount of gallons of fuel consumed, we noted that for a CDI design, lowering the traffic volume by 20% resulted in an average reduction in all emissions rates (that is, including $CO2$, CO, NOx, and fuel consumption) by 57% and a 20% increase in traffic volume resulted in an average increase of 44% in emissions rates. For a SPUI design, lowering the traffic volume by 20% resulted into an average reduction in emissions rates by 40% and a 20% increase in traffic volume resulted into an average increase of 104% in emissions rates. For a DDI design, lowering the traffic volume by 20% resulted in an average reduction in emissions rates by 10% and a 20% increase in traffic volume resulted in an average increase of only 11% in emissions. This again reveals that for a DDI design, emissions rates tend to increase at a slower pace due to an increase in the traffic volume, which may also favor selecting a DDI when the traffic demand is expected to be high enough to lead in a congested operation when compared to a SPUI or a CDI. Therefore, this study has shown that although the performances of the SPUI and DDI seem to be very close, in terms of emissions, the DDI performs much better than the SPUI at higher traffic volumes. In terms of layout design, although the DDI increases the distances traveled, still it improves the travel speeds and reduces stops and hence queue lengths compared to the other two design alternatives.

There is an important point to observe when interpreting the emissions assessment results from this study. The node emissions impact evaluation results in Vissim, which is used to determine exhaust emissions is based on standard formulas for consumption values of vehicles from TRANSYT 7-F, a program for optimizing signal times as well as data on emissions of the Oak Ridge National Laboratory of the U.S. Department of energy [14]. The data used in the methodology are typical of North American vehicle fleet but does not differentiate between individual vehicle types. Thus, the node evaluation is recommended for a simpler comparison of the emissions produced during different scenarios, similar to the current study [14]. In our extensive literature search we did not find any study that directly used Vissim node's emissions analysis methodology. Thus, the results from the current study are good for comparing scenarios, not producing accurate emission values.

5. Conclusions

According to the results of this study, the DDI and SPUI have better performance in terms of average queue length and stop delays in the node's entire network (interchange area). They also perform at higher average speeds and with fewer stop delays than the existing CDI, resulting in a better level of service due to less congestion. Consequently, we observe much better emission rates and fuel consumption in alternative designs than the existing CDI. Although the SPUI's and DDI's performances are very close, the DDI design happens to result in lower emissions than the SPUI at higher traffic volumes (when the interchange is experiencing congestion).

A CDI design seems to quickly result into operational and environmental problems as the traffic demand increases, thus underperforming CDIs should be considered to be replaced with DDIs or SPUIs. The emissions' impacts of interchanges and other roadway designs are as significant as safety and operational performances when assessing the type of interchange design to implement during the planning and designing stages. The environmental impacts and air pollution need to be accounted for as we all hope to pass the gift of life to our next generations.

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