

# PRELIMINARY REPORT

## Do Trenchless Pipeline Construction Methods Reduce Greenhouse Gas Emissions?

Report Prepared for:



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# **Do Trenchless Pipeline Construction Methods Reduce Greenhouse Gas Emissions?**

## **EXECUTIVE SUMMARY**

This document investigates the following hypothesis.

*What reduction in greenhouse gas emissions can be expected when trenchless construction methods are used for municipal pipeline construction?*

To answer this question a review of the published literature was completed. The literature found no publications on greenhouse gas emissions resulting from open cut or trenchless construction methods. Publications were found that compare trenchless and open cut methods for pipeline construction in terms of traffic delays, direct costs, indirect costs, social costs, and environmental costs. Using information obtained from the literature review a methodology was developed to estimate the amount of greenhouse gas resulting from trenchless and open cut traffic delays on roadways with varying traffic volumes and construction equipment use. Using the methodology developed trenchless and open cut greenhouse gas emissions were determined for the construction of a 300mm diameter pipeline 250m long.

The preliminary analysis found that the use of trenchless construction methods can result in 78 to 100 percent lower green house gas emissions than open-cut pipeline installation methods. The reduction in emissions associated with trenchless construction are achieved mainly due to its shorter job duration using less construction equipment and limited or no disruption to traffic flow. It must be emphasized that this is a preliminary estimate that does not include greenhouse gas emissions resulting from: the production and transportation of additional quantities of asphalt concrete and trench restoration materials; loss of pavement life; and/or pavement maintenance and rehabilitation. Thus, it is a conservative preliminary estimate.

The report concludes by identifying further research needs that will expand further trenchless technology greenhouse gas emission savings and the applicability of the green house gas calculation methodology.

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## 1. Introduction

A major portion of the underground water and wastewater infrastructure in North America is rapidly approaching the end of its useful service life. Accordingly, large scale construction works will need to be undertaken for rehabilitating or renewing these vital infrastructure assets. Underground infrastructure networks have traditionally been installed, repaired, rehabilitated or renewed using open cut construction - a trench has to be excavated to the required depth and width along the entire length of pipeline. Although open cut may appear economical in terms of direct cost it can have high social and environmental costs when the construction work is executed in densely populated urban areas. Over the past two decades, innovative trenchless construction methods have become popular for installation and renovation of underground pipe networks in densely populated urban areas. The North America Society of Trenchless Technology (NASTT) defines trenchless technology as *techniques for utility line installation, replacement, rehabilitation, renovation, repair, inspection, location and leak detection, with minimum excavation from the ground surface*. Since trenchless construction methods typically require only minimal excavation (entrance and/or exit pits) or no excavation to install a pipeline they are considered have lower direct costs and significantly lower social and environmental costs than open cut. Trenchless technologies include construction methods known as pipe ramming, horizontal auger boring, micro tunneling, horizontal directional drilling, cured in place pipe lining, sliplining, and pipe bursting, etc (Najafi and Gokhale, 2005).

This paper completes a preliminary study on open cut and trenchless construction in terms of their carbon dioxide (CO<sub>2</sub>) greenhouse gas emissions. Section 2 presents a review of the published literature with respect to the comparative assessment of open cut and trenchless technologies while Section 3 provides the problem statement. Section 4 describes a new

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methodology for completing a preliminary CO<sub>2</sub> comparative analysis while Section 5 uses this methodology to compare open cut and trenchless CO<sub>2</sub> emissions for three case studies. A summary is presented in Section 6 and research needs are discussed in Section 7.

### **2. Literature Review**

Social and environmental cost comparisons among the open cut methods and trenchless technologies have been of considerable interest to researchers during the past two decades. McKim, 1997 defined social costs as “costs of construction to society which are not included in the construction bid.” Cited examples of social costs include post-construction reinstatement of public and private property, traffic delay and safety costs, environmental costs due to large scale earthmoving, lost business and tax revenues etc. Jung and Sinha, 2007 also included workers’ safety, and air, water, and noise pollution as social and environmental costs.

Gangavarapu *et. al*, 2003 compared open cut and trenchless technologies in terms of costs arising from traffic disruption. In their analysis they considered fuel costs, time delay costs, and vehicle depreciation costs (for additional miles traveled). Fuel costs were calculated on the basis of additional detour miles traveled with an average miles per gallon consumption. Labour wages per hour were used to determine time delay costs.

