Quantification of Vehicle-induced Turbulence on Roadways
Using Computational Fluid Dynamics Simulation

by

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A thesis submitted in conformity with the requirements
for the degree of Master of Applied Science
Graduate Department of Chemical Engineering and Applied Chemistry
University of Toronto

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Abstract

Turbulence is a significant factor in near-road air quality, as it affects the initial dilution, dispersion, and the ultimate fate of pollutants. This study used computational fluid dynamics simulations to model the turbulent kinetic energy (TKE) on roadways, focusing on vehicle-induced turbulence. TKE was shown to decay with different power-law exponents depending on vehicle types; vehicle speeds and winds affect TKE; and thermal impacts are negligible. It was found that TKE is superimposed for vehicles in series; TKE does not dissipate far laterally, and the side-by-side interactions are not significant regardless of the directions. Thus, TKE for different traffic compositions may be expressed as a sum of the contribution from each type of vehicle. Insights gained in this study may enable the quantification of TKE for various traffic scenarios based on TKE values of single vehicle of different types, and simplify the TKE estimations in regional air quality models.
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1 Introduction

Traffic emission is the dominant factor in urban air pollution, and pollutants produced from vehicle exhausts, either directly emitted or indirectly produced through photochemical reactions, pose serious risks for human health. In urban areas where the population exposed to high levels of traffic-emission-induced pollution is high, it is becoming increasingly important that the dispersion behaviors and aerosol dynamics of the traffic-related pollutants are accurately predicted.

Studies have indicated that turbulent air flow near the roadways affects the initial mixing of the pollutants; which would then lead to changes in the ultimate fate of the pollutants by affecting conditions such as concentration, temperature and relative humidity that are important in various aerosol dynamics processes including condensation/evaporation, coagulation, nucleation, gravitational settling and reactions. Also, the dispersion of the pollutants from tailpipe to roadway, and roadway to the vicinity is affected by the turbulent air flow on roadways.

There are a number of mechanisms by which turbulence is produced on roadways. Different structures, roadside boundaries, and road embankment cause flow modifications to increase turbulence on road (Structural road induced turbulence, S-RIT). Also, there are thermally induced turbulence, caused by the difference in sensible heat over the road surface and the surrounding surfaces (Thermal road induced turbulence, T-RIT). Lastly, there is the vehicle-induced turbulence (VIT), in which the turbulent wake region produced behind moving vehicle increases the turbulence on road. While the structure-induced turbulence is an inherent characteristic of the specific roadway, and the thermal-induced turbulences vary in magnitude depending on seasons and surrounding land uses, VIT has consistently been shown to be a significant factor in turbulence on road.

Various approaches have been taken by different groups to study VIT. Such approaches include: numerical models, reduced-scale wind tunnel experiments, field measurements,
and computational fluid dynamics (CFD) models. One major difficulty in addressing VIT is isolating VIT from other sources of TKE, especially on road where many factors play roles. In order to resolve this, a vehicle chasing study was carried out in controlled environment (Rao et al. 2002). But the study was limited in types and sizes of vehicles, as only one type of vehicle was used; and different traffic conditions were not captured as it was carried out in a single-vehicle environment. To fill in this gap, a field campaign FEVER (Fast Evolution of Vehicle Emissions from Roadways) has been carried out as part of Environment Canada’s ALMITEE (Advancing Local-Scale Modeling through Inclusion of Traffic Emission Experiments) project. Turbulence and traffic emissions were measured while chasing different types of vehicles on a highway at varying distances using a mobile lab, and on stationary sites at different distances away from the highway (Gordon et al. 2011).

Various CFD studies have tried to simulate the VIT and its effect on pollutant dispersion (Sahlodin et al. 2007; Solazzo et al. 2008; Wang and Zhang 2009) but their study was limited to the specific traffic composition used in their study. Consequently, their findings can only be applied to conditions specific to their studies. As it is important to extend the findings beyond the study domain, there needs parameterizations that can be applied to different traffic conditions with versatility.

The current study, as part of ALMITEE project, aims to develop an effective method to simulate the production and decay characteristics of turbulence on roadways, particularly to quantify VIT. Using a single vehicle in the computational domain, the effects of ambient wind, thermal conditions and types of vehicles on the TKE production on roadways are analyzed. Then, with multiple vehicles in the domain, the vehicle-vehicle interactions and their impacts on TKE are investigated by varying distances, directions, densities and compositions of the traffic. The results and parameterizations obtained from this study may be applied in simplifying the input parameters in regional air quality models to improve their performance on predicting pollutant concentrations.
2 Research Problem Statement

2.1 PERD ALMITEE Project

Environment Canada’s ALMITEE project is part of the PERD (Program of Energy Research and Development). The goal of ALMITEE project is to improve the current air quality model with emphasis on urban scale. ALMITEE project consists of 6 main task areas (PERD 2009):

1. Chemical and physical characterization
2. Laboratory studies
3. Field studies
4. Process model development and emissions improvement
5. Air quality model development and application
6. Synthesis and reporting

The current simulation study fits under Task area 4, Process model development and emissions improvement.

Task area 3, a field study entitled FEVER, is also relevant in this study as the field measurements obtained in Task area 3 will be compared with the simulation results from this study. FEVER was carried out in August and September of 2010 on Hwy 400 and Hwy 401 in Toronto area using both fixed instrumentation at a stationary site, and the mobile lab CRUISER (Canadian Regional and Urban Investigation System for Environmental Research) which allowed in-situ turbulence measurements while chasing vehicles on the highway. FEVER is the first in-situ turbulence measurements study that accounts for different vehicle types and different following distances (Gordon et al. 2011).

The current study, as part of Task area 4, aims to simulate the effect of different traffic scenarios and meteorological conditions on the turbulent air flow on a highway. The simulation results will be evaluated against the field measurements from FEVER campaign and from other studies. Furthermore, parameterizations will be developed from
the simulation results, and these parameterizations can be used to modify the input parameters in a larger scale meteorological model to improve its performance.

2.2 Vehicle-induced Turbulence Modeling

2.2.1 TKE Simulation for Single Vehicle Case and Validation of the Results
TKE generated in the wake region of a single vehicle travelling at various velocities will be simulated for three different types of vehicles: a passenger vehicle, a SUV, and a truck. In addition to the VIT, the effect of ambient temperature, tailpipe exhaust temperature, and the effect of external winds from different directions at different speeds will also be simulated to provide insights on their significance on the TKE generation and decay characteristics on roadways.

The results will then be normalized for evaluation against results from FEVER campaign and from two other previous studies in order to validate the simulation set up.

2.2.2 TKE Simulation for Various Traffic Conditions and Parameterizations
Once the results from the single-vehicle cases are evaluated against results from other studies and field measurements, the effects of vehicle-vehicle interactions will be studied in a larger computational domain with multiple vehicles for different traffic densities and compositions.

Previous studies have only considered traffic and meteorological conditions that are fixed and are specific to their study; and have not considered the different vehicle interactions or changes in vehicle densities. Therefore it is necessary to investigate various traffic conditions and parameterize the result, so that it can be extended to different traffic situations, beyond the study domain.

Sensitivity analysis will be performed to decide which traffic parameters are important on roadway TKE. Such parameters would include the distance between adjacent vehicles, traffic density in the domain, vehicle mixes and fraction of heavy-duty trucks, and effect of two-way traffic. Then parameterizations will be developed on the effect of different traffic conditions on roadway TKE.
3 Literature Review

3.1 Effect of Vehicle Emissions on Near-Road Air Quality

One of the major contributors in urban air pollution is vehicle emissions. Studies have observed that despite recent improvements in fuel and engine technology, present day concentrations of urban air pollutants such as CO, nitrogen oxides (NOx), volatile organic compounds (VOCs) and particulate matter (PM) are strongly correlated with traffic emissions (Fenger 1999; Colvile et al. 2001; Lloyd and Cackette 2001; Colbeck and Lazaridis 2010; HEI 2010). While meteorology and atmospheric stability are important factors in determining the size of the impact zones, if the range of exposure zones are assumed to be 500m from highways and 100m from major roads, it is estimated that 30% to 45% of people in large North American cities live within such areas exposed to traffic-related air pollutions (HEI 2010).

The main traffic-related pollutants are CO, hydrocarbons, PM, VOCs and NOx (Vardoulakis et al. 2003). These pollutants are directly emitted as primary pollutants and they act as precursors to secondary pollutants such as ground-level ozone, which is produced through a series of oxidation and photochemical reactions of CO and hydrocarbons in the presence of NOx (Logan 1985). The precursors also undergo changes in number and size distribution by physical processes. Such aerosol dynamics processes include formation of new particles by nucleation and growth of particle sizes by condensation and coagulation (Jacob 1999; Zhang and Wexler 2002). PM can be primary or secondary pollutant as it can either be directly emitted, formed from gaseous precursors, or grow larger via physical processes (Colbeck and Lazaridis 2010).

