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A Synthesis of Roadway Surface Impact on GHG and PM_{10} Emissions

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ABSTRACT

Greenhouse gases (GHG) and tiny particulate matters (PM_{10}) are important components of air pollution. Land transportation mode is considered a significant contributor to GHG and PM_{10} emissions. Traffic-related air pollutants are due to exhaust and non-exhaust emissions, which are both influenced by pavement systems. It is of paramount importance to consider these emissions in the evaluation of alternative pavement designs, in strategies for pavement maintenance and pavement management systems, and in life cycle cost analysis of various pavement systems. This study aims at synthesizing the available knowledge on the influence of road pavement on GHG and PM_{10} emissions. Pavement systems according to their characteristics and conditions play an important role in the amount of paved road emissions. To this end, pavement aggregate size, pavement roughness, and pavement type are considered key potential factors. For example, pavement aggregate size is found to affect PM_{10}emissions, with larger aggregates resulting in lower emissions. Pavement overlay systems with smoother surface and smaller International Roughness Index (IRI) values also lead to less GHG and PM_{10} emissions. In terms of pavement type, recently emerged sustainable pavement overlay systems are shown to contribute to reduced levels of emissions. These results are significant in their impact on GHG and PM_{10} emissions and may be utilized to better plan and fund pavement maintenance activities.

INTRODUCTION

The construction, operation, and maintenance of the roadway system entail substantial energy and resource consumption. The current system of paved roads in the U.S. handles a volume of traffic on the order of five trillion vehicle-kilometers per year, or about 13 billion vehicle-kilometers per day *(1).* Due to high energy demand, road transport contributed the most to greenhouse gas (GHG) emissions of any transport mode in 2007, accounting for 83% of GHG emissions from the transportation sector and 27% of all GHG emissions in the U.S. *(2).*Due to the high environmental and economic impact of pavements, there is growing interest in the ability to rigorously quantify the performance of pavements and their impact to the society. The design and operation of pavements in future decades will likely follow a similar path toward greater concern for sustainability. Improving the sustainability of pavements requires first of all, a better understanding of how this infrastructure impacts the natural environment.

Most Pavement Management Systems (PMS) do not endogenously predict road accidents or their costs. They also do not consider environmental impacts such as air and noise pollution, nor traffic delay costs during road construction or maintenance. However, most PMS software can be easily modified to incorporate accident costs, delays, and environmental impacts where exogenous estimates are available. Therefore, the development of relationships between pavement condition and emissions is paramount for an effective PMS system and for incorporating sustainability principles in the road network managing process. This study aims at synthesizing the available knowledge on the influence of road pavement on emissions. Several factors may influence the type and amount of paved road emissions. Pavement characteristics such as roughness and surface friction, pavement type and pavement aggregate size are considered as key potential factors. Tiny particulate matters (PM_{10})and GHGs are important components of air pollution which affect the quality of air and the health of our environment. In this study the impact of pavement characteristics and conditions on PM_{10} and GHG emissions is investigated.

PM_{10} EMISSIONS

PM_{10} particles are those less than 10 micrometers (µm) in size or one fifth of the diameter of a human hair*(3).* PM_{10} pollution consists of very small liquid and solid particles floating in the air.It is generally used as an indicator of sources and effects of other air pollutants because it has the ability to accumulate and combine with other pollutants and particles. This means that if levels of PM_{10} reduce, it is likely that levels of other air pollutants will also be reduced*(3).* These particles are small enough to be inhaled and reach the deepest parts of the lung. As such,they are considered a major component of air pollution that threatens both human and environmental health according to the California Environmental Protection Agency*(4).*

Particulate matter (PM_{10}) air pollutantscaused by road traffic have two main sources; exhaust and non-exhaust emissions.Exhaust emissions are a significant source of PM_{10}. However, by improving engine operation and tailpipe controls during the last decades, vehicle fleet emissions have been remarkably reduced. And the downward trend is expected to continue until goal of “zero emissions” for vehicles is reached. Non-exhaust emissions, on the other hand, are due totire wear, road wear, break wear, and resuspended road dust. Reduction in vehicle emissions, which is currently witnessed and is going to improve in the future, makes the non-exhaust emissions a relatively more important component of PM_{10} emissions *(5).*Since the intent of this study is to document the contribution of pavement to particulate matter pollution, the focus is on the pavement wear and those characteristics of pavement which influence the road dust resuspension emissions.