Boyce and Bried, 1994 developed detailed equations for estimating trenchless construction social cost savings. In their analysis they considered traffic and pedestrian disruption costs, costs of public awareness in terms of lost productivity, and lost revenue from parking meters and parking tickets. In contrast to these detailed estimating methods, McKim, 1997 put forward a generalized, albeit rough, estimating method based on average social costs from 14 construction

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projects. Using this generalized estimate method McKim demonstrated the need for including social costs in selection process of municipal bids.

Tighe *et. al*, 1999 analyzed costs associated with traffic disruptions due to utility cuts using various construction durations and typical traffic control plans. In their analysis, equations were developed that relate costs to annual average daily traffic (AADT) under various traffic control plans. Costs are determined based on user delays arising from speed delays, queuing delays and detour delays. Open cut excavation for pipe installations were also shown to result in premature pavement deterioration. Tighe *et. al*, 2002 reported that open cut construction can result in a flexible pavement service life loss of at least 30%. This pavement life loss implies increased maintenance and rehabilitation costs to maintain the road at an acceptable level of service.

Jung and Sinha, 2007 in their comparative evaluation of trenchless technologies and open cut methods considered direct, social, and environmental costs. Under social costs, they calculated traffic delay costs (based on the work of (Tighe *et al.*, 1999)) and income loss to businesses. Under the environmental category, they evaluated only noise costs. Furthermore, they discussed but did not quantify productivity, workers' safety, and structural costs.

No papers were found that estimated or compared greenhouse gases (GHG) emissions resulting from trenchless or open cut construction methods.

### **3. Problem Statement**

Carbon dioxide (CO<sub>2</sub>) is one of the major greenhouse gases. This paper attempts to determine the CO<sub>2</sub> emissions associated with open cut and trenchless construction methods for the installation of municipal pipelines –water and sewer. CO<sub>2</sub> emissions result from:

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- Increased fuel consumption due to traffic delays and increased travel distances for detours;
- Fuel consumption of construction machinery and equipment involved in excavation, compaction, backfilling, and repaving operations;
- Fuel consumption used to haul materials to and from the site; and
- Manufacture of materials such as pipes, asphalt concrete, back fill materials, chemicals, etc.

This paper addresses only the first two CO<sub>2</sub> emissions sources noted above. Depending upon the nature of construction work being executed, one or several lanes of a road may be closed to traffic, lane or shoulder widths may be reduced, or the road may be closed completely to traffic. These road conditions often cause reduced speeds thereby reducing the road capacity resulting in queues to build up. When the road is completely closed, traffic has to be diverted to alternate routes. This result in longer travel distances, more traffic on the detour route and speed reductions. When the traffic exceeds the capacity of a road, queues build up and vehicles have to spend more time on the road resulting in higher fuel consumption. Thus in construction zones, CO<sub>2</sub> emission regimes will increase due to altered traffic speeds, idling in queues, and/or increased travel distances.

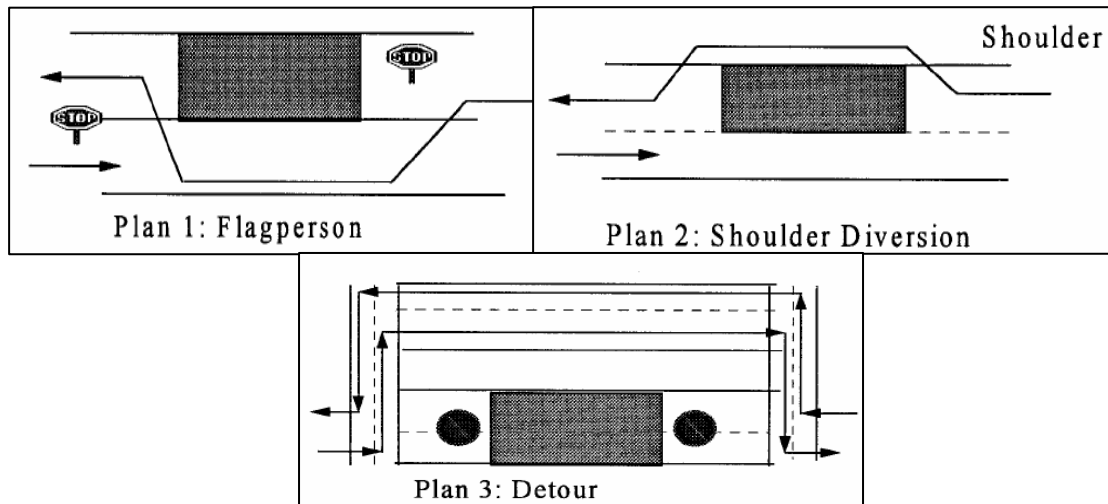
The installation of pipelines is completed using heavy machinery that consumes diesel fuel. Davis and Diegel, 2007 indicate that commercial diesel fuel equipment generates more CO<sub>2</sub> than non commercial gasoline vehicles. According to the EPA (2005) 10.1 kg of CO<sub>2</sub> is generated for each a gallon of diesel fuel consumed.