Both of these primary and secondary pollutants pose serious health hazard for human and have other environmental implications (Lighty et al. 2000; Lloyd and Cackette 2001; HEI 2010). Numerous groups have studied the effects of the near-road air pollution on different aspects of human health. Just to list some of the health risks that have been studied; urban air pollution has been associated with increased lung cancer risk (Nyberg
et al. 2000), likelihood of asthma hospitalization in children (Lin et al. 2002), cardiopulmonary mortality (Hoek et al. 2002) and adverse birth outcomes risk (Wilhelm and Ritz 2003). Other environmental implications of traffic-related emissions such as visibility reduction due to urban smog, global warming potential, soil and water pollution, and materials corrosion via acid rain also have been identified and investigated for regional and global scale air pollution, focusing on diesel engine emissions (Lloyd and Cackette 2001).

Personal exposure is calculated as the product of the pollutant concentration and the time the individual spends in the specific microenvironment. However, it may be misleading to assume a spatial uniformity of air pollution in certain microenvironments, and rigorous concentration predictions within the microenvironment may be required (Vardoulakis et al. 2003), especially for air quality models with larger grid sizes. Thus, there is a need for an accurate understanding and prediction of temporal and spatial gradients of pollutants in order for optimum emission control and traffic planning strategies to be developed.

### 3.2 Role of Turbulence on the Fate of Pollutants

Initial dispersion behavior of vehicle exhaust is important as it does not only affect the downwind concentrations but it also affects the ultimate fate of pollutants by altering the sets of conditions which affect aerosol dynamics processes. Studies have analyzed and evaluated different aerosol dynamics processes that affect the aerosol number distribution predictions, such as condensation/evaporation, coagulation, nucleation, gravitational settling, and heterogeneous chemical reactions. These studies have concluded that the relative time scales, energy barriers and favorable conditions involved in each processes are different, and that there exist a critical particle size that dictates the particle collision and growth rates (Jacob 2000; Zhang and Wexler 2002).

Other studies have shown that the concentrations and sizes of particles are impacted by dilution ratio, partial pressure, temperature and relative humidity (Casati et al. 2007;
Ronkko et al. 2007) which in turn are affected by the initial dispersion and mixing of vehicle exhausts, while turbulence enhances mixing.

It was also found that the turbulence over the road surface generated by vehicle movements enhanced the particle deposition locally, contributing to the removal of approximately 10% of the particles originally emitted (Gidhagen et al. 2004).

Zhang and Wexler divided the near-roadway dilution process into two stages: ‘tailpipe-to-road’ stage and ‘road-to-ambient’ stage. In the first stage, the dominant mixing force is the moving traffic, and dilution ratios of about 1000 can be reached within a second. A sharp temperature and concentration gradients are found in this stage. In the second stage, the main mixing force is atmospheric shear and ambient wind, and dilution ratio is only up to about 10 while the timescale is in order of 10 minutes. Temperature gradients are a lot less steep in this stage (Zhang and Wexler 2004; Zhang et al. 2004). These studies have shown that there are different types of turbulences involved at different scales of microenvironment, and the fate of pollutants may be affected by these turbulences.

3.3 Mechanisms for Turbulence Generation

There are different mechanisms in TKE generation on roadways. Vehicle-induced turbulence (VIT) is distinguished from atmospheric boundary layer turbulence (ABLT) and road-induced turbulence (RIT), where RIT can be sub-divided into structural road-induced turbulence (S-RIT) and thermal effects due to the difference in surface properties between road and surrounding lands (T-RIT) (Rao and Sedefian 1979; Wang and Zhang 2009). VIT originates from the momentum wakes behind moving vehicles, and is related to vehicle speed and shape (Kalthoff et al. 2005; Wang and Zhang 2009), while S-RIT is caused by roadside structures such as noise barrier and elevation in the roadways, since these structures modify the air flow and enhance turbulence. The thermal effect is caused by the air flow due to heat flux, driven by the temperature difference of the asphalted roadway surface and the surroundings. S-RIT varies for different studies due to its
intrinsic dependence on the road structures; while T-RIT changes with seasons and therefore is negligible during winter; and VIT changes with vehicle speed, vehicle mixes and traffic densities (Wang and Zhang 2009).

It is difficult to separate the contribution of each term in the overall TKE in field experiments, as these effects are felt simultaneously. A number of simulation attempts have been made to study the effect of each term contributing to the overall TKE. Wang and Zhang showed that the total TKE change with seasons and highway structures, and that VIT accounts for 41 to 77% of total TKE in summer and 54 to 96% in winter; while T-RIT accounts for 18 to 20% in summer and is negligible in winter (Wang and Zhang 2009). While Kalthoff et al. showed that although the available energy of highway and the surroundings may differ slightly due to their differences in albedo, the turbulence generated from the sensible heat flux is less significant when compared to that of VIT in their springtime study (Kalthoff et al. 2005).

Clearly, S-RIT is hard to generalize as the value depends heavily on the road structures; and T-RIT is of variable significance depending on seasons, time of the day and surrounding land uses. Yet, the results from these studies all agree that VIT is the most important source of TKE on roadways and thus that it is worth further investigation.

### 3.4 Field Measurements and TKE Decay Parameterization

There has been a limited vehicle chasing studies on TKE. A number of studies pointed out that the field measurements of VIT are not readily available; and that it is difficult in a field experiment to separate VIT from other forms of turbulence such as wind-generated or thermally generated turbulence (DiSabatino et al. 2003; Solazzo et al. 2008).

One of the first field studies of TKE behind a moving vehicles was done by Rao et al., who analyzed the data obtained from chasing a van in a controlled environment of airport runway, and studied the TKE in the wake region using a towed array of 3-D sonic anemometers (Rao et al. 2002). Their wake parameterizations was based on wind tunnel
results from a previous work (Eskridge and Thompson 1982). Rao et al. found that significant turbulence production takes place in the wake behind a moving vehicle. Also, they have found that the flow velocities decrease rapidly with increasing lateral distance from the centerline of the wake, and with increasing distance away behind the vehicle (Rao et al. 2002), which is consistent with what had been observed in previous studies.

One of the conditions in Rao et al.’s work was that the vehicle speed must be much greater than the ambient wind speed, which is easily met under most highway traffic conditions. However, this could mean more field measurements need be taken under different meteorological conditions. Rao et al. also suggested that the study needs to be extended for different types of vehicles to provide additional details.

In an attempt to fill in the gap, FEVER study has measured TKE along with pollutant concentrations while chasing different types of vehicles on highways using a mobile lab, and at different distances away from the highway using stationary equipments (Gordon et al. 2011). The objective of this study was to better understand the TKE generation on roadways and to be able to develop parameterizations.

The same study was able to compare their measurements with results from two of the previous works (Eskridge and Thompson 1982; Rao et al. 2002) using an equation in the following form:

\[
\frac{k}{u^2} = \exp \left( a \left( \frac{x}{h} \right)^b \right)
\]

(3.1)

where \( k \) is TKE in m\(^2\)/s\(^2\), \( u \) is the mean speed of the vehicle in m/s, \( x \) is the following distance behind the vehicle, and \( h \) is the characteristic vehicle height in m.

It was found that the TKE decay behind the vehicles follow this form of equation, with different values of decay exponent \( b \) depending on the type of vehicle. The decay parameters obtained from Gordon et al.’s study were -0.92, -0.34 and -0.23 for heavy-duty, mid-size, and passenger cars respectively. This compared well with the previous studies which suggested -1.20 (Eskridge and Thompson 1982) and -0.19 (Rao et al. 2002) for mid-size vehicles.
Gordon et al. also found that the horizontal decay of TKE with distance away from the highway can be fitted using the same decay equation, with a decay exponent value of -0.57. The enhancement in TKE on roadways was found to be strongly dependent on the traffic flow.

3.5 CFD Modeling of TKE on Roadways and the Lack of Study on Various Traffic Conditions

The importance of TKE on the initial dispersion of pollutants was recognized and documented at early stages of air quality modeling (Rao and Sedefian 1979; Chock 1980) but according to a review study by Vardoulakis et al., many empirical models used fleet-average emission factors on the road and they did not explicitly model the turbulence on-road. Such models used predetermined emission factors based on fuel consumption or traffic pattern surveys (Vardoulakis et al. 2003). Another review study by Holmes and Morawska also mentioned that the various dispersion models treat the pollution sources as either point, line, area and volume release, with simplified treatment of turbulence and meteorology (Holmes and Morawska 2006).

Existing aerosol dynamics models use different approaches in their treatment of particle size distributions. Such approaches include moving size or stationary size particle dynamics modules, mono-disperse approaches, multiple size sectional and various groupings (Holmes and Morawska 2006). In a recent study by Makar et al., it was speculated that the reason for over-predicted primary pollutant concentration values near ground may be the lack of treatment of turbulence in the model (Makar et al. 2010; Gordon et al. 2011). Some models (Gidhagen et al. 2004; Holmes and Morawska 2006) have coupled the particle dynamics models with different dispersion models to calculate number concentrations, size distributions and chemical compositions of particles; and demonstrated that TKE was important to street level dispersion, especially in low-wind conditions.
Since TKE has been proved to be important, various studies have been using different approaches to predict TKEs on roadways and street canyons. Numerical models were used to predict the TKE generation (Baumer et al. 2005); reduced-scale wind tunnels studies were done to obtain vertical and lateral profiles of vehicle wakes (Eskridge and Thompson 1982; Kastner-Klein et al. 2000; Gidhagen et al. 2004); field studies were carried out to obtain measurements and parameterizations (Rao and Sedefian 1979; Rao et al. 2002; Kalthoff et al. 2005); and computational fluid dynamics (CFD) models were used to model the air flow and its effect on pollutant dispersion in various scales and geometries from small box around tailpipe to street canyons and highway conditions (Kim et al. 2001; Wang et al. 2006; Sahlodin et al. 2007; Blocken et al. 2008; Solazzo et al. 2008; Wang and Zhang 2009; Wang et al. 2011).

