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# Approximation Assessment of Photocatalytic Air Cleaning Pavements

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This paper examines an approximation method to qualitatively assess the air-cleaning performance (i.e., specifically the elimination of aerial nitrogen oxide, NO, released within vehicular exhaust) by full-scale pavements which contain photo-catalytically reactive titanium dioxide under optimal conditions. Two hypothetical road configurations were considered using this method, including both a two-lane, low traffic density (i.e., 4,000 full-day AADT) and a four-lane, moderate traffic density (i.e., 10,000 full-day AADT) design. These options were then comparatively examined on the basis of expected European Union or United States vehicular emission levels. In each case, this method's day-time-only percentile elimination approximation results were derived using an extrapolation of lab-based specific contaminant elimination rates (i.e., mass NO removed per surface area per time) relative to contaminant release rates which were projected for EU or US vehicular contaminant emission levels. Using this paper's approximation method, and assuming best-case scenario conditions (i.e., original, un-aged, peak catalytic performance under optimal temperature, relative humidity, etc. conditions), day-timeonly percentile removals in the ~mid-60% to ~90% range were predicted for EU two- and fourlane roadways with low to moderate traffic densities. These EU contaminant elimination approximation percentiles were higher than the actual, observed range (e.g., typically ~mid-10% to ~mid-60% day-time removal percentiles) of published contaminant elimination values which had been measured according to gas-phase contaminant changes during a number of full-scale studies completed at various EU locations and with EU-related vehicle types and emissions. In the case of similar US highway options, this method's approximated day-time-only elimination percentile results were lower than what was predicted for similar EU road options, with a range of ~30% to ~40%. These latter, lower US road approximations were believed to be related to higher expected US versus EU vehicle emission levels (i.e., by a factor of ~two- to ~three-fold for light and heavy duty vehicles).

## Keywords

approximation theory, pavements, nitric oxide, elimination, roads

## Disciplines

Civil Engineering

## Comments

This paper was presented by co-author James E. Alleman at the International Concrete Sustainability Conference held in Washington, D.C. on May 16, 2016.

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## Introduction

International interest has continued to grow in regards to the potential air-cleaning capabilities and full-scale application of photocatalytic concrete pavement (i.e., and other highway-adjacent structures, including crash barriers, noise walls, etc.) and building surfaces which contain titanium dioxide. Indeed, this interest is prompted by the expected beneficial capability of these photocatalytic surfaces when suitably exposed to solar ultraviolet irradiation to help remove otherwise reactive and problematic contaminants (e.g., such as inorganic nitrogen oxides or organic volatile compounds). Given this interest, therefore, the body of knowledge regarding these photocatalytic pavements continues to expand on both fundamental and pragmatic levels facilitated by an ongoing combination of academic, public, and private sector evaluation (i.e., as cited within the following 'General Overview' section of this paper).

Based on the latter interest, considerable past and ongoing experimentation has accordingly been applied to evaluating the efficacy of these photocatalytic surfaces. As will be covered in more detail within upcoming sections of this paper, these studies have included both lab- and full-scale experimentation where researchers examined a range of factors believed to be linked with observed performance. Within the lab-level testing efforts, these evaluations have typically examined a group of environmental factors, notably including ambient relative humidity, air temperature, solar insolation intensity (and specifically ultraviolet irradiation), aerial contaminant concentration, and duration of reactive contact. The approach used for surface-finishing newly constructed surfaces has also been evaluated (and considered to be another a potentially important variable; Hanson [2013]). Taken collectively, therefore, this published, lab-based knowledge about the general performance and specific rate characteristics of photocatalytic pavement reactivity has considerable intrinsic value as a foundational starting point with developing predictive, albeit approximate and best-case scenario, estimates with performance which might possibly be achieved at full-scale sites.

When considering the performance studies published for full-scale assessments, the vast majority of these studies were more-so focused on directly measuring net percentile levels based on observed aerial contaminant removal (see Table 1). Admittedly, a limited number of these full-scale studies also involved on-site analyses of actual surficial elimination rates, using a field-based surface gas-contact measurement plate device intended to mimic lab-based surface testing. This latter evaluation strategy, though, is not normally used, and as such quantified on-site surficial elimination rates are not routinely determined such that these rates could then be extrapolated to other pavements.