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### 4. Methodology

#### 4.1. Determination of Speed Reductions and Queuing Delays

Depending upon the layout of the construction zone on a road, various traffic control plans can be implemented. These traffic control plans will alter the geometric conditions of road and hence influence the traffic operating speeds. Figure 1 below shows three typical traffic control plans that could be implemented on two lane highways as suggested by (Tighe *et. al*, 1999).



**Figure 1:** Traffic Control Plans  
source: (Tighe et al., 1999)

Traffic control Plan 1 refers to a situation in which construction work warrants closure of one lane of the road for a certain length. Traffic from the two directions is controlled by a flag person who alternately opens and closes the other lane to the two directional streams of traffic. In traffic control Plan 2, one lane is closed to the traffic but enough shoulder width is available so that the traffic of closed lane could be diverted onto the shoulder for the length of the construction zone. Traffic Plan 3 depicts a situation in which the construction work is such that requires complete closure of both the lanes to traffic. For instance, when a pipeline has to be constructed across the road width, Plan 3 would be implemented. Traffic on the closed road would be diverted onto alternate routes where after it will re-merge onto the closed road.

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Tighe et al., 1999 have utilized traffic analysis techniques provided in TRB, 1994 to derive a simplified approach for calculating speed reductions and queuing delays arising due to the above mentioned traffic control plans. A brief description of this approach is presented below. The following discussion has been adopted from Tighe et al., 1999 unless indicated otherwise.

The normal capacity of a two-lane road is calculated using:

$$CAP_n = 1400 \times 0.72 \times F_{wn} \quad (1)$$

where  $CAP_n$  is normal capacity of a single lane (vehicles/hour/lane), 1400 is the number of passenger cars on each lane under ideal conditions (vehicles/hour/lane), 0.72 is an adjustment factor that reduces capacity to account for the presence of heavy vehicles, and  $F_{wn}$  is an adjustment factor that incorporates the effects of narrow lanes and shoulder widths on capacity.

For different lane widths (metres),  $F_{wn}$  is calculated as a function of shoulder width ( $SHD$  in metres) using:

$$F_{wn} = 0.71285 + 0.20935SHD - 0.021040SHD^2 \quad (2)$$

$$F_{wn} = 0.67295 + 0.19016SHD - 0.016662SHD^2 \quad (3)$$

$$F_{wn} = 0.62588 + 0.17889SHD - 0.015654SHD^2 \quad (4)$$

$$F_{wn} = 0.56485 + 0.17525SHD - 0.020156SHD^2 \quad (5)$$

$$F_{wn} = 0.49142 + 0.15413SHD - 0.020156SHD^2 \quad (6)$$

where equations 2, 3, 4, 5 and 6 are for lane widths of 3.75, 3.5, 3.25, 3.0, and 2.75 metres respectively.

When the lanes are narrow and shoulders are restricted, such as under plans 1 and 2, the reduced capacity of a lane is calculated using Equation 1 with  $F_{wn}$  modified accordingly.

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To determine the reduced traffic speeds under the changed traffic flow regimes, another parameter, i.e. hourly volume ( $HV$ ), needs to be calculated.  $HV$  (vehicles/hour/lane) translates the annual average daily flow volume into an hourly volume for one lane while taking seasonal and directional split ( $DF$ ) factors into account. For a two-lane highway, it is given by:

$$HV = 1.2 \times DF \times AADT \times 0.125 \quad (7)$$

where 1.2 is average summer factor for Ontario, and 0.125 is an adjustment factor for two-lane highways. With the normal capacity, reduced capacity and hourly volume known, the normal speed and reduced speed is calculated using:

$$V_n = 99.322 - 71.047 \left( \frac{HV}{CAP_n} \right) + 100.14 \left( \frac{HV}{CAP_n} \right)^2 - 61.622 \left( \frac{HV}{CAP_n} \right)^3 \quad (8)$$

$$V_r = 94.584 - 60.406 \left( \frac{HV}{CAP_r} \right) + 90.133 \left( \frac{HV}{CAP_r} \right)^2 - 58.505 \left( \frac{HV}{CAP_r} \right)^3 \quad (9)$$

where  $V_n$  and  $V_r$  are speeds under the normal conditions and under a traffic control plan respectively.