The Effect of Pavement Wear on PM_{10} Emissions

Pavement wear is an important source of PM_{10} emissions on the paved roads. Pavement wear is a process which is influenced by a variety of factors such as environmental factors, traffic load, axle loads, tire type, and pavement condition. In this section, the influence of pavement characteristics such as pavement roughness and frictional characteristics, pavement type, and aggregate size on pavementwear and thereforeproduction of PM_{10}emissions is investigated.

Aggregate Size

Photographic analysis is a common method to determine the aggregate mean size of the pavement *(6,7).*In this method, average aggregate size and aggregate classification are estimated from the close up photos by counting the number of aggregates along the ruler. Mean size of pavement aggregate could influence the resistance of the pavement to wear; probably due to the surface available for friction with tires and hardness of minerals used.This will in turn influence the amount of the road dust production *(8).*

A negative trend was found by China and James (2012) between PM_{10} mass emissions and the mean size of pavement aggregate*(7).* They found smaller emissions for larger adjusted aggregate sizes. Amato et. al. (2013) also found a negative power relationship between the mean size of pavement aggregates and road dust loadings with diameters less than10 µm*(6).* These results could be explained due to the higher wear rate of finer aggregates, which is probably related to the higher surface available for friction or lower hardness of minerals involved *(8).* Increasing aggregate size normally decreases the total wear of a pavement *(9).*However, quartzite pavement with smaller aggregate sizes leads to less PM_{10} production than the larger aggregate sizes*(10).*Other aggregate properties such as aggregate type arealso found to beas important for PM_{10} production as the aggregate size*(10).*

Pavement Type

Regarding the type of pavement, two varieties of pavements; an asphalt concrete containing granite stone material and a stone mastic asphalt of quartzite stone material with same aggregate sizewere used to study the differences in particle generation*(10)*. The study was done for a constant speed of 70 km/h (43 mph)using studded tires. A circular road simulator, which can be equipped with any type of pavement and light-duty vehicle tires, was used to generate wear particles and a DustTrak instrument (TSI) was placed above the simulator to sample particles. It was found that a granite pavement resulted in 70% higher PM_{10} concentration than a quartzite pavement for the same aggregate size*(10)*.

Moreover, aerosol measurement techniques wereapplied to evaluate tire wear emissions from the vehicle fleet using the Deck Park highway tunnel in Phoenix, AZ *(5)*.Particulate matter emissionswere measured from the on-road vehicle traffic during typical highway driving conditions for two different roadway surfaces; Portland Cement Concrete (PCC) and Asphalt Rubber Friction Course (ARFC). The study showed that the emissions rate of tire wear was higher at the PCC road surface layer than at the ARFC road surface, as summarized in Table 1.

TABLE 1 Tire Wear Emission Rates Measured in Deck Park Tunnel *(5)*

Tire Wear emission rate based on	PCC Road Surface (µg/km)	ARFC Road Surface (µg/km)
Study 1	354±71	177±35
Study 2	172±34	120±24

Pavement Roughness

Pavement roughness is another contributing factor in PM_{10} emissions for both exhaust and non-exhaust emissions. The International Roughness Index (IRI) provides a numeric scale of measuring roughness, which ranges from 0 to 1267 in/mi. The larger IRI values indicate a greater pavement roughness. The value of 125 in/mi is considered the appropriate break point to determine if the pavement is smooth or rough. A smooth pavement is considered to have an IRI value less than 125 in/mi. According to the FHWA guidelines, IRI values measured for very smooth pavement should be less than 60 in/mi *(5)*.