The concept of characterizing percentile-based contaminant elimination based on observed gas-phase removal is understandable given that several important performance factors (i.e., temperature, relative humidity, UV irradiance, etc.) are inherently subject to daily, seasonal, etc. *in-situ* fluctuations under real-world, full-scale conditions. However, whether or not full-scale observations of percentile contaminant removal can be used to predict contaminant elimination performance at other sites is subject to question. Notably, will the performance (and percentile contaminant removal level) observed with pavement ‘X’ be similarly observed at pavement ‘Y’ when these ‘X’ and ‘Y’ pavements have different physical dimensions and have varying levels of reactive surface area? Similarly, how will these varied pavements behave when they involve different vehicular traffic densities, different types of vehicles with varied exhaust emission levels (e.g., larger, heavier, higher polluting US engines *versus* typically smaller, lighter, cleaner EU engines), etc.? And yet another important variable would be the issue and extent of possibly evolving air-cleaning performance in relation to pavement aging and associated changes in photocatalytic reactivity.

This paper consequently explores an alternative conceptual strategy for approximating photocatalytic air contaminant elimination on a full-scale estimation basis. This method’s approach, though, has an important qualification where it makes several key assumptions on what are likely to be a best-case scenario. For example, this paper’s approximation method not only assumes optimal environmental conditions but also uses a presumed peak rate of photocatalytic reactivity which was extrapolated from lab-scale testing completed with fresh, un-aged, best-possible photocatalytic catalytic specimens. The suitability of this new approach for qualitatively approximating $TiO_2$ pavement performance based on specific surficial reactivity, though, can also be drawn from recent efforts to evaluate similarly photocatalytic building, roofing, cladding, etc. surfaces, where much the same transition from only evaluating gas-phase percentile-removal performance to considering specific surficial elimination rates has also taken place.

As mentioned previously, and explained within the following section of this paper, this method involves multiple assumptions covering a set of elimination rate and environmental factors. Only one such environmental factor was taken into account, however, with each example used to demonstrate this model's outcomes (i.e., that of the impact with ambient NO contaminant levels in the ~50 part per billion by volume [i.e., ppbv] range *versus* a 1,000 ppbv level typically used for calibrating maximal lab-scale surficial reactivity). This assumed ambient concentration was chosen for two reasons. First, this level matches up with the 53 ppbv regulatory level established by the USEPA (2015) national ambient air quality standard for nitrogen dioxide ($NO_2$), where NO is the critical precursor species for this regulated nitrogen dioxide parameter. Second, this level also matches up with actual ambient US air contaminant levels, as were identified within a recent USEPA (2014) web-based posting for 'National Trends in Nitrogen Dioxide Levels' extending until 2014. After making this assumption, therefore, an ambient NO concentration of ~50 ppbv would subsequently reduce the predicted peak specific elimination rate by nearly a ~three-fold level.

There are also additional, multiple factors where even lower contaminant elimination rates might be experienced. Indeed, these sorts of less reactive pavements could occur with non-optimal temperature, relative humidity, reduced solar and UV irradiation, dirt-, grime-, and oil-blinding of the reactive surface, etc. In turn, each (or even all) of these potentially retarding impacts would warrant further consideration for those more carefully considered performance predictions where these sub-optimal circumstances would be expected.

The paper's approximation method subsequently assumed the following six factors: 1) an initial lab-derived contaminant elimination rate considered to be a best-case value (i.e., ~50 nmol $NO{\cdot}m^{-2}{\cdot}s^{-1}$, under optimal conditions), 2) an approximately ~three-fold reduction in the actual specific contaminant elimination rate (i.e., down to ~20 nmol $NO{\cdot}m^{-2}{\cdot}s^{-1}$) based on an expected ambient contaminant concentration (i.e., ~50 ppbv NO versus ~1000 ppbv NO typically used within lab-scale reaction rate studies), 3) pavement dimensions (i.e., net surface area, including both lane and shoulder areas paved with the photocatalytic materials), 4) daily traffic density during day-time, solar-irradiated periods, 5) distribution of vehicular types, whether light- or heavy-duty engine levels, and 6) expected cumulative contaminant emission rates for a projected light- plus heavy-duty vehicle makeup and emission levels relative to either EU or US norms.