Of all these approaches taken by previous studies, the current study will be taking the CFD approach. A review study compared various mathematical approaches from Gaussian plume models to CFD models and reduced-scale physical models, to model gaseous pollutant dispersion in street canyons (Vardoulakis et al. 2003) and concluded that although CFD models may not provide results readily comparable with regulatory standards due to its dependence on the quality of input data, they can reproduce the flow and concentration fields within study domains which can improve the understanding of the behavior of a system (Vardoulakis et al. 2003). With the ever-increasing computational power, high resolution CFD models now have become a useful tool in reproducing realistic flow fields (Li et al. 2006; Solazzo et al. 2008). Studies have shown that CFD model results are comparable with the results from well-validated Atmospheric Dispersion Modeling System (ADMS), and that CFD models could be more appropriate for more complex environments and in understanding the behavior of the system (Riddle et al. 2004; Di Sabatino et al. 2007; Di Sabatino et al. 2008).

Increasing number of more recent CFD studies now include the effect of on-road turbulences, and their results confirm the effectiveness of explicitly simulating turbulences in reproducing pollutant concentrations measurements for different kinds of pollutants under different conditions and different scale. Kim et al. modeled the dispersion behavior of an exhaust plume from a tractor truck around the truck body (Kim
et al. 2001); Wang et al. modeled dispersion of CO from exhaust pipe under different wind directions (Wang et al. 2006); Shalodin et al., simulated dispersion near roadways that contain multiple passenger cars and trucks (Sahlodin et al. 2007); Solazzo et al. simulated wind flow and vehicle-induced turbulence in urban street canyons with multiple, rectangular shaped vehicles (Solazzo et al. 2008); and Wang and Zhang modeled TKE in near-road conditions and their computational domain included multiple passenger vehicles and trucks (Wang and Zhang 2009).

However, in all of the studies mentioned above, each study domain only contained a fixed set of vehicles at certain distances apart. In their studies, the vehicle-vehicle interactions, traffic densities and compositions were not varied, and thus the changes in TKE were not studied systematically and their results were specific to their study domain and traffic conditions.
4 Theoretical Background and Methodology

4.1 CFD Software and Governing Equations

The commercial CFD software FLUENT was used in this study. FLUENT is a multipurpose fluid dynamics software, which has been widely used in complex air flow and pollutant dispersion applications in various environments.

All of the governing equations are discretized using the finite volume method and are solved by using the SIMPLE (Semi-Implicit Method for Pressure-Linked Equation) algorithm in FLUENT, which uses a relationship between velocity and pressure corrections to enforce mass conservation and to obtain the pressure field (ANSYS.Inc. 2010).

4.1.1 Mass, Momentum and Energy Transfer Equations

To account for the small-scale fluctuations in turbulence, Reynolds-averaged Navier-Stokes (RANS) equations with time-averaged flow properties are used (ANSYS.Inc. 2009). The governing equations used in FLUENT codes are as follows:

Continuity equation:

\[ \frac{\partial}{\partial x_i} (\rho u_i) = 0 \]  

Conservation of momentum equation:

\[ u_j \frac{\partial}{\partial x_j} (\rho u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \rho u_i u_j \right] + \rho g_i \]  

where the subscript \( i \) and \( j \) describe the \( i \)th and \( j \)th direction coordinates, respectively, \( \rho \) is the fluid density, \( u \) is the velocity components, \( \mu \) is the laminar viscosity, and \( g \) is the gravitational acceleration in the corresponding direction coordinate.
The additional term in the governing equation $-\rho \overline{u_i u_j}$ represents Reynolds stresses, and is present due to the effect of turbulence and must be modeled in order to close the conservation of momentum equation (ANSYS.Inc. 2009). The equation for $-\rho \overline{u_i u_j}$ reads:

$$-\rho \overline{u_i u_j} = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \quad (4.2a)$$

where $\mu_t$ is the turbulent viscosity, $k$ is TKE, and the operator $\delta_{ij}$ is unity for $i=j$ and zero otherwise.

The detailed description on the turbulence model is to be given in section 4.1.2.

In addition to the conservation of mass and momentum, the conservation of energy equation is also solved using the following equation:

$$\frac{\partial (\rho u_i h)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( (k + k_t) \frac{\partial T}{\partial x_i} \right) - \frac{\partial}{\partial x_i} \sum_j (h_j J_{ij}) + \frac{Dp}{Dt} + \tau_{ik} \frac{\partial u_i}{\partial x_k} \quad (4.3)$$

where $T$ is temperature, $h$ is the static enthalpy, $k$ is the molecular conductivity, $k_t$ is the effective conductivity due to turbulent transport, $J_i$ is the diffusion flux of the species $i$ due to the concentration gradients and $\tau_{ik}$ is the stress tensor.

The equation for the effective conductivity reads:

$$k_t = \frac{\mu_t}{Pr_t} \quad (4.3a)$$

where $Pr_t$ is the turbulent Prandtl number, defining the ratio between the momentum eddy diffusivity and the heat transfer eddy diffusivity.
4.1.2 Turbulent Kinetic Energy and Standard k-ε Model

If a flow is partitioned into its mean and turbulent parts, the total kinetic energy of the flow is the sum of the kinetic energy of the mean and turbulent flows, and the turbulent kinetic energy is the sum of the kinetic energy of the velocity fluctuations.

Velocity $u$ may be expressed as:

$$ u = \bar{u} + u' $$

(4.4)

where $\bar{u}$ is the time-averaged mean velocity, and $u'$ is the fluctuating part of the velocity that differs from the average value.

Then the TKE per unit mass of the flow can be expressed as:

$$ TKE = k = \frac{1}{2} (u'^2 + v'^2 + w'^2) $$

(4.5)

where $u$, $v$, $w$ are the fluctuating velocity components in $x$, $y$, $z$ directions.

Since the instantaneous values of TKE can vary dramatically, a mean TKE value is often calculated to represent the overall flow.

$$ TKE_{avg} = \bar{k} = \frac{1}{2} (\bar{u}'^2 + \bar{v}'^2 + \bar{w}'^2) $$

(4.5a)

Although it is not possible to exactly predict the random and irregular details of turbulent flow, various models have been developed to provide “closure” to the equations governing the average flow.

The standard k-ε turbulence model is one of the most widely used and validated CFD turbulence model (Kim et al. 2001; Katolicky and Jicha 2005; Wang et al. 2006; Sahlodin et al. 2007; Solazzo et al. 2008; Wang and Zhang 2009). It offers a good compromise between result accuracy and computational cost in the absence of swirling flow.
The assumptions used in this model are that the flow is fully turbulent and the effects of molecular viscosity are negligible.

The standard k-ε model is a semi-empirical model; the model transport equation for the turbulent kinetic energy k is derived from the exact equation, while the model transport equation for the dissipation rate ε is derived from physical reasoning. These two quantities are treated as variables in transport equations, which are solved together with RANS equations given in section 4.1.1 (ANSYS.Inc. 2009). The transport equations for k and ε terms are as follows:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right) \frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho \varepsilon$$

$$\frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right) \frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_2 \varepsilon G_b) - C_2 \varepsilon \frac{\varepsilon^2}{k}$$

$$\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}$$

$$G_k = \mu_t \frac{\partial u_i}{\partial x_i} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$G_b = -\beta g_i \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i}$$

$$\beta = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T}\right)_p$$

where μ is the laminar viscosity, μₜ is the turbulent viscosity, σₖ and σₑ are the turbulent Prandtl numbers for k and ε, respectively, Gₖ is the TKE generation due to the mean velocity gradients, Gₖ is the TKE generation due to buoyancy, and β is the thermal expansion coefficient.
The model constants

\[ C_{1\varepsilon} = 1.44, \quad C_{2\varepsilon} = 1.92, \quad C_{3\varepsilon} = 1.44, \quad C_\mu = 0.09, \quad \sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3 \]

are determined from experiments, and are found to work fairly well for a wide range of flows (ANSYS.Inc. 2009). Although most studies adopt the values listed above as they are used in FLUENT codes, some studies have suggested that these constants may be altered to better fit the observed turbulences (Richards and Hoxey 1993; Bottema 1997; Richards and Norris 2011). The effect of modifying these parameters can be found in Appendix A.

### 4.2 Simulation Domain and Mesh Setup

In order to model a realistic roadway conditions three different types of vehicles were used in this study; a passenger vehicle, a SUV, and a truck. These vehicles were modeled in real-shape rather than block-shape, since block-shaped vehicles are estimated to produce 25% more turbulence than real-shaped vehicles (Thompson and Eskridge 1987).

Figure 4.1 shows the three different vehicles used in this study and the dimensions of the vehicles are given in Table 4.1.