Pavement roughness has a significantinfluence on non-exhaust emissions. The results from a study conducted by Bukowieckiet. al. (2010) show that non-exhaust emissions contributed up to 60% of the total traffic related PM_{10} emissions*(11)*. In general, pavements in good condition contribute less to abrasion emissions. However, damaged pavements result in considerable particle emissions due to abrasion *(12)*. Aging causes deterioration of the pavement, which leads to increase in IRI.

In a study, Alexandrovaet.al. (2007) showed that the roughness and frictional characteristics of a pavement surface play an important role in tire wear and therefore the PM_{10} emissions generated by the interaction of tire and road surface*(5)*. For this purpose, roughness (IRI) and frictional characteristics of Portland Cement Concrete (PCC) overlay and Asphalt Rubber Friction Course (ARFC) overlay were measured. It is shown that the PCC overlay system results in higher PM_{10} emissions than the ARFC overlay system as shown in Table 2.It can be noted in Table 2 that the ARFC pavement with smoother surface (less IRI) emits less PM_{10}emissions despite having a higher friction value*(5)*.

TABLE 2 PM_{10} Emission Rate and Pavement Roughness and Friction*(5)*

Pavement Type	Avg. IRI (in/mi)	Average Friction Value	Tire Wear Emission Rate (µg/km)	
			Study 1	Study 2
PCC	100.436	0.508	354±71	172±34
ARFC	45.226	0.589	177±35	120±24

Effect of Dust Resuspension on PM_{10} Emissions

Resuspension of deposited dust on the road surface is another significant contributor to the PM_{10} emissions from road traffic. Road dust originates from different sources including incomplete fuel combustion, tire and break wear, vegetative plant fragments and soil *(7)*.Bukowieckiet. al. (2010) stated that 38% of the traffic-related PM_{10} emissions in urban street canyonsare attributed to resuspension (in comparison with 21% brake wear and 41% exhaust emissions)*(11)*.The respective contribution along freewaysis 56% resuspended road dust in comparison with 3% brake wear and 41% exhaust emissions, respectively.

Pavement could retain or expose surface dust and thus is a significant contributor to the amount of PM_{10} emissions from resuspension process. The pavement capability to expose or shelter the roadway dirt load is determined by the pavement macrotexture*(7)*. Gehrig et. al. (2010) stated that dense pavement with compact surface structure like asphalt concrete cannot keep deposited dust as much as porous pavement such as porous asphalt*(12)*. Therefore, dense pavements cause more particle emissions due to resuspension compared to porous pavements.

GHG EMISSIONS

Greenhouse gasses (GHG) are from different sources. They come from natural sources or from human activities, according to the U.S. Energy Information Administration*(13)*.Regarding the human activities, GHG emissions can be attributed to several areas such as transportation, residential, industrial and commercial sectors. According to the EPA*(14)*, in 2011 GHG emissions from transportation sector were about 28% of the total U.S. GHG emissions, making it the second largest contributor of the U.S. GHG emissions after the electricity sector. It is stated in the same source that Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and Fluorinated gases are the major GHG emissions through human activities*(14)*. Among those, CO_2 is the most widespread GHGcomponents, and among all factors, the transportation sector is the largest emitter of CO_2*(15)*.

In the transportation sector, factors that may affect the amount of GHG emissions include, but are not limited to, vehicle type and size, ambient temperature, traffic flow, fuel type, frequent deceleration and acceleration and vehicle speed *(16)*. Pavement characteristics in term of pavement type and roughness could affect some of these factors. In this section, the effects of pavement type and roughness on the GHG emissions are assessed.