The following key observations can subsequently be drawn from the following approximation examples outlined within this paper:

**1)** Photocatalytic pavements appear likely to perform better (i.e., with higher NO elimination levels) within full-scale EU applications than full-scale USA sites due to the expected lower contaminant emission levels which might be expected with EU vehicles (i.e., such that they impose a lower contaminant burden on photocatalytic pavements).

**2)** An EU two-lane, low-traffic density (i.e., estimated at 4,000 total AADT, and having 3,000 'day-time-only' vehicles during sunlight irradiation) road would appear to have a projected peak (i.e., assumed peak ~summer-time reactivity) photocatalytic NO elimination rate which matched (or even slightly exceeded that of the involved vehicular exhaust rate (i.e., such that ~100% NO removal might be achievable under the assumed, best-case scenario conditions).

**3)** This latter predicted EU performance estimate decreased when considering a four-lane, higher traffic density highway (i.e., estimated at 10,000 AADT, and having 7,500 'day-time' vehicles during sunlight irradiation), to a ~70% elimination level.

**4)** These approximated EU removal percentiles, at ~100 and ~70% elimination levels, are higher than the removal percentiles previously documented at multiple European highway locations (i.e., where these published values ranged between ~mid-10% to approximately 60% values). This decreased range may reflect that fact that the documented full-scale tests were completed on older, aged pavement sections under less-than-optimal real-world environmental conditions, where maximal photocatalytic performance (i.e., with fresh, un-aged pavement) would likely have been decreased.

5) The higher contaminant emission levels expected with inherently larger, heavier, higher polluting US vehicles appears to present a larger challenge for photocatalytic elimination, with commensurately lower expected removals.

**6)** A US two-lane, 4,000 AADT (i.e., 3,000 'day-time' traffic density) highway was predicted to have an approximate summertime (i.e., again, assuming peak reactivity based on all environmental factors with the exception of the aerial contaminant level) photocatalytic NO elimination percentile at a ~40% level at the predicted US vehicular exhaust rate. This elimination performance was even lower with a modelled four-lane, higher AADT highway, at a ~30% level.

7) Again, these approximations with contaminant elimination would likely decrease in relation to daily or seasonal weather variations as the photocatalytic efficiency of these pavement surfaces declined under non-optimal environmental conditions (i.e., relative to temperature, relative humidity, solar insolation plus UV irradiance intensity, etc.). Even then, the original, optimal photocatalytic activity assumed for these roadway surfaces with this qualitative approximation method might also decline in relation with progressive age-related surface blinding, dirt or grime buildup, etc. None of these impacts, though, were factored into the approximations presented within this paper, and as mentioned previously these predicted results should clearly be characterized as best-case scenario outcomes. Considering this paper's approximation results with an EU low-traffic density roadway, for example, the difference between approximation model prediction (~100%) and observed (i.e., ~15 to ~60%) elimination percentiles might conceivably reflect this very sort of un-aged, optimal *versus* aged, reduced-active surficial activity.

## General Overview of Full-Scale Photocatalytic Performance Factors

Before exploring this new estimation method and associated results, the following synopsis addresses the various factors which may impact the air-cleaning capabilities of a photocatalytic pavement. In each case, a short explanation is provided as to the rationale for the cause-and-effect correlations tied to these factors, plus an additional explanation as to how this factor was, or was not, considered within this paper's predictive performance estimation method.

***Variations in Solar Insolation and UV Irradiance:*** As their name implies, photocatalytic reactions need light, and more specifically ultraviolet (UV) light within the so-called UV-A spectrum. This UV fraction of sunlight's energy spectrum provides the photonic motivation to oxidatively convert water (hence the additional significance of relative humidity as a source of this water) into a set of highly reactive 'hydroxyl radical' ($^{*}OH$) and 'superoxide radical-anion' ($O_2^{*-}$) species (i.e., Sikkema, 2013; Ramirez, *et al.,* 2010) which are the actual catalytic agent for contaminant transformation and final elimination. UV-A irradiance intensities at or above about 5 to 10 $W{\cdot}m^{-2}$ intensity are typically considered a reasonable threshold to effectively drive the air-cleaning, contaminant elimination reactions. By comparison, Grant and Slusser (2005) have reported a mean daytime UV-A irradiance range within the United States between a far-northern ~10 $W{\cdot}m^{-2}$ (Fairbanks, Alaska) to a far-southern ~20 $W{\cdot}m^{-2}$ (Homestead, Florida). Solar insolation does follow a diurnal cycle, though, ramping up and down on a daily basis, and there would also be winter-time drops in these mid-day values by a factor of about 2 to 2.5. As such, the activating ultraviolet portion of the incoming solar energy should reach and/or exceed an optimal level for most of the sunlight day. And as a result, the expected reactivity of a photocatalytic surface would reach a peak within about an hour after sun-up and remain strong throughout the day ramping down until about the last hour prior to sun-set. While this variability in irradiation intensity has non-trivial significance, our estimation model assumed that this parameter was sufficiently high in value throughout the day to avoid any negative impact.