![Figure 4.1 Shapes of three different types of vehicles: a passenger vehicle, a SUV and a truck](image)
Table 4.1 Vehicle dimensions

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Length (m) in x direction</th>
<th>Width (m) in y direction</th>
<th>Height (m) in z direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Vehicle</td>
<td>4.5</td>
<td>1.8</td>
<td>1.5</td>
</tr>
<tr>
<td>SUV</td>
<td>4.5</td>
<td>2</td>
<td>1.85</td>
</tr>
<tr>
<td>Truck</td>
<td>15</td>
<td>2.5</td>
<td>4</td>
</tr>
</tbody>
</table>

These vehicles were set to travel along the x-axis, while the y-axis is the width of the domain going into the screen, and the z-axis is the height of the domain.

The dimensions of computational domain for single vehicle cases were set to be 8 times the vehicle length in x direction, 7 times the vehicle width in y direction, and 4 times the vehicle height in z direction. Note that the computational domain was scaled with respect to the vehicle dimensions, thus the domain size used for each of the passenger vehicle, SUV, and truck is different.

For the multi-vehicle interaction cases, a fixed domain size of 100m by 20m in the horizontal and 20m in the vertical direction was used. For these cases, the domain size was fixed in order to analyze the effect of different traffic density and compositions on the overall turbulence on the roadways.

The computational domain was meshed using ICEM CFD, a software widely used for generating meshes. Tetra/mixed volume mesh was used to mesh the computational domain. In order to maintain the balance between results accuracy and computational expense, variable mesh size was used. Since the gradients in the model variables are more steep right around the vehicles and in the vehicle wake region, finer mesh density was used around the vehicles, and the mesh size was set to grow at a certain ratio as it moves away from the vehicles. Up to 6 million cells were created in each mesh setup. Detailed procedure for mesh generation is outlined in Appendix B. Figure 4.2 shows a typical mesh setup where the fine mesh density is shown right around the vehicle; note that there are volume meshes that fill the whole domain but only the surface meshes are shown here and also that some surfaces are left invisible for the ease of view.
4.3 **Boundary Conditions**

Movement of the vehicles in a steady-date flow was simulated by modeling the vehicles as moving walls with specified translational velocities in x-direction. For the vehicle surface, an equivalent roughness height of 0.0015m was used (Wang and Zhang 2009); while the ground was set as a stationary wall with a surface roughness of 0.01m. The road is not raised and there is no barrier or obstacle to air flow, other than the surface roughness. Non-slip boundary conditions and specified surface temperatures were applied to the vehicle and the ground surfaces. The inert exhaust composed of CO₂ was emitted out at 28m/s normal to the exhaust pipe surface. The exhaust pipe was on the right end of the vehicle body for passenger vehicle and SUV, and behind the right side of the cabin for truck. The diameter of the exhaust pipe was 7.5cm for passenger vehicle and SUV, and 10cm for truck.
The symmetric boundary conditions were applied to the two side faces and the top face; which means that there is zero gradient in the variables normal to these surfaces, and that there is no flux of all quantities across these surfaces. The front side was modeled as a velocity inlet with zero velocity; while the back side was modeled as an outflow with zero normal first derivatives of all quantities, which means that there is bulk flow only and no diffusive flux for all flow variables in the direction normal to the plane. When external wind was introduced, the side from which the wind blows from was also treated as a velocity inlet, with specified wind velocity components. Figure 4.3 presents the boundary conditions for the surrounding walls in the absence of external wind.

Figure 4.3 Boundary conditions for the case without ambient wind
5 Impact of Vehicle Types, Velocities, Thermal Conditions and External Winds on TKE

5.1 Introduction

The initial mixing and dilution of vehicle exhaust is important in pollutant dispersion and air quality modeling as it affects both the downwind concentrations and the subsequent fate of pollutants. Zhang and Wexler analyzed different aerosol dynamics equations as they relate to aerosol number distributions; condensation/evaporation, coagulation, nucleation, gravitational settling, and heterogeneous chemical reactions, and determined that aerosol dilution, dispersion, and dynamics are distinctly different in terms of their time scales, energy barriers and favorable conditions involved in each process (Zhang and Wexler 2002; Zhang and Wexler 2004). Since the relative humidity and the initial concentrations are affected by the initial dilution of vehicle exhaust, the initial mixing is an important factor in the first steps of pollutant dispersion. Other studies also have shown the importance of the dilution ratio, temperature and relative humidity on the concentrations and sizes of particles (Casati et al. 2007; Ronkko et al. 2007); and some models (Gidhagen et al. 2004; Holmes and Morawska 2006) have coupled the particle dynamics model with different dispersion models to demonstrate that traffic induced turbulence is important to street level number concentrations, size distributions and chemical compositions.

There are a number of studies which included the effects of on-road turbulences in dispersion modeling. The results from such studies confirmed the importance of turbulences in reproducing the qualitative features of airflow and pollutant concentrations for different kinds of pollutants such as CO, CO₂ and NOₓ (Kim et al. 2001; Wang et al. 2006; Sahlodin et al. 2007; Wang and Zhang 2009; Wang et al. 2011), from near-source regions right after the tailpipe to far field regions of up to few hundred meters extending into regional scales.
Previous studies have shown that VIT is the dominant factor on roadside TKE, greater in magnitude compared to structural RIT and thermal RIT (Kalthoff et al. 2005; Wang et al. 2009). However, there has not been an extensive study on TKE generation by moving vehicles, and its decay with increasing distance away from the source. A study by Rao et al., (2002) is one of the first to analyze the field measurements of TKE behind a moving vehicle by using a trailer equipped with sonic anemometers while chasing a van. The study was able to conclude that the turbulence decays with power law both with increasing lateral distance from the centerline of the wake and with increasing distance behind the vehicle. Although they were able to present some results, it was suggested in this study that additional field work to be done in vehicle wakes.

To fill in the gap, Environment Canada’s FEVER project has measured TKE while chasing different vehicle types at varying distances on highway (Gordon et al. 2011). Following previous studies (Eskridge and Thompson 1982; Rao et al. 2002), TKE data obtained in FEVER campaign has been fitted using a power-law decay equation; and the result has shown to be within the range created by the two previous studies.

This study aims to simulate the TKE induced by a single vehicle, and to validate the simulation results against previous results from other studies and FEVER measurements, before more complex traffic scenarios are investigated.

5.2 Simulation Setup

The governing equations, domain setup, and meshing strategies have been previously described in section 4.1 to 4.3. Therefore, only the boundary conditions are described in this section, as they would be different for each simulation scenario.

5.2.1 Different Vehicle Types

As mentioned in section 4.2, three types of vehicles were used in this study: a passenger vehicle, a SUV, and a truck. These three different types of vehicles represent the realistic
traffic mix on a highway. FEVER study treated these vehicles separately, and they have showed that turbulence generation and turbulence decay patterns are different for each of them (Gordon et al. 2011). The current study simulated the turbulence generated by these three types of vehicles in order to compare them with FEVER results, and also to use them as building blocks for resolving vehicle-induced turbulence in a larger section of highway.

5.2.2 Different Travel Velocities
The effect of different velocities on turbulence was studied by setting a single passenger vehicle to travel at three different velocities: 7m/s, 14m/s, 21m/s, and 28m/s (all in the positive x-direction), which is equivalent to 25km/h, 50km/h, 75km/h, and 100km/h, respectively.

5.2.3 Exhaust Temperature and Road Surface Temperature
The temperature of the vehicle exhaust was varied from 300K to 500K to determine the significance of the exhaust temperature on turbulence generation. Also, the road surface temperature was varied from 263K to 300K and then to 320K to represent winter, spring/fall and summer conditions, respectively. The exhaust temperature and the road surface temperature were varied in order to investigate the effect of different temperatures on roadways, in addition to the VIT. To determine the influence of vehicle velocity on the relative importance of thermal effects, for each set of thermal condition two different vehicle velocities were used: 28m/s and 7m/s.

5.2.4 External Wind
The effect of ambient wind with specified velocity was studied by introducing external winds from different directions at different speeds. Wind blowing from positive y-direction, perpendicular to the traffic flow, was used as the base case wind direction and different wind speeds of 2m/s, 5m/s, 10m/s, and 25m/s were introduced from this
direction. Then, a speed of 5 m/s was used as the base case wind speed, and different wind directions were considered. The wind directions include: perpendicular to the traffic flow, at 45° angle to the traffic flow, from in front of the vehicle against the traffic flow, and from behind the vehicle along the traffic flow. For the perpendicular wind case, a velocity inlet boundary condition of 5m/s was imposed on the lateral side face. For the wind blowing from the front, the front side face was used as velocity inlet with a specified wind velocity of 5m/s. Lastly, wind was introduced at a 2° angle from the lateral face to represent the case when the wind was blowing from behind, since the back face was specified as outflow.

5.3 Results

5.3.1 Effect of Different Vehicle Types
The aim of this part of the study was to investigate the difference in TKE generated by different types of vehicles. The result clearly indicates that the type or the shape of the vehicle is an important factor in determining the TKE in the study domain. Figure 5.1 shows the TKE contours behind the vehicle along the centerline of the vehicles. It can be seen that due to its higher height and less streamlined shape, SUV generates higher TKE than passenger vehicle, and truck generates more TKE than SUV. This is consistent with what one would expect, as passenger vehicles have more sloping back part, the flow can remain attached longer on a passenger vehicle than it can on a SUV or for truck. As a result, the wake produced behind the passenger vehicle is smaller.