The Effect of Pavement Roughness on GHG Emissions

A number of studies have confirmed that a relationship exists between GHG emissions and pavement roughness. Pavement roughness could be a factor affecting vehicle speeds, and speed could in turn affect the amount of GHG emissions *(16)*. Therefore, pavement surface conditions, in term of the roughness, may indirectly affect CO_2 emissions. Kalemboet. al. (2012) investigated the relationship between International Roughness Index (IRI) and vehicular speed, and subsequently estimated the GHG emissions*(16)*. IRI data for state roads and speed data on selected road segments were collected in Baltimore County, Maryland. They estimated the CO_2 emissions quantities by using the MOVES2010a program. MOVES2010a is a vehicle emissions modeling software that could estimate emissions factors and inventories of several pollutants produced by vehicles. All other factors that could influence emissions other than the average speed were assumed constant. According to Table 3, roads with lower IRI values have relatively higher mean speeds,resulting in less CO_2 emissions. This relationship was detected for speeds lower than 55 mph. It is interesting to note, however,thatfor speeds higher than 55 mph, emissions increase with higher speeds *(16, 17)*.

TABLE 3 MOVES2010a Results per Passenger Car (16)

Average Speed (mph)		CO_2 Emissions (grams)		Change in CO_2 (grams)
Poor (IRI > 170 in/mi)	**Good** (IRI < 95 in/mi)	**Poor** (IRI > 170 in/mi)	**Good** (IRI < 95 in/mi)	**Poor to Good**
42.4	-	245	-	-
41.2	-	-	-	-
44.1	47.1	243	239	-4
-	48.5	-	-	-
48.3	54.1	238	233	-5
55.7	66.8	231	241	+10

According to the Bureau of Transport and Communications Economics (BTCE) *(18)*, road surface roughness is also related to the vehicle fuel consumption, which would also affect the GHG emissions. TheBTCE studyshows that reducing the roughness of highways has the potential to reduce the amount of fuel consumption and therefore reduce greenhouse emissions.Zhang et. al. (2010) applied a dynamic life-cycle modeling to quantify the life-cycle energy consumption for three overlay systems includingengineered cementitious composites(ECC), hot-mix asphalt (HMA), and conventional concrete*(19)*. It was the first time that roughness-related energy consumption was studied using Life-Cycle Assessment (LCA). The results show reductions of 36%, 14%, and 23% in the life-cycle energy consumption for ECC, HMA, and concrete overlay systems, respectively. Indeed, the results indicate that the pavement roughness effect is one of the greatest contributors to GHG emissions throughout the service life of an overlay system*(19)*.

Increasing pavement roughness causes both more speed variability (speed noise) and an overall reduction in speeds, thus increasing fuel consumption and pollutant emissions. A relationship between Fuel consumption factor (FCF) and IRI is used to model fuel consumptions of vehicles driven on pavements with different IRIs *(20)*.The resulting models for passenger cars and trucks are as follows:

$FCF=7.377\times10^{-3}\ IRI + 0.993$ (passenger cars)(1)

$FCF=2.163\times10^{-2}\ IRI + 0.993$ (trucks)(2)

where IRI isin m/km.In another study, Zhang et. al. (2008) used almost similar equationto show the effect of roughness on fuel consumption for trucks *(21)*:

$FCF=0.0667IRI + 0.8667$ (3)

From these equations,it is obvious that increasing pavement roughness causes more fuel consumption. Generally, CO_2 emissionsare directly proportional tofuel consumption; therefore increases in FCF translate to increases in GHG emissions.