***Variations in Constitutive $TiO_2$ Levels and Reactivity:*** The amount and type (i.e., highly reactive anatase-$TiO_2$ versus low-reactive rutile-$TiO_2$) of catalyst originally added to, or alternatively sprayed onto, a photocatalytic surface are important factors within the context of a pavement's full-scale air-cleaning performance. While these parameters are solely controlled by industry vendors and generally retained as a non-disclosed parameter, it is likely that material-specific variations with these factors account for the different 'reactivities' which have been observed by various researchers with both lab- and full-scale materials. Without this sort of further insight, though, our estimation modelling was conducted with an assumed best-case elimination rate drawn from a group a similar lab-based observations. These assumptions could be refined in the event that vendors decide to either provide exact percentile composition data for their cement mixtures, or should they provide either elimination percentile or surficial reactivity rate guarantees for their product's achievable elimination performance and rates.

***Variations in Environmental Relative Humidity (RH):*** As mentioned above, surficial water is required for these photocatalytic reactions, where this moisture again serves as the precursor for the formation of catalytic hydroxyl radicals. This water, however, is both a blessing and curse for photocatalytic surfaces. While some amount of water is needed, and even consumed during the photocatalytic reactions, too much water will start to degrade a surface's catalytic reactivity due to blinding of the necessary UV irradiation. Indeed, and as noted by a variety of researchers (e.g., Sikkema, 2013; Hüsken, *et al.,* 2009; Demeestere, et al., 2009; Murata, et al., 2000; Murata and Tobinai, 2002)**,** higher relative humidity values actually provided successively lower elimination rate percentile. Demeestere, *et al.*'s (2009) observations showed that successive increases of RH to 1, 30, 52, and 77% levels generated successive reductions in percentile contaminant elimination to 78, 65, 47, and 16% removals. Similarly, a ~50% reduction in the lab-scale contaminant elimination rates have been observed at ~50% RH levels (i.e., Murata, et al., 2000 and Sikkema, 2012). Here again, this relative humidity factor was similarly ignored within our preliminary estimation model, but could be considered within any further refinement of a performance prediction.

***Variations in Environmental Temperature:*** Catalytic chemical reactions of all sorts, including those of a photocatalytic nature, tend to exhibit an inverse rate relationship with temperature. As temperature declines, catalytic reactions tend to slow down. Observations by various photocatalytic pavement researchers (i.e., Beeldens, *et al.,* 2011, Dylla, *et al.,* 2011, Chen and Chu, 2011, Herrmann, 1999, and Sikkema, 2013) have all examined this issue. Admittedly, there have been vague and even contrary findings in the case of some research findings with the impact of temperature, but the general convention would be that warmer pavements have higher contaminant elimination rates and colder pavements do not. Once again, this temperature factor was ignored within our preliminary estimation model, on the basis of estimating elimination rates where temperature was sufficiently high to not retard reactivity.

***Seasonal Variations in Vehicular Exhaust Contaminants:*** Air temperature will also impact the fuel conversion efficiency, and exhaust gas strength, with internal combustion engines used in vehicles. In turn, there is a compounding effect during cold weather periods, where cooler air and pavement surface temperatures will reduce the contaminant elimination rate at the same point as the colder weather also causes a higher release of vehicular contaminants. As such, the overlapping impact of higher-contaminants and lower-elimination will yield less effective cold weather air-cleaning performance. For the purposes of the estimation efforts reported within this paper, though, this factor is irrelevant.