Tighe et al., 1999 have used these equations only for determining the speed reductions under traffic control Plan 2. Since Tighe et al., 1999 are primarily interested in time delays that are caused, (traffic control Plan 1), they focused only on the delay arising from the traffic streams coming to complete stop and then waiting for the lane to be cleared for them alternately. Similarly, for traffic Plan 3, they have measured only the additional time that has to be spent while traversing the detour.

The present study takes into consideration the speed reductions for both plans 1 and 3. For Plan 1, the reduced speed given by Equation 9 modified to consider that traffic will have to accelerate

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from a state of rest when it is cleared for moving. While this effect can be calculated using Newton's First and Second laws of motion, it was assumed to be taken into account by an arbitrary 20 percent reduction to the speed determined using Equation 9 under traffic control Plan 1. For traffic control Plan 3, the normal speed is calculated for the detour road using its own hourly volume of traffic, lane width and shoulder width. To calculate the reduced speed, the hourly volume is the sum of the hourly volume of the diverted traffic and the existing traffic on the detour road. This summation of hourly volumes is inserted into Equation 9 to arrive at the reduced speed that will prevail on the detour road.

As mentioned earlier, for traffic control Plan 1, traffic streams are stopped to use the sole open lane alternately. Tighe et al., 1999 calculated the idling time using:

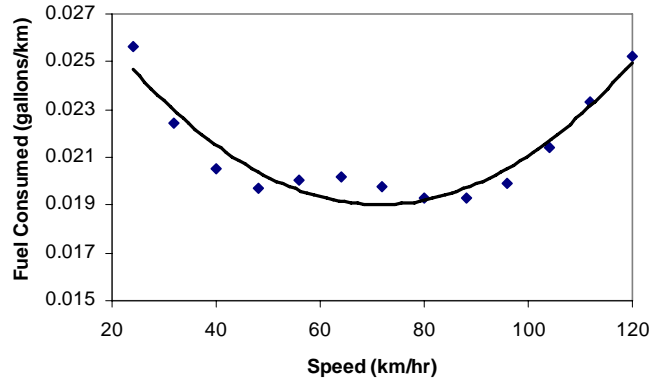
$$D = \frac{[0.38C(1 - g/C)^2]}{3600} + \frac{173X^2[(X - 1) + ((X - 1)^2 + 16X/CAP_r)^{0.5}]}{3600} \quad (10)$$

where  $D$  is the average delay time (hour/vehicle/hour),  $C$  is the cycle length time (seconds) under Plan 1 for the stop and go signals by the flag person,  $g$  is the green time (seconds), and  $X = HV/CAP_r$ .  $C$  and  $g$  are dependent on the annual average daily traffic ( $AADT$ ). Values of both  $C$  and  $g$  for different  $AADT$  ranges have been presented in Tighe et al., 1999.

### 4.2. Determination of CO<sub>2</sub> Emissions for different Traffic Control Plans

As mentioned earlier, vehicle fuel consumption depends upon the operating speeds. Data for average fuel economy for a mix of various vehicle types under varying operating speeds has been reported in Davis and Diegel, 2007. The fuel economy, provided as miles per gallon, was converted gallons per kilometre and speed was converted from miles per hour into kilometres per hour to produce Figure 2.

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**Figure 2:** Fuel Consumption by Speed, data from (Davis and Diegel, 2007)

A polynomial trend line was fitted to the data to yield the following equation relating *speed* (km/hr) and *fuel consumption* (gallons/km), with an  $R^2$  value of 0.9104:

$$fuel\ consumption = 3 \times 10^{-6} speed^2 - 0.0004 speed + 0.0319 \quad (11)$$

For traffic control Plan 1, CO<sub>2</sub> emission impact is calculated as the sum of fuel consumed due to change in vehicle speed and idling time. The change in vehicle speed fuel consumption is calculated as the difference between fuel consumption when vehicles travel at normal speed and reduced speeds under Plan 1 for the length of construction zone. For the idle time fuel consumption, it has been assumed that an idling vehicle consume 0.5 gallons of gasoline per hour.

Change in fuel consumption for traffic going through a construction zone with traffic control Plan 2 is calculated considering the impact of changed speeds only, as explained above.