It can also be noted that the TKE does not spread very far up in the vertical direction above the vehicle height, and most of the notable changes occur in the wake region behind the vehicle.
TKE can also be plotted against the distance behind the vehicle along a line, at a specific height. Since the magnitude of TKE is rather small above the vehicle, the change in TKE with distance behind the vehicle was plotted along the line at vehicle-top height (1.5m, 1.85m, and 4m for passenger vehicle, SUV and truck, respectively). Figure 5.2 shows the change in TKE with increasing distance away from the vehicle for the three different vehicle types.

Figure 5.2 shows that the magnitudes of initial TKE behind the vehicles are significantly different for the three different vehicles. SUV produces up to 2 times as much initial TKE than passenger vehicle, but the TKE quickly decays and after about 5m, the difference between TKE behind passenger vehicle and SUV are small. However, truck produces up to 5 times more initial TKE than passenger vehicle, and up to 2.5 times more initial TKE than SUV. Also, the difference remains significant even after 15m.
Figure 5.2 TKE vs. Distance behind vehicle for passenger vehicle, SUV, and truck at vehicle-top height

There are two points worth mentioning in Figure 5.2. Firstly, the maximum x-axis is different for each vehicle; this is because the domain size was proportional to the vehicle length in each simulation. As a result, a larger computational domain was used for the truck. Secondly, the maximum TKE does not seem to appear until about after 2m behind the truck, unlike the case for passenger vehicle and SUV. This is because at the end of the roof of the truck, the flow detaches and the separation bubbles begin to form (Genta 1997). Due to its blunt shape at the end, the turbulent wake region created at the end of the truck is much wider than that of the passenger vehicle or SUV; as a result, the maximum TKE happens to be located few meters behind the vehicle.
5.3.2 Effect of different Travel Velocities

This section investigates the effect of different travelling velocities of a passenger vehicle on TKE. Figure 5.3 shows the TKE contour of the passenger vehicle each travelling at 28m/s, 21m/s, and 14m/s (100km/h, 75km/h, and 50km/h, respectively) from the top. These contours are shown on the plane that cuts the center of the passenger vehicles.

![TKE contours on planes that cut the center of passenger vehicles travelling at 28m/s, 21m/s, and 14m/s](image)

As can be seen from these contours, higher velocity causes higher TKE right behind the vehicles, and it spreads further down the distance.

The change in TKE behind the vehicle with increasing distance away can also be plotted along a line that runs at the center of the vehicle, at the top of the vehicle height. The plots are shown on Figure 5.4, with each line representing different vehicle velocity case.
These TKE plots show that TKE produced from vehicles travelling at higher velocity is greater than that produced from vehicles travelling at lower velocity.

These plots were fitted with power law equations. Although they have different pre-exponent factors that dictate the magnitude of TKE; they all seem to decay at similar rates with distance, with decay exponents ranging from -0.40 to -0.41. This means that there is a constant factor increase in TKE as velocity increases.

In addition to the TKE decay plots, a volume-averaged TKE values are calculated to compare the effect of different vehicle velocities. The volume-averaged values were calculated for the air in the domain under an arbitrary mixing height, and were regarded as the average value of TKE in the computational zone. The mixing zone height of 3m was chosen, based on different mixing zone heights used in previous studies: 2.5m (Held et al. 2003), 4.5m for major truck routes (Sahlodin et al. 2007), and 2.5m for roads dominated by cars and vans, and 3.5m for major truck routes (Wang and Zhang 2009).
The results are summarized in Table 5.1, which lists the volume-averaged TKE in the zone under the mixing height of 3m, for the cases of a single passenger vehicle travelling at different velocities.

Table 5.1 Different travelling velocities of a passenger vehicle and the resulting volume-averaged TKE in the mixing zone

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Volume-Averaged TKE (m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.42</td>
</tr>
<tr>
<td>14</td>
<td>0.82</td>
</tr>
<tr>
<td>21</td>
<td>1.14</td>
</tr>
<tr>
<td>28</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Figure 5.5 Volume-averaged TKE vs. Velocity of a passenger vehicle

Figure 5.5 plots the data from Table 5.1, from which the line of best fit with the following linear equation is obtained, with $R^2$ value of 0.99.

$$y = 0.057x + 0.005$$ (5.1)
The y-intercept value deviates slightly from the expected value of zero, as when the vehicle velocity is 0, there is no source of turbulence in the absence of any external wind. However, the y-intercept value is relatively small at 0.005; this may be regarded as an error occurred in numerical fitting of data.

This equation relates the volume-averaged TKE on a segment of highway (36m by 12m) under the mixing height of 3m, as a function of velocity of a passenger vehicle, within a realistic highway driving speed range of 7m/s (25km/h) to 28m/s (100km/h).

5.3.3 Effect of Different Thermal Conditions
Both the road surface temperature and the exhaust temperature were varied to study the impact of temperature on the TKE generation in the domain, but a significant different was not observed. Figure 5.6 shows the resulting TKE plots for the cases with different temperature combinations. In the legend, $R$ and $Exh$ stand for the road and the exhaust temperatures respectively; and the vehicle surface temperature was constant at 300K.

![TKE vs. Distance: Thermal Effects](image)

Figure 5.6 TKE vs. Distance behind passenger vehicle for different temperature variations for a passenger vehicle travelling at 28m/s
From Figure 5.6 it seems that the TKE behind the vehicle in the wake region is not affected to any noticeable extent when there are changes in the temperature of the road surface or the exhaust, when the vehicle is travelling at 28m/s.

In addition to the TKE plot, volume-averaged TKE values are calculated to determine the significance of different thermal conditions.

Table 5.2 Effect of variations in the road surface and exhaust temperature on the volume-averaged TKE for passenger vehicles travelling at 28m/s and at 7m/s

<table>
<thead>
<tr>
<th>Velocity of vehicle (m/s)</th>
<th>Temperature of the Road surface (K)</th>
<th>Temperature of the Exhaust (K)</th>
<th>Volume-averaged TKE (m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>300</td>
<td>300</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>500</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>263</td>
<td>500</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>320</td>
<td>300</td>
<td>1.67</td>
</tr>
<tr>
<td>7</td>
<td>300</td>
<td>300</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>500</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>320</td>
<td>300</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Table 5.2 compares the volume-averaged TKE for different combinations of temperature, for two different vehicle velocity cases. It can be seen that when the vehicle is travelling at 28m/s, a change in the exhaust temperature or a decrease in the road surface temperature has no effect on the volume-averaged TKE; while an increase in the road surface temperature produces a slightly higher volume-averaged TKE but the impact is not significant. When the vehicle is travelling at a lower velocity of 7m/s, similar results are obtained, indicating the thermal effects are not important even when the magnitude of VIT is small.

A previous study experimentally determined that the thermally generated turbulence due to the difference in surface temperature of roadways relative to that of surroundings is relatively small (Kalthoff et al. 2005). However, another study compared the simulation results for summer and winter cases, and concluded that during summer season the
difference in temperature between air and roadway surface adds thermal TKE which can account for up to 20\% of total TKE (Wang and Zhang 2009). But the same study included the thermal effects as part of the atmospheric wind, as the difference in surface heating causes stronger winds. It can thus be suggested that the effect of surface temperature cannot be captured unless the difference in temperature is accounted for its ability to alter the atmospheric boundary layer stability.

And for the exhaust temperature, it can be said that the effect is negligible since the volumetric flow rate of exhaust is relatively small compared to the turbulent wake region created behind the moving vehicles. This is consistent with Rao et al. as the study mentioned that the mechanical mixing in the wake of vehicles reduces the influence of the buoyant plume rise caused by heat of exhaust gases (Rao et al. 2002).

5.3.4 Effect of Ambient Wind
The effect of ambient wind on the TKE generation and its distribution was studied in this part of the study. Based on the direction the wind is blowing from, this section is subdivided into three parts: wind blowing perpendicular to the direction of traffic flow, wind blowing from 45° angle, and wind blowing parallel to the direction of traffic flow.
Figure 5.7 TKE contours on XY-plane at the height of exhaust pipe for different wind velocity cases of 0m/s, 2m/s, 5m/s, 10m/s and 25m/s for a passenger vehicle travelling at 28m/s

Figure 5.7 shows the TKE contours for each wind velocity case. The contours are shown on the X-Y plane at the height of the tailpipe, which is 0.5m above the ground. It is clear from these contours that the shape of the TKE wake is affected by the ambient wind. As the wind speed increases, the TKE zone is shifted further downwind. For the case with high wind velocities of 10m/s and 25m/s, not only the TKE wake is shifted but the magnitude of TKE is significantly higher than the cases with lower wind velocities.
Figure 5.8 TKE vs. Distance behind the vehicle at vehicle-top height, with different wind velocity for a passenger vehicle travelling at 28m/s.

Figure 5.8 plots the changes in TKE with distance behind the vehicle, along the line that runs through the centerline at the top of the vehicle. When compared to the no-wind base case, the cases with wind velocities of 2m/s and 5m/s seem to lower the TKE along the centerline, as the zone of high TKE has been translated along the wind direction.