***Variations in Aerial Contaminant Concentrations:*** Based on the findings presented by a number of published bench-scale studies (i.e., Sikkema, 2013; Murata*, et al.,* 2000; Hüsken and Brouwers, 2008; Husken, *et al.,* 2009; Ballari *et al.,* 2010; Ballari *et al.,* 2011), there is positive correlation between the concentration of a contaminant gas (e.g., NO) and the rate at which this contaminant might be catalytically eliminated. The significance of this relationship is understandable, in that having more contaminant present within a pavement's overlying gas volume would then set up a concentration gradient (i.e., bulk gas phase contaminant level less assumed near-zero contaminant level at the reactive surface) which accelerated this gas's transport and movement towards, contact with, attachment to, and catalytic conversion by the underlying reactive surface.

***Variations in Roadway Configuration, Layout, Shading, and Aerial Dilution:*** The location, topographic openness, surrounding building layout, wind speed, and perhaps even compass orientation of a photocatalytic pavement can also be expected to impact the rates of both aerial contaminant dilution and elimination. For example, so-called street-canyon sites within inner-urban locations might be expected to experience less wind-induced dilution and higher contaminant buildup, which might then favor higher photocatalytic removal…as long as the necessary solar irradiation remains unblocked and/or unshaded. Several of the published full-scale studies showing higher-level (i.e., ~60% level) contaminant elimination percentiles were completed under these sorts of conditions (see Table 1). On the other hand, though, far more open highway settings accompanied by higher ambient winds would likely experience much greater levels of wind-induced dilution, such that the contaminant 'removal' might then be attributed (perhaps to some extent mistakenly) to lateral wind-induced drift and aerial dilution versus actual reactive elimination. The assumption regarding wind and wind-borne dilution, drift, etc. with this method, though, was that there was no such prevailing wind.

***Lab-Based Elimination Rates for NO:*** The published results for best-case lab-based measurements of contaminant elimination rates observed with varying gas contaminant concentrations, test cell gas flow rates (i.e., and resultant test contact times), ambient temperatures, ambient relative humidity, and varied solar insolation, tend to fall at or below a peak value (i.e., when exposed to 1,000 ppbv NO) of about ~30 to ~60 nanomoles NO eliminated per square meter of pavement surface area per second [i.e., nmol NO $\cdot$ $m^{-2}\cdot$ $s^{-1}$] (Murata, et al., 2000; Murata and Tobinai, 2002; Sikkema, 2013; Overman, 2009; Hüsken, et al., 2009; Ballari *et al.,* 2010a; Ballari *et al.,* 2011). In one instance (i.e., Murata, et al., 2000; Murata and Tobinai, 2002), these authors reported peak specific elimination rates several times higher (i.e., from ~200 to ~300 nmol NO $\cdot$ $m^{-2}\cdot$ $s^{-1}$)., but multiple other studies have shown peak, optimal rates in fairly close proximity to a lower peak value of about ~50 nmol $NO\cdot m^{-2}\cdot s^{-1}$ level. Furthermore, the predictive model developed by Ballari *et al.,* 2010b to calculate rates of NO elimination (rNO) on the basis of ambient contaminant levels produced a similar peak value of ~50 at a 1,000 ppbv NO level. Here again, the fact that different researchers have reported somewhat varying peak elimination rates likely reflects inherent variations in material properties (i.e., percent $TiO_2$, anatase versus rutile fraction, etc.) which are rarely, if ever, known to or characterized by the involved researchers.

***Elimination Rates for Other Air Contaminants:*** With a goal of further validating the latter NO elimination rate values, it is worth comparing these latter NO-related rates against those observed for other air contaminants subject to photocatalytic elimination. For example, this comparison can be derived using literature results observed with the removal of volatile organic compounds (i.e., VOC's such as benzene, toluene, ethylbenzene and xylene, otherwise known as BTEX) where these compounds are found within vehicle fuels and would also represent important highway contaminants. After adjusting the published BTEX-type contaminant elimination rates to the same sort of nmol NO $\cdot$ $m^{2}\cdot$ $s^{-1}$ units cited previously for NO elimination, the following observed rates have been reported for either BTEX or specific toluene removal:

| | |
|---|---|
| - 56 nmol BTEX $\cdot$ $m^{-2}\cdot$ $s^{-1}$; | Strini, Cassese, and Schiavi (2005) |
| - 145 nmol toluene $\cdot$ $m^{-2}\cdot$ $s^{-1}$; | Ramirez, *et al.* (2010) |
| - 300 nmol toluene $\cdot$ $m^{-2}\cdot$ $s^{-1}$; | Demeestere, *et al.,* (2009) |