For traffic control Plan 3, the speeds of diverted traffic and traffic of the detour road are determined. The speeds are then converted to fuel consumed. For the diverted traffic, the fuel required to complete the detour is also determined. Fuel consumption is then converted to CO<sub>2</sub> emissions using (EPA, 2005):

$$CO_2\ emissions\ (in\ tonnes) = 0.0088 \times fuel\ consumed\ (in\ gallons) \quad (12)$$

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### **4.3. Determination of CO<sub>2</sub> Emissions due to Operation of Construction Machinery**

The installation of pipelines using open cut and trenchless construction methods involves the use of construction machinery, such as, excavators, backhoes, loaders, and hauling trucks, etc.

To determine the heavy construction equipment CO<sub>2</sub> emissions, the time duration for which any piece of equipment is operated has to be determined and the associated fuel consumption. Data reported in RS Means (2006) was used to estimate the time for various construction activities to be completed. Peurifoy, et al (2002) indicates that construction equipment fuel consumption can range from one gallon per hour to 11.5 gallons per hour depending on the equipment utilization - low, medium or high. For this analysis a conservative fuel consumption rate of 2.4 gallons per hour was used to determine the amount of CO<sub>2</sub> generated. The fuel consumption was converted to kg of CO<sub>2</sub> using 10.1 kg of CO<sub>2</sub> for each a gallon of diesel fuel used (EPA, 2005).

For example, a 100m long, 3m deep and 1m wide trench required excavating 300m<sup>3</sup> (392 cubic yards) of earth. RS Means (2006) suggests that an excavator with 1 cubic metre bucket capacity can excavate 400 cubic metres per day (for 8 hour work day). Thus, the excavator would need to operate for 8 hours to complete the 100 m long, 3m deep and 1m wide trench. Using 2.4 gallons of fuel per hour the excavation of the trench would produce approximately 200 kg of CO<sub>2</sub>. Similarly, the job durations for backhoes, front end loaders, compactors, required for excavating, backfilling and restoring the trench or pits were determined.

The total amount of CO<sub>2</sub> was determined by adding the amount determined in Section 4.2 and 4.3.

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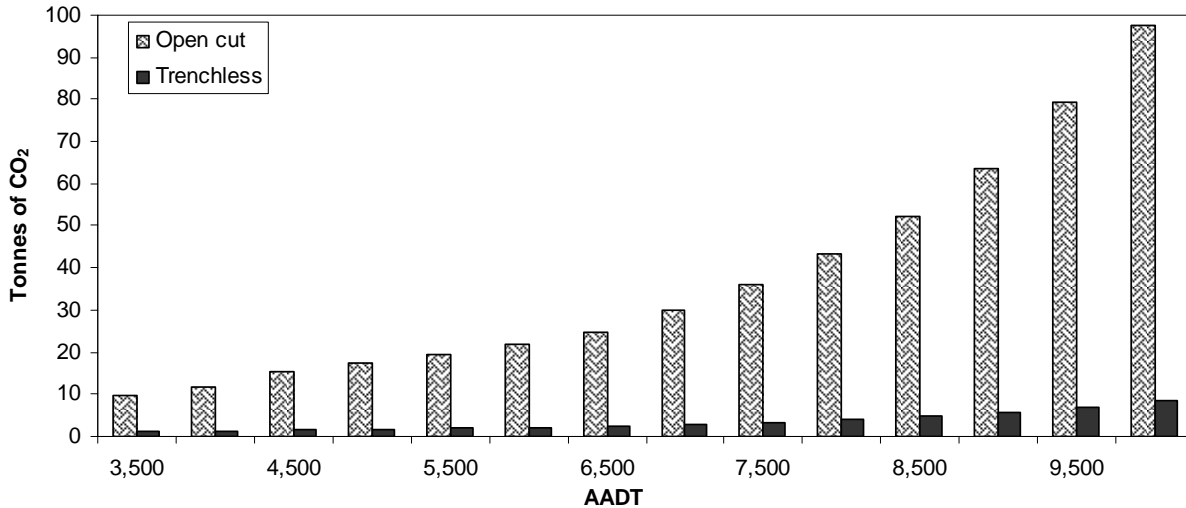
### **5. Case Studies**

To facilitate calculations for various scenarios, a spreadsheet model was developed using the foregoing discussion in Section 4. The utility of this model is demonstrated through the use of hypothetical case studies where CO<sub>2</sub> emissions from open-cut and trenchless construction methods are compared. Job duration for the open-cut pipeline installation is estimated using the approach described in Section 4.3. For trenchless construction pipeline installation the Jung and Sinha, (2007) production rate of 200 m/day was used and it was assumed that only entrance and exit pits would be required at the start and end of the project. Each case study investigates the installation of a 250 metres long, 300mm diameter pipeline to replace an existing sewer or watermain whose performance has been determined as inadequate. Three case studies are presented, one each for traffic control plans 1, 2 and 3.