However, for the high wind velocity cases with wind speed of 10m/s and 25m/s, where the wind speed is comparable in magnitude with the velocity of the vehicle (28m/s), even when the maximum TKE is shifted downwind, the TKE value right behind the vehicle is still higher than that of the no-wind case. While the lower wind velocities resulted in the translation of TKE wake zones, the high wind velocities have more significant impacts on TKE by increasing the size of the TKE wake zone, in addition to the centerline...
translation. As a result, there are large fluctuations in TKE behind the vehicle for the strong wind cases.

The TKE wake zone shifts along the wind down the y-axis in the lateral direction, and at the same time, the shape of the wake zone changes. As a result, it is difficult to capture the change in TKE along a single line that runs in the x-axis. Therefore, the volume-averaged TKE has been calculated for each case under the mixing height of 3m. Also, the TKE generated by the ambient wind was isolated from VIT by calculating volume-averaged TKE without the vehicle for different wind velocity cases, since the roughness of the road surface also causes TKE in form of RIT, irrespective of VIT. The results were compared to the results from wind + vehicle cases. The result is presented in Table 5.3

<table>
<thead>
<tr>
<th>Perpendicular wind speed (m/s)</th>
<th>Volume-averaged TKE (m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wind-only</td>
</tr>
<tr>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1.03</td>
</tr>
<tr>
<td>5</td>
<td>1.22</td>
</tr>
<tr>
<td>10</td>
<td>1.57</td>
</tr>
<tr>
<td>25</td>
<td>2.85</td>
</tr>
</tbody>
</table>

The case with high wind velocity of 25m/s creates the largest incremental change in volume-averaged TKE compared to the cases with lower wind velocities. This is because there is a larger TKE wake zone created on the side of the vehicle, in addition to the wake zone behind the vehicle.
Figure 5.9 Volume-averaged TKE vs. Wind Speed for cases with and without a passenger vehicle travelling at 28m/s

Figure 5.9 denotes that the wind speed and the volume-averaged TKE from wind show a near-linear relationship, in the absence of the vehicle. However, in the presence of a moving vehicle, the TKE increases at a higher rate with increasing wind speed. This is due to the larger TKE wake zone created on the side of the vehicle (due to wind), in addition to the one created behind the vehicle (due to vehicle movement).

Therefore, it can be concluded that the external wind velocity is significant in determining the volume-averaged TKE in the domain; and it is increasingly so as the wind velocity increases. Care should be taken in predicting TKE in cases of high wind conditions.
5.3.4.2 Wind at 45° angle to the Vehicle Movement

Figure 5.10 compares the two cases with different wind angles: wind blowing perpendicular to the vehicle movement and wind is blowing from 45° angle to the vehicle movement. In both cases, the wind velocity was 5m/s. When the wind is blowing at an angle, the TKE wake zone extends further back with less translation in the y-direction, as the velocity component in the y-axis is less for the wind at 45° angle.

The volume averaged TKE under mixing height of 3m is 2.11m²/s² for the case of wind from 45° angle; the value is similar in magnitude to 2.15m²/s² in the case of parallel wind. Therefore, although the effect of wind directions at higher wind velocity is still to be determined, it may be concluded that the direction of the wind is not a significant factor in determining the average TKE in the domain, at a reasonably realistic ambient wind velocity of 5m/s.

The effect of further altering the angle of wind is to be followed in the next section.
5.3.4.3 Wind Parallel to the Vehicle Movement

In this section, two cases were studied in which the wind is blowing in parallel with the direction of vehicle movement. The first case is when the wind is blowing from the front, and the second case is when the wind is blowing from behind the vehicle.

Figure 5.11 and Figure 5.12 shows the TKE contours on different planes for the two wind cases. Figure 5.11 is the top view on XY-plane at the tailpipe height; Figure 5.12 is the side view along the centerline of the vehicle on XZ-plane.

![Figure 5.11 TKE contours on XY-plane for two different parallel wind cases](image)

From Figure 5.11 it can be seen that when the wind is blowing from the front, it aids in the TKE wake dissipation, and extends the TKE zone further behind the vehicle. The TKE wake region is narrower and extends straight backward with not much dissipation in the lateral direction.

On the other hand, for the case where the wind is blowing from the back, TKE is dispersed further in the lateral direction due to a flow resistance in the reversed direction. A shift in the lateral direction seems to be due to the angle at which the wind was introduced. This was inevitable since the wind could not be directly introduced from behind the vehicle due to a limitation in boundary condition specifying the back side as an outflow.
Figure 5.12 TKE contours on XZ-plane for two different parallel wind cases

Figure 5.12 illustrates the difference in the magnitude of TKE for the two wind cases. When the wind blows from the front, it effectively works as an increment in the velocity at which the vehicle is travelling at. As a result, larger TKE is generated behind the vehicle. On the other hand, when the wind blows from behind, it works as a resistance to the flow and reduces the TKE in the wake region behind the vehicle.

Figure 5.13 TKE vs. Distance for different parallel wind directions: from front and from behind the vehicle
The results from these two wind cases can also be represented by plots showing TKE value against the distance behind the vehicle along the centerline at the top of the vehicle, as seen on Figure 5.13.

Compared to the base case with no wind, the effect of wind directions is evident. When the wind blows from the front, TKE magnitude is consistently higher than the case when there is no wind. In comparison, the case of wind from behind seems to produce lower TKE than the base case with no wind.

However, Figure 5.13 is plotted along a single line that runs through the center of the vehicle, and thus misses out the fact that the TKE wake region is wider in transverse direction when the wind is blowing from behind. To account for this, a volume-averaged TKE has been calculated under the mixing height of 3m, and the result shows that wind from behind produces a higher volume-averaged TKE value than the base case; but lower volume-averaged TKE value than the case with wind from front. The values are summarized in Table 5.4.

Table 5.4 Different parallel winds and corresponding volume-averaged TKE in the mixing zone height of 3m

<table>
<thead>
<tr>
<th>Parallel wind direction</th>
<th>Volume-averaged TKE (m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No wind</td>
<td>1.65</td>
</tr>
<tr>
<td>From front</td>
<td>2.62</td>
</tr>
<tr>
<td>From behind</td>
<td>1.89</td>
</tr>
</tbody>
</table>

In real roadway conditions, the frequency at which the wind blows exactly parallel to the traffic flow may be low. However, since its effect on the TKE is different from the effect of non-parallel winds, the parallel winds cases deserve attention.
5.4 Evaluation of Simulation Results

The simulation result from the present study was compared with results from previous studies and also with the field measurements from FEVER for validation.

There were three limitations in comparing the results from this study to FEVER data. The first limitation was that this study simulated TKE generated by a single vehicle while FEVER measurements were taken on a real highway; as a result the magnitude of TKE from FEVER was higher than what was obtained from this study. The second limitation was that the TKE measurements in FEVER study were made at a height of 3m, but the result from the current study was obtained along a line at the top of the vehicle height, as the simulated TKE values are too low to give any conclusive result above this height. Therefore, the main focus of comparison would be the decay characteristics rather than the absolute magnitude. Lastly, FEVER measurements were made over a much larger range of normalized following distance (distance normalized by the vehicle height), from about 3 to 100. Since the range used in this study was smaller, from immediately behind the vehicles to up to 8, the comparison between the simulated result and field measurements is limited to the near-region of normalized following distance less than about 8.

Previous studies (Eskridge and Thompson 1982; Rao et al. 2002) and FEVER project (Gordon et al. 2011) have related the decay of TKE with the distance behind the vehicle using the following power-law equation:

\[
\frac{k}{u^2} = \exp(a) \left(\frac{x}{h}\right)^b
\]  

(3.1)

which can also be expressed as:

\[
\ln \left(\frac{k}{u^2}\right) = a + b \ln \left(\frac{x}{h}\right)
\]  

(3.1a)

where \(k\) is TKE in \(m^2/s^2\), \(u\) is the mean speed of the vehicle in \(m/s\), \(x\) is the following distance behind the vehicle, and \(h\) is the characteristic vehicle height in \(m\).
normalized by $u^2$, and $x$ is normalized by $h$. The $\exp(a)$ value represents the magnitude of initial TKE right behind the vehicle, while the value of exponent $b$ represents the decay strength of TKE with increasing distance.

The data from this study were processed in the same way in order for them to be comparable with the results from previous studies. Note that for the case with the truck, the TKE value for the following distance of less than 2m was excluded, as the maximum TKE is not reached until after 2m behind the truck at the vehicle-top height. This should not interfere with the comparison, as the field measurement was not made at such short following distance behind trucks.

Figure 5.14 shows the normalized TKE with normalized distance behind the three types of vehicles, and the line of best fit for each case.

Figure 5.14 Normalized TKE vs. Normalized distance behind different types of vehicles from simulation, with equations for the fitted lines
The TKE decay patterns are similar for passenger vehicle and SUV, while a heavy-duty truck generates much higher TKE which also decays fast. This means that the TKE generated by trucks demonstrate a stronger dependence on normalized following distance than the TKE generated by passenger vehicles or SUVs, which agrees with what has been observed for FEVER (Gordon et al. 2011).

For comparison, the equation parameters obtained from this study and other studies are listed in Table 5.7.