This sort of direct comparison with contaminant elimination rates likely warrants further adjustment on the basis of photocatalytic electron flow required to sustain a specific elimination rate, where the oxidation of nitrogen oxide (i.e., three electrons required per mole of oxidized NO) needs far fewer electrons (i.e., twelve times less) than is required for oxidatively eliminating a far more reduced organic compound such as toluene (i.e., requiring thirty-six electrons per mole of toluene). Taking this difference into account, relative to electron flow rates seemingly able to be achieved with BTEX organics, it would appear that an assumed peak NO elimination rate of ~50 nmol NO · m$^{-2}$· s$^{-1}$ is reasonable, and perhaps even lower than would have been expected.

### Comparative Full-Scale Percentile Removal Observations

The following overview provides a sampling of published full-scale roadway test results for photocatalytic systems. This information offers a comparative framework for considering the alternative approach of qualifying prospective contaminant elimination on the basis of extrapolated specific elimination rates relative to assumed pavement dimensions, traffic densities and makeup, and projected vehicular contaminant release rates.

Table 1: Published Reports of Full-Scale NO Removal Percentiles by Photocatalytic Surfaces

| Year | Author(s) | Testing Conditions and Performance Observations | Observed Percentile NO Removal Levels |
|---|---|---|---|
| 2006 | Plassais and Guillot *(Note: cited by Guerrini and Peccati @ 2007* | Location: Via Morandi, Segrate, Italy<br>Surface: Thin mortar overlay | 60% max |
| 2007 | Guerrini and Peccati | Location: Borgo Palazzo, Bergamo, Italy<br>Surface: Concrete paving blocks | 66% max<br>20% min |
| 2007<br>2009 | Guerrini and Peccati<br>Borgarello | Location: Rue Jean Bleuzen, Vanves, France<br>Surface: Concrete overlay | 20% min |
| 2009 | Borgarello | Location: Calusco d'Adda, Bergamo, Italy<br>Surface: Concrete block | 45% avg |
| 2009 | Borgarello | Location: Porpora Street, Milan, Italy<br>Surface: Concrete, photo-catalytic ceiling paint | 23% @ minimum UV irradiance level |
| 2009 | Rousseau | Location: St-Denis, France<br>Surface: Concrete overlay | 30% @ 2 m height<br>15% @ 20 m height |
| 2009 | Overman | Location: Hengelo-Overijssel, The Netherlands<br>Surface: Paving stones w/ TiO$_2$ concrete topping | 2-10% @ late winter day |
| 2010 | Gignoux, *et al.* | Location: Vanves, France<br>Surface: Concrete paving blocks | 40-50% avg |
| 2013 | Ballari and Brouwers | Location: Hengelo, The Netherlands<br>Surface: Concrete paving blocks | 19% avg |

Two noteworthy aspects can be drawn from this tabular summary:

1) These testing locations were all within the EU, where the expected vehicular exhaust levels would be expected at lower vehicular contaminant release rates than would be expected within the US.
2) Many of these observed full-scale NO removal percentiles are notably high, with several in excess of 40% and reaching ~60%.

## Basic Assumptions Applied to New Performance Estimation Method

The adjacent Figure 1 summary lists the basic environmental, pavement, emission, and specific elimination rate assumption categories which were considered in the four estimations (i.e., EU two- and four-lane road, and US two- and four-lane road) reported on within this paper. In each case, these assumption categories involved a further sub-set of further assumptions which were cumulatively considered within each final estimation assessment. Further detailed breakdowns of these sub-set assumption factors and their associated settings are provided in the following summary. In this regard, though, there are ultimately three major primary factors being considered: 1) the predicted surficial reactivity rate for contaminant elimination, 2) the net, photocatalytic surficial area of the pavement, and 3) the cumulative contaminant emission load released at this pavement site.