#### **5.1. Case Study I**

The existing pipeline is under a two-way highway. The open-cut method requires excavation of a trench along the road to extract the existing pipe and replace it with a new one. If trenchless construction is used, then an entry pit and exit pit will be needed at the starting and terminating points of the pipe being installed. Hence both methods would require closing of one lane of the road for construction purposes. Hence traffic control Plan 1 will be implemented, that will close a 250 metres long section of the highway. Using the methodology described in Section 4.3, the job duration for open-cut method was estimated to be 120 working hours, while that for trenchless construction, the job duration was estimated to be 10 hours. Simulations were performed for AADT values ranging from 3,500 to 10,000 on the highway. The results for increased emissions due to construction activities using open-cut and trenchless construction are shown Figure 3.

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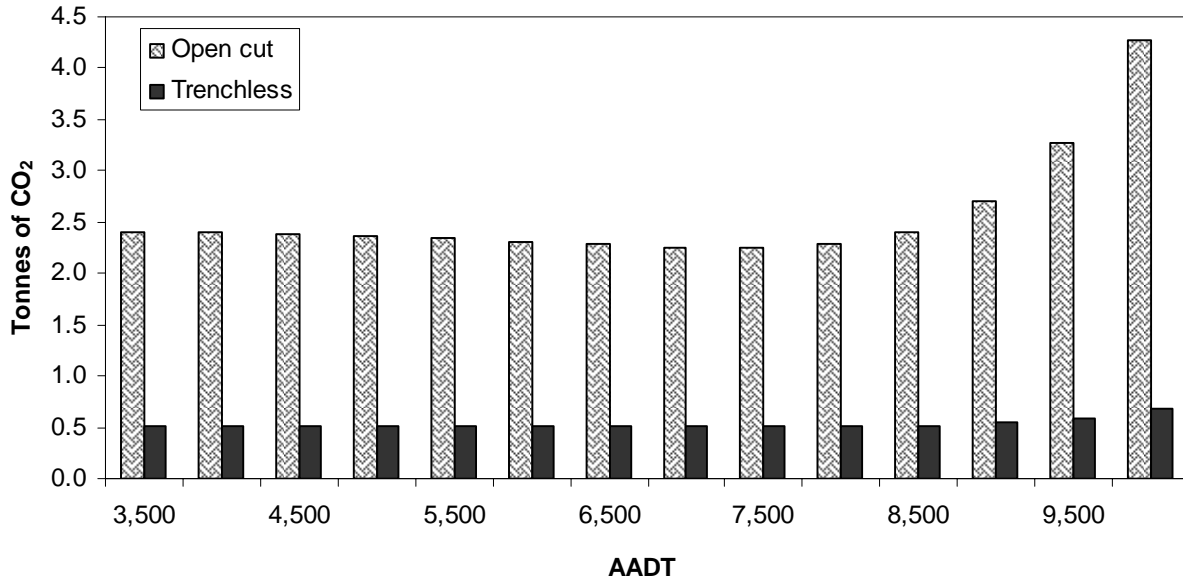
**Figure 3:** CO<sub>2</sub> Emissions at various AADT under traffic control Plan 1

Figure 3 shows that even with very low AADT value of 3,500, undertaking an open cut method of construction will release about 10 tonnes of CO<sub>2</sub> emissions. With the high AADT value of 10,000, the amount of CO<sub>2</sub> released into the atmosphere increases 10 folds to almost 100 tonnes. If the same pipeline installation is installed using trenchless method, even with an AADT of 10,000, the amount of CO<sub>2</sub> released is less than that for the open cut at AADT of 3,500. For this case trenchless construction reduced greenhouse gas emissions by approximately 90 percent.

### 5.2. Case Study II

This case study is similar to Case Study I, except that in this case the shoulders widths on each side of the road are sufficiently wide so that instead of adopting traffic control Plan 1, traffic of the closed lane is temporarily moved onto the shoulder, a situation depicted by the traffic control Plan 2. Results for this case study are shown in Figure 4.