The effect of the roughness on exhaust emissions can be explained in two ways. First, roughness reduces the speed and negatively affects highway capacity. Therefore, it leads to formation of queues and route detours. Highway capacity decreases approximately by 150 passenger car units per hour per lane as IRI increases by 1 m/km(63 in/mi)*(19).* Zhang et. al. (2010) conducted a study to calculate emissions for a vehicle traveling on a rough overlay versus on a smooth overlay using the speed adjustment factor and the lane capacity change factor*(19).* The results show relatively higher emissions on a rough overlay. A second source of increased vehicle emissions due to pavement roughness is engine load changes owing to increased friction and vertical acceleration of the vehicle body caused by additional roughness *(19).*

The Effect of Pavement Type on GHG Emissions

Pavement type is one of the significant contributors to the GHG emissions. Different types of pavements could have different environmental impacts.These impacts result from pavement life stages including material production and distribution, overlay construction and preservation, construction related traffic congestion, overlay usage, and end of life management*(19).* In order to assess the influence of the pavement type on the environment throughout the pavement life, LCAmodels are developed in the recent years. Improving sustainability in pavement design is of paramount importance to the related science and technology fields. In recent decades, the trends are towards designing more sustainable pavements which have lower impacts on the environmentcompared tothe traditional overlay systems. In order to investigate the influence of pavement type on GHG emissions, the impacts of different pavement overlay systems are compared. Zhang et. al. (2010), for example, compared the effects of three pavement overlay systems including conventional concrete, HMA and ECC exhaust emissions during a 40-year service life*(19).* It was shown, as depicted in Figure 1,that the ECC overlay system reduces life-cycle greenhouse gas emissions by 32% and 37% compared to PCC and HMA overlay systems, respectively.

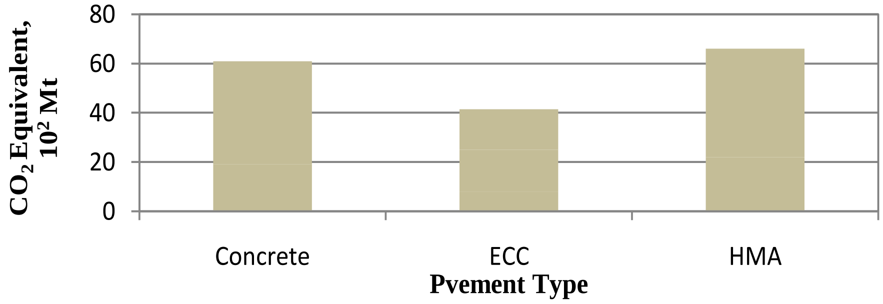

FIGURE 1 Greenhouse gas emissions during life-cycle (19)

The Ministry of Transportation of Ontario, Canada (MTO) used a number of different pavement preservation treatments to achieve sustainability*(22).* For a sustainable pavement, reducing natural resources use, energy consumption and GHG emissions as well as improving the safety and comfort for the users are established as main criteria. Three pavement overlay systems including a 50-mm Mill and a 50-mmoverlay withWarm-Mix Asphalt(WMA), a 50-mm Hot In-Place Recycling (HIR), and a 10-mmmicrosurfacing were compared with a traditional 50-mm mill and 50-mm overlay Hot Mixed Asphalt (HMA). The environmental effects including CO_2 emissions were quantified using PaLATE.The results show, as summarized in Table 4, themicrosurfacing overlay system reduces CO_2emissions by 91%, 85% and 89%compared to HMA, WMA and HIR, respectively *(22).*

TABLE 4 Annualized CO_2 Emissions Generated by Different Type of Pavement Preservation Treatments*(22)*

Pavement Preservation Treatment	Service Life (years)	Annualized CO_2 Emissions Generated (metric tons)
Mill 50 mm-Pave 50 mm HMA	10	3.5
Mill 50 mm-Pave 50 mm WMA	10	2.0
50-mm HIR	10	2.7
10-mm microsurfacing	7	0.3

In a similar study, an LCA model is applied by Yu and Lu (2012) to explore three overlay systems includingPortland Cement Concrete (PCC), Hot MixAsphalt (HMA) and Crack, Seal, and Overlay (CSOL), compared with an old PCC pavement*(20).* CO_2 equivalentis used to express the global warming impacts of each overlay system. According to this study, GHG is dominated by material, congestion, and usage modules for all the three pavement rehabilitation options. It is shown (Table 5) that the PCC overlay systems contribute to GHG emissions 43% and 31% less than the HMA and CSOL, respectively, during the service life*(20).*