Table 5.5 Comparison of the TKE decay equation parameters

<table>
<thead>
<tr>
<th>Study</th>
<th>Vehicle Type</th>
<th>(\exp(a))</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>Passenger Vehicle</td>
<td>0.0058</td>
<td>-0.34</td>
</tr>
<tr>
<td></td>
<td>Mid-size SUV</td>
<td>0.0070</td>
<td>-0.36</td>
</tr>
<tr>
<td></td>
<td>Truck</td>
<td>0.0259</td>
<td>-0.94</td>
</tr>
<tr>
<td>FEVER</td>
<td>Passenger Vehicle</td>
<td>0.0092</td>
<td>-0.23</td>
</tr>
<tr>
<td></td>
<td>Mid-size SUV</td>
<td>0.0125</td>
<td>-0.34</td>
</tr>
<tr>
<td></td>
<td>Truck</td>
<td>0.0821</td>
<td>-0.92</td>
</tr>
<tr>
<td>Eskridge and Thompson (1982)</td>
<td>Mid-size Vehicle</td>
<td>0.0051</td>
<td>-1.2</td>
</tr>
<tr>
<td>fitted by (Gordon et al. 2011)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rao et al. (2002)</td>
<td>Mid-size Vehicle</td>
<td>0.0099</td>
<td>-0.19</td>
</tr>
<tr>
<td>fitted by (Gordon et al. 2011)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The \(\exp(a)\) values from this study are consistently smaller than the corresponding values for FEVER. Had the TKE values from this study been collected at 3m height, the same height as the FEVER measurements were taken at, this difference would have been even larger. This is because the simulations from this study only included a single vehicle travelling in a controlled environment in the absence of external winds or roadside barriers, while FEVER campaign was carried out on a real highway under real driving conditions. The study by Eskridge and Thompson (1982) was carried out on a wind tunnel, and the study by Rao et al. (2002) was on an airport runway, both using a single mid-size vehicle. The values from these two studies compare better with the value from
this study than FEVER study does. As for the relative differences in \( \exp(a) \) values for different types of vehicles, the values from this study follow the same trend seen on FEVER study; while the same comparison is not applicable to the studies by Eskridge and Thompson (1982) and Rao et al. (2002), since they had only used one type of vehicle.

The \( b \) values from this study are similar to the values from FEVER for the corresponding type of vehicle, and the value for SUV from this study falls in the range created by Eskridge and Thompson (1982) and Rao et al. (2002), suggesting that this study is able to capture the rate of TKE decay behind the vehicles.

![Normalized TKE vs. Normalized distance behind vehicle](image)

Figure 5.15 Fitted TKE decay equations from this study compared with previous studies

Shown on Figure 5.15 are the equations plotted on the same log-scale axis, graphically representing how the values from this study compare with the ones from other studies.
5.5 Conclusions and Implications

In this study, CFD simulations were conducted using the standard k-ε turbulence model in FLUENT to characterize the TKE generation by moving vehicles under different conditions; and to determine the suitability of using such a model to study more complex vehicle interactions scenarios. The following conclusions were obtained from this study:

1. TKE values were plotted behind the vehicles to quantify the turbulence generated by various types of vehicles. Specifically, trucks produce higher TKE than SUV and passenger vehicle. The simulated result is consistent with the qualitative observation made by others.

2. It was shown qualitatively by previous studies that the magnitude of turbulence in the wake region behind the vehicle increased with vehicle speed; this study was able to quantitatively relate the change in the volume-averaged TKE to vehicle speed with a linear function. For passenger vehicles within the domain volume specified in this study, the linear function is as follows:

\[ TKE_{vol.avg@3m} = 0.057(velocity) + 0.005 \]

3. Increasing the exhaust temperature from 300K to 500K; or changing the road surface temperature from 263K to 320K did not result in a notable difference in the TKE, for the two cases when the vehicle velocity was 28m/s and 7m/s. This suggests that the thermally generated turbulence is insignificant compared to the mechanically generated VIT, even at a low-VIT condition. This agrees with the common belief that any heat input to the system would be dissipated quickly by the mechanical turbulence.

4. The impact of external winds on TKE is significant. The wind blowing perpendicular to the traffic flow causes a translation in the TKE wake region, while the overall average TKE in the computational domain increases with wind speed. Parallel to the traffic flow, the wind blowing from front increases the magnitude of TKE behind the vehicle. On the other hand, the wind blowing from behind reduces the TKE value right behind the vehicle due to the flow resistance in the opposite direction, but increases the width of
TKE wake region. Consequently, it is shown that the overall volume-averaged TKE increases in the presence of external wind regardless of the wind direction.

5. In the absence of external wind or thermal effects, the decay of TKE with increasing distance behind the vehicle follows approximately a power-law equation. The decay power-law exponents are -0.94 for trucks, -0.36 for SUVs and -0.34 for passenger vehicles. These values compare reasonably well with the field measurements reported in the recent literature and fall within the range created by previous studies.

Further work will focus on extending the current domain setup, solution methods and boundary conditions to simulate more complex traffic conditions such as vehicle-vehicle interactions and changes in traffic compositions.
6  Impact of Vehicle-vehicle Interactions and Different Traffic Density and Composition on TKE

6.1  Introduction

Various CFD studies have modeled typical highway conditions using realistic vehicle shapes and compositions and investigated the TKE generated on roadways and its effect on pollutant dispersion (Sahlodin et al. 2007; Solazzo et al. 2008; Wang and Zhang 2009).

One difficulty in reproducing realistic roadway conditions using CFD models is simulating two-way traffic. Hu et al. developed a solution procedure, adopting a sliding-mesh approach in which the mesh points are updated as the vehicles move at a specified velocity in opposite directions (Hu et al. 2007). Hu et al. was able to investigate the transient behavior of the air flow in between the two vehicles, and the pressure distributions. However, such rigorous approaches are computationally expensive, and their transient nature made it not suitable for highway-scale TKE models. Other studies have suggested different approaches with some simplifying assumptions. One study made an assumption that if the vehicle flow is continuous enough for the TKE to stay constant over time, then a segment of highway can be used as a representative section of the overall highway (Sahlodin et al. 2007) and vehicles were set to moving walls with specified velocities. Similar approach has been used by other studies (Wang and Zhang 2009).

Studies mentioned above have built only one set of vehicles for each highway study, claiming that traffic volumes change little between seasons (Wang and Zhang 2009) and the traffic composition does not vary much (Sahlodin et al. 2007). Their work is limited to the specific conditions under which their simulations were set up for, and the results cannot be extended to other roadway conditions. Although the traffic volume may change little between seasons, the hour-to-hour variations were proven to be more significant as shown in field measurements (Lin and Yu 2008; Gordon et al. 2011). Also, these studies
were not able to capture the different vehicle-vehicle interactions and its effect on TKE generation, or its decay characteristics, although it could be important. One study showed how the pollutant dispersion and turbulent mixing are impacted by building arrays and packing density in street canyon environments (Di Sabatino et al. 2007). Impacts of similar significance may be expected from different arrays and densities of vehicles on roadways.

Since it is important that the results are taken and applied beyond the simulation domain, the current study aims to provide insights into different factors that may affect TKE on roadways and to develop parameterizations that can be applied in future studies.

### 6.2 Simulation Setup

While the size of the computational domain was scaled with length scales of each vehicle type in the single vehicle simulations in section 5, the domain size in this section was fixed at 100m x 20m x 20m (in x, y, z directions, respectively). This was to compare the volume-averaged TKE when there are multiple vehicle interactions, changes in traffic densities and changes in traffic compositions. Meshing procedures remained the same: finer mesh around the vehicles and the mesh size was set to grow larger with increasing distance away from the vehicle. Any change in the boundary conditions is to be described below.

#### 6.2.1 Vehicles Travelling in Series

A single passenger vehicle travelling at 28m/s (100km/h) was used as a base case. Then, a second passenger vehicle was added directly behind the first vehicle, and the distance between the two vehicles travelling in series was varied from 1, 1.5, 2, 3 and 5 multiples of body length, where the body length of the passenger vehicle is 4.5m.

#### 6.2.2 Vehicles Travelling Side-by-side

Again, a single passenger vehicle with velocity 28m/s was used as a base case, and a second vehicle was added next to the first vehicle, travelling in the same direction. The
distance between the two side-by-side travelling vehicles were varied from 1, 1.5 and 2 multiples of body width for 2 passenger vehicle cases; 1 body width for 1 passenger vehicle and 1 SUV case; and 1 body width for 1 passenger vehicle and 1 truck case; where the body width of the passenger vehicle is 1.8m. For the cases of different vehicle body lengths, the centerline of the vehicles was matched to represent a side-by-side position.

6.2.3 Vehicles Travelling in Opposite Directions
The effect of vehicles travelling in opposite directions was studied in this section. The vehicles were treated as moving walls with velocities in the opposite directions. Two passenger vehicles were set to travel in the opposite directions, while the distance between them was varied from 1 and 2 multiples of body width, 1.8m.

6.2.4 Different Traffic Density
The traffic density was varied from 1, 2, 4, 6, to 8 passenger vehicles evenly spaced out in the computational domain. Similar steps were taken with increasing number of trucks in the absence of passenger vehicles. The number of trucks in the domain was increased from 1, 2, to 3. Only one type of vehicle was used in each part, as the effect of traffic composition is studied in a separate section. As will be shown in later sections, the effect of side-by-side interaction of vehicles travelling in opposite directions is not significant on the overall TKE in the computational domain, therefore the traffic density studies were carried out in one-way traffic only. For illustrative purpose, the simulation domain and geometry setup for 6 passenger vehicle case is given in Figure 6.1. The axis orientation, scale, and the relative spacing of the vehicles can be seen.