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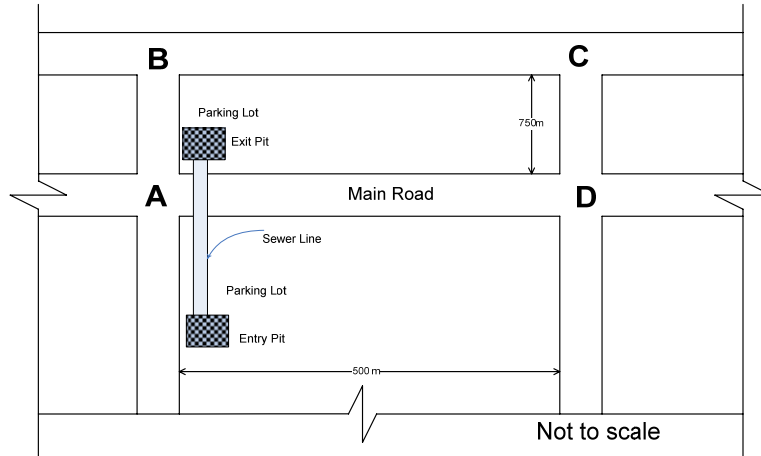
**Figure 4:** CO<sub>2</sub> Emissions at various AADT under traffic control Plan 2

The results show that CO<sub>2</sub> emissions for both methods of construction are significantly less than those under Plan 1 for the corresponding volumes of traffic. This is due to the fact that under traffic control Plan 2, traffic delays are minimal and the major contribution to CO<sub>2</sub> emissions is the use of heavy construction equipment. For this case trenchless construction showed a 78 to 84 percent reduction in green house gas emissions.

### 5.3. Case Study III

This case study is different from the above two case studies in that a pipeline is installed across a road, as shown in Figure 5.

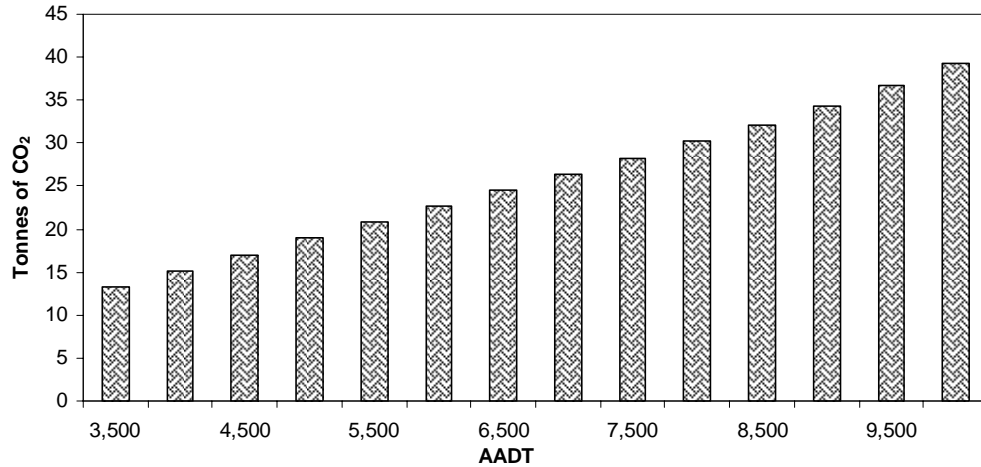
## Do Trenchless Pipeline Construction Methods Reduce Greenhouse Gas Emissions?



**Figure 5:** Schematic view of construction zone in Case Study III

In this scenario, the pipeline is being underlain under a parking lot and a small portion of the line crosses a main road. Enough space is available at both ends for excavating entry and exit pits for the trenchless construction. Except for these two pits, no other excavation for trenchless method is required. Thus, using trenchless construction, no disruptions would be caused to the traffic and CO<sub>2</sub> emissions due to traffic delay would be nil. If open cut construction method were to be used, a trench would have to be excavated all along the length of the pipeline. This would imply excavating a trench across the main road as well. In this situation the main road will have to be closed to traffic for the job duration. Thus, the traffic on main road instead of flowing between points A and D would have to take a detour along ABCD. Traffic control Plan 3 would need to be implemented to allow open cut construction. Since lesser amount of pavement dismantling and reinstatement would be involved as compared to the first two case studies, the total job duration for this scenario was estimated to be 80 hours. For trenchless construction CO<sub>2</sub> emissions were determined to excavate and reinstate entry and exit pits - approximately 0.5 tonnes of CO<sub>2</sub>. For the open-cut method, CO<sub>2</sub> emissions were calculated for various AADT values of the closed road with an existing AADT of 3,500 for the detour route. Results are shown in Figure 6.

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**Figure 6:** Open-cut CO<sub>2</sub> Emissions at various AADT under traffic control Plan 3 for AADT<sub>detour</sub>=3,500

The same set of simulations was also repeated for other values of AADT<sub>detour</sub>. Results for these simulations are tabulated in Table 1.