TABLE 5 CO_2Emissions Associated withthe Alternatives (20)

Pavement Type	CO_2Emissions (metric tons)
PCC	3872
HMA	6733
CSOL	5598

In another study, pavement surface type in terms of rigid (PCC) and flexible (AC)were compared in relation to fuel consumption and emission rates *(15).*An instrumented van was used to measure the fuel consumption on a rigid and a flexible section of two parallel streets in urban areas.It was reported that under similar surface and ambient conditions and a constant speed of 30 mph, the rigid pavement resulted in a 5% reduction in fuel consumption relative to a flexible section with similar roughness index and longitudinal gradient under the same wind, temperature and humidity conditions *(15)*.It was also estimated that the lower fuel consumption rates would result in similar reductions in CO_2 generation. For the mix of vehicles and vehicle-miles of travel in the Dallas-Fort Worth region, the report projected an annual potential reduction in CO_2 emissions of 0.62 million metric tons. The impact of pavement stiffness on fuel consumption was further confirmed through a similar study conducted at Massachusetts Institute of Technology (MIT) *(23)*. The MIT researchers reported an overall 3% reduction in vehicle fuel consumption through improvements in basic properties of the pavement by using stiffer road materials.

CONCLUSIONS AND DISCUSSION:

The studies reviewed in this research could not be directly compared due to significant differences in their focus, methods, and assumptions. For example, some have compared the effect of pavement type on fuel consumption in urban streets while others investigated that effect on freeways. Another variation among the studies is that some of them measured the emissions throughout the life of pavement whereas other studies focused on the usage stage of the pavement during normal traffic flow.

Despite these varied focus and research methodologies, a number of common threads have emerged from these studies. In terms of PM_{10} emissions, there is general consensus that pavement aggregate size, type, and roughness directly or indirectly contribute to the PM_{10}emissions from the pavement. Normally, increasing pavement aggregate size reduces the amount of PM_{10}pollutions. This phenomenon happens due to the smaller wear rate for course aggregates, which is related to the smaller surface available for friction with tires or hardness of minerals used. Regarding the type of pavement and roughness, pavement overlay systems with smoother surface and smaller IRI values lead to less PM_{10} emissions rather than surfaces with greater IRI values. For instance, ARFC overlay compared with PCC overlay has smaller IRI values and emits less PM_{10}. Also, an asphalt concrete containinggranite stone material leads to higher PM_{10} concentration than stone mastic asphalt containing quartzite stone material. Moreover, the phenomenon of tire wears as one of the significant contributors to PM_{10} emissions is more witnessed in overlay surfaces with greater IRI values.

GHG emissions rates are also found to be influenced by pavement roughness and type. Pavement roughness is a factor which affects vehicle speed and fuel consumption and thus GHG emissions. Pavements with smaller IRI values contribute to relatively higher mean speeds and lower speed noise and subsequently lower fuel consumption, hence less CO_2 emissions. Also, increase in surface overlay roughness as an external factor leads to more engine load and consequently more tailpipe GHG emissions. Regarding the type of pavement, efforts to design more sustainable pavements have contributed to less GHG emissions during the years of service. Recently emerged pavement preservation treatments such as ECC and microsurfacing are also shown to reduce GHG emissions compared to traditional treatments such as PCC and HMA.

Overall, it appears that pavement characteristics such as type and roughnesshave significant impacts on GHG and PM_{10} emissions. As such, these emissions should be considered in evaluation of alternative pavement design, in strategies for pavement maintenance and pavement management systems, and life cycle cost analysis of various pavement systems. These results can also be used to better allocate roadway maintenance funds in order to reduce PM_{10} and GHG emissions associated with the pavement characteristics and conditions.

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