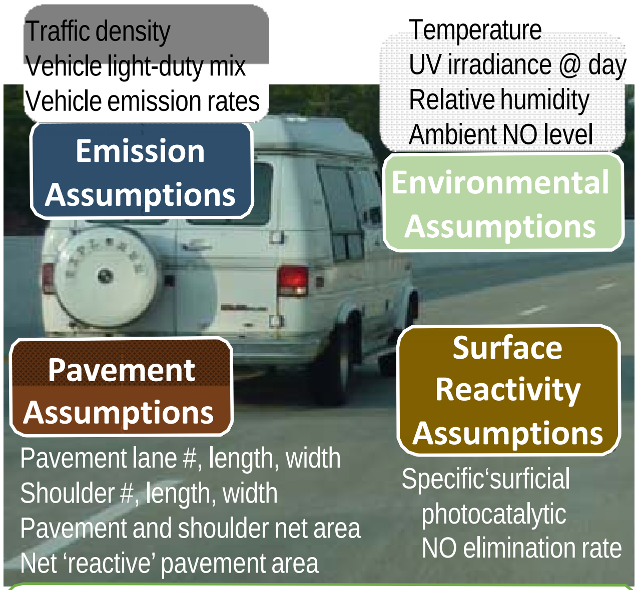

Figure 1: General Summary of Assumptions for Photocatalytic Contaminant Elimination

***Environmental Assumptions:***

| | |
|---|---|
| Seasonal option | Summer (assumed optimal season due to temperatures and expected higher solar insolation magnitude and duration) |
| Day versus night | Daytime, sun-illuminated |
| Solar insolation level | Assumed full-sun, non-cloudy solar insolation with non-limiting UV irradiance levels *(i.e., ≥ 10 W/m$^2$)* |
| Air temperature | Assumed non-limiting summer warm/hot temperature (~>85$^o$F) |
| Relative humidity | Assumed non-limiting relative humidity levels @ low to moderate values *(e.g.,~>5-10% RH)* |
| Wind-induced aerial dilution and/or lateral drift | Assumed to be nil<br>*(Note: this is an admittedly unlikely circumstance, but this assumption was adopted for the sake of simplicity; conversely, though, wind-induced dilution and/or migration either vertically or laterally of emission contaminants away from photocatalytic contact with the pavement would be expected to occur.* |
| Ambient contaminant (NO) | ~50 ppbv |

| | |
|---|---|
| concentration level | *(Note: this assumption impacts the assumed specific elimination rate; the justification stems from an assumed ambient NO being approximately equivalent to that of the USEPA National Ambient Air Quality Standard (NAAQS) for secondary annual average nitrogen oxides concentration @ 53 ppbv (i.e., which are inherently based on vegetation damage)* |

***Pavement Assumptions:***

| | |
|---|---|
| Traffic lanes | Either two- or four-lane pavement designs |
| Traffic lane dimension | 12ft lane width |
| Shoulder presence | Yes; similarly paved with photocatalytic pavement |
| Shoulder dimension | 4ft shoulder width (on two sides) |
| Net photocatalytic pavement surface area on a cumulative per-mile basis | Two-lane plus shoulders = 15,697 square meters<br>Four-lane plus shoulders = 27,469 square meters |

***Vehicle Emission Assumptions:***

| | |
|---|---|
| Traffic average daily density | Two-lane system = 4,000 vehicles per 24-hr day and night period<br>Four-lane system = 10,000 vehicles per 24-hr day and night period |
| Traffic ‘day-time-only density (assumed ¾ traffic flow @ day and ¼ @ night) | Two-lane system = 3,000 vehicles per ~12-hr ‘day-time-only’ period<br>Four-lane system = 7,500 vehicles per ~12-hr ‘day-time-only’ period |
| Vehicular type distribution | 85% light-duty sedan and truck/gasoline; 15% heavy-duty/diesel<br>*(Notes: This 85-15% breakdown for a light-heavy-duty vehicle composition was estimated on a qualitative basis relative to expected net vehicular NO emission percentiles reported by Kota, et al., 2014)* |
| Low-traffic density count @ ~12-hr day-time-only period | 2,550 light-duty vehicles<br>450 heavy-duty vehicles |
| Moderate-traffic density count @ ~12-hr day-time-only period | 6,375 light-duty vehicles<br>1,125 heavy-duty vehicles |
| EU vehicle emissions | |
| EU Light-duty emissions | 0.1 gm NO/mile (see EU emission justification below) |
| EU Heavy-duty emissions | 0.3 gm NO /mile (see EU emission justification below) |
| US vehicle emissions* | |
| US Light-duty emissions | 0.2 gm NO /mile (see US emission justification below) |
| US Heavy-duty emissions | 1.06 gm NO /mile (see US emission justification below) |

**Notes:*