**Table 1:** Simulation results for CO<sub>2</sub> emissions (tonnes) under varying main road and detour road AADTs using open-cut method of construction

AADT Main Rd	AADT on Detour Road									
	3,500	4,000	4,500	5,000	5,500	6,000	6,500	7,000	7,500	8,000
3,500	13.23	13.18	13.12	13.05	12.97	12.88	12.78	12.70	12.65	12.66
4,000	15.17	15.11	15.03	14.94	14.84	14.74	14.65	14.58	14.57	14.67
4,500	17.05	16.97	16.87	16.77	16.66	16.56	16.48	16.46	16.53	16.77
5,000	18.96	18.86	18.75	18.64	18.53	18.44	18.41	18.48	18.69	19.14
5,500	20.81	20.69	20.57	20.45	20.36	20.32	20.37	20.58	20.99	21.75
6,000	22.69	22.56	22.44	22.34	22.30	22.34	22.53	22.95	23.67	24.87
6,500	24.51	24.38	24.28	24.22	24.26	24.44	24.84	25.56	26.70	28.49
7,000	26.38	26.27	26.21	26.25	26.42	26.82	27.52	28.68	30.41	32.99
7,500	28.22	28.15	28.18	28.35	28.73	29.43	30.55	32.30	34.79	38.39
8,000	30.16	30.18	30.34	30.73	31.41	32.56	34.26	36.81	40.31	45.26
8,500	32.13	32.29	32.65	33.35	34.45	36.18	38.64	42.21	46.99	53.61
9,000	34.29	34.67	35.34	36.47	38.16	40.69	44.17	49.09	55.54	64.31
9,500	36.61	37.29	38.38	40.10	42.54	46.09	50.85	57.44	65.93	77.30
10,000	39.30	40.42	42.10	44.62	48.08	52.98	59.41	68.14	79.23	93.88

Reading across the rows, one can note that for the same value of main road AADT, CO<sub>2</sub> emissions decrease with increasing AADT of the detour road. This downward shift continues until the detour road AADT reaches a threshold value whereupon the emissions start rising again with further increases in detour road AADT. These critical values have been highlighted in the

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table for ready reference. Furthermore, it can be seen that the above trends are valid only up to main road AADT of 8,000. For main road AADTs above 8,000, the emissions follow an increasing trend with the rising values of detour road AADTs. For Case III the analysis indicates that the use of trenchless construction will result in a 100 percent reduction in greenhouse gas emissions.

### **5.4. Summary**

This study demonstrated that large amounts of CO<sub>2</sub> are released due to traffic disruptions associated with construction of sewers under major roads. It also shows that depending on the traffic plan used a small net reduction in CO<sub>2</sub> emissions may occur due to reduced speeds that increases vehicle fuel economy. Time delays during vehicle slow downs will still occur. It was also shown that trenchless construction is considerably efficient in reducing CO<sub>2</sub> emissions. This reduction in emissions is mainly due to its shorter job duration for heavy construction equipment and limited or no disruption to traffic flow. The three case studies show that 78 to 100 percent reduction in green house gas emission can be realized through the use of trenchless construction methods.

The amount of CO<sub>2</sub> emissions determined in this study are considered to be conservative as sources of CO<sub>2</sub> emissions associated with the production and transportation of additional quantities of asphalt concrete, and trench restoration materials were not calculated. CO<sub>2</sub> emissions resulting from loss of pavement life, pavement maintenance and rehabilitation were also not determined. Since these activities would increase traffic delays they are expected to increase the total amount of CO<sub>2</sub> emissions for open-cut method.

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### **6. Research Needs**

This study addressed the need of comparing CO<sub>2</sub> emissions associated with open cut and trenchless construction. Many simplifying assumptions were made in this study. Thus, there is considerable room to increase the scope of this research topic.

This study was limited in application to a short pipe length and small diameter. Annual net CO<sub>2</sub> emissions need to be calculated based on typical sewer construction projects. These net savings can be then be compared to reductions in the number of vehicles off the road, etc. Other factors that can be investigated include: small and large diameter (1m and greater) pipeline projects; other trenchless construction methods (directional drilling, microtunnelling, jack and bore, and renovation); road type (multi-lane highways - divided and undivided), and the development of a more rigorous analytical method. The study can also be expanded to include CO<sub>2</sub> contributions resulting from materials' production and transportation and other second order effects, such as, open-cut pavement loss of service life.

### **Acknowledgement**

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