6.2.5 Different Traffic Composition
Different traffic compositions were simulated with increasing number of trucks, while keeping the total number of vehicles constant at 8 vehicles. The cases simulated were 1 truck and 7 passenger vehicles; 2trucks and 6 passenger vehicles; and 3 trucks and 5 passenger vehicles. For the same reason described in the traffic density cases, only one-way traffic was simulated.
Figure 6.1 Computational domain setup for traffic density of 6 passenger vehicles

6.3 Results

6.3.1 Effect of Distance between Vehicles

6.3.1.1 Vehicles Travelling in Series

Figure 6.2 shows the TKE contour on XZ-plane when two vehicles are travelling in series. TKE values have been plotted against the distance behind the first vehicle along the centerline of the vehicle at vehicle top height. The results are presented in Figure 6.3. Zero on the x-axis corresponds to the end of the first vehicle, thus the peak that appear before zero is above the body of the first vehicle.

It can be seen that as the second vehicle drives into the TKE wake region created by the vehicle in front, the TKE behind the second vehicle peaks up. As the distance between
them increases, the TKE generated by the first vehicle is allowed to decay further down before the second vehicle approaches it, but as the second vehicle drives in, the TKE value is superimposed on the existing TKE value at the point. At about 5 body lengths apart, the effect of the first vehicle is not significant anymore, and the peak produced by the second vehicle is as high as the peak produced by the first vehicle.

Figure 6.2 TKE contour on XZ-plane for two passenger vehicles in series

<table>
<thead>
<tr>
<th>Distance behind the end of the 1st vehicle (m)</th>
<th>TKE (m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>35</td>
<td>35</td>
</tr>
</tbody>
</table>

Figure 6.3 TKE vs. distance behind the 1st vehicle for different distances between vehicles in series
The volume-averaged TKE values are calculated for each of the case, under a mixing height of 3m and the result is presented in Table 6.1. The volume-averaged TKE value for a single passenger vehicle case is listed as a base case for comparison.

Table 6.1 Volume-averaged TKE for passenger vehicles travelling in series with different distances between them

<table>
<thead>
<tr>
<th>Distance between the vehicles (multiples of 4.5m)</th>
<th>Volume-averaged TKE (m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Passenger Vehicle: Base Case</td>
<td>1.62</td>
</tr>
<tr>
<td>1</td>
<td>2.16</td>
</tr>
<tr>
<td>1.5</td>
<td>2.16</td>
</tr>
<tr>
<td>2</td>
<td>2.16</td>
</tr>
<tr>
<td>3</td>
<td>2.17</td>
</tr>
<tr>
<td>5</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Comparing the single passenger vehicle case to two passenger vehicles cases, it can be seen that the volume averaged-TKE values are not simple multiples of the vehicle numbers, since the roughness of the ground surface of the road acts as a source of TKE regardless of the presence of a vehicle. The relationship between the number of vehicles and the average TKE is to be discussed in detail in section 6.3.2.

Considering the volume-averaged TKE values for the two-vehicle cases with different distance between them, the volume-averaged TKE values remain constant regardless of the distance between the two vehicles. This means that the TKE values are linearly superimposed when the second vehicle travels into the TKE wake region created by the first vehicle, and there are no other interactions that would further change the value of the average TKE.

Note that the volume-averaged TKE value for 5BL-apart case is lower than the other cases. This is because the second vehicle is located very far behind the first vehicle; thus a significant portion of the TKE wake behind the second vehicle is located outside the computational domain, resulting in lower average TKE value.
6.3.1.2 Vehicles Travelling Side-by-side

TKE generation was simulated for two passenger vehicles travelling next to each other at various distances apart. Figure 6.4 shows the TKE value plotted along a line that runs behind the vehicle through the center of one of the vehicles.

From Figure 6.4, it can be concluded that there is little impact on the TKE behind one of the vehicles, even if there is another vehicle travelling next to it. The same can also be said from the TKE contour shown in Figure 6.5. TKE wake regions do not extend far in the lateral direction; as a result, one vehicle’s wake region has very little impact on another vehicle’s.

![TKE vs. Distance behind vehicle: Side-by-Side Passenger Vehicles](image)

Figure 6.4 TKE vs. distance behind a vehicle: for different distances between side-by-side vehicles
Then, the effect of having different types of vehicle in the adjacent lane was simulated. The distance between the two vehicles was fixed at 1 body width (1.8m); while the type of vehicle in the adjacent lane was changed from a passenger vehicle to a SUV and then to a truck.

The results are presented in Figure 6.6 and Figure 6.7.

Figure 6.6 shows the TKE value plotted along a line that runs through the center of the passenger vehicle as distance increases away from the vehicle, and the height at the top of the vehicle. It is clear that even for the case of a truck in the adjacent lane, there is not a significant change in the TKE wake region behind a passenger vehicle.
Figure 6.6 TKE vs. distance behind a passenger vehicle: for different types of vehicle in the adjacent lane at 1 body-width apart

As can be seen on the TKE contour in Figure 6.7, the TKE wake region does not extend very far in the lateral direction, so the side-by-side interaction is not significant even when there is a truck in the adjacent lane.

Figure 6.7 TKE contour on YZ-plane for one passenger vehicle and one truck travelling in adjacent lanes
6.3.1.3 Vehicles Travelling in Opposite Directions

This section analyzes the TKE production when vehicles are travelling in the opposite directions.

Figure 6.8 compares the two cases when the distance between the two passenger vehicles is 1.5 times the body width; one case is when the two vehicles are travelling in the same direction and the other case is when they are traveling in the opposite directions. It is clear from Figure 6.8 that there is not a significant difference between the two cases being compared. It has been determined in section 6.3.1.2 that the horizontal interaction between the vehicles is small when they are moving in the same direction; the same can be said for the vehicles moving in the opposite directions.

Figure 6.8 TKE vs. distance behind one of the two passenger vehicles travelling at 28m/s in the same or in the opposite directions
Figure 6.9 compares TKE values plotted against the distance behind one of the two vehicles, when the other vehicle is travelling in the opposite direction in the next lane at various distances away. The initial TKE values are similar for all three cases. It is only after about 15m that there is a slight difference: when the vehicles are very close together only at 1 body-width apart, the resulting TKE is slightly higher in the far field compared to the cases when the vehicles are further apart at 1.5 or 2 body-widths apart.

To see how significant this difference is, the volume-averaged TKE was calculated for the cases with various separation distances, for both the same and the opposite travelling directions. Again, a mixing height of 3m was used.

From Table 6.2, it can be concluded that there is not a big difference in the volume-averaged TKE values when these vehicles are moving in the same direction or in the opposite directions, as the difference in volume-averaged TKE between the cases does not exceed 5%. This result confirms the earlier conclusion that there is a very little
horizontal interaction, regardless of the vehicles' travel direction, vehicle types, and the distance between them.

Table 6.2 Volume-averaged TKE for two passenger vehicles travelling in adjacent lanes

<table>
<thead>
<tr>
<th>Distance apart (multiples of 1.8m)</th>
<th>Volume-averaged TKE (m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travelling in the same direction</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.23</td>
</tr>
<tr>
<td>1.5</td>
<td>2.22</td>
</tr>
<tr>
<td>2</td>
<td>2.20</td>
</tr>
<tr>
<td>Travelling in the opposite directions</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.21</td>
</tr>
<tr>
<td>1.5</td>
<td>2.20</td>
</tr>
<tr>
<td>2</td>
<td>2.16</td>
</tr>
</tbody>
</table>

6.3.2 Effect of Number of Vehicles in the Domain

In this section, the effect of the number of vehicles in the domain, or traffic density, on the overall volume-average TKE was determined. The number of passenger vehicles was increased from 1 to 2, 4, 6, and 8 in the absence of trucks; and the number of trucks was increased from 1 to 2, and then to 3 in the absence of passenger vehicles. Since it has been found in the previous sections that the travel directions do not have a significant impact on the average TKE in the domain, the vehicles were all set to travel in the same direction.

The volume-averaged TKE under a mixing height of 3m has been plotted as a function of the number of passenger vehicles and number of trucks in the domain. The data was fitted using linear equations as shown in Figure 6.10.
The equations for the passenger vehicle and truck are:

\[
TKE_{\text{vol.avg.PV}} = 0.20 \times \text{(number of passenger vehicles)} + 1.59 \tag{6.1}
\]

\[
TKE_{\text{vol.avg.Truck}} = 1.21 \times \text{(number of trucks)} + 2.45 \tag{6.2}
\]

These two equations relate the volume-averaged TKE under a mixing height of 3m, on a 100m (x-direction) by 20m (y-direction) segment of the road, with increasing number of each type of vehicle. All of the vehicles are set to travel at 28m/s in the positive x-direction.

The slopes indicate the incremental change in the volume-averaged TKE with increasing number of each type of vehicle, and the y-intercept values represent RIT. Theoretically, the RIT values for the passenger vehicles and the trucks should be very similar, but the y-intercept values obtained for passenger vehicles and trucks from this study are different. This could be due to a possible limitation in the size of the computational domain, especially with the trucks because of their lengths. When there are multiple trucks in the
domain, a fraction of the TKE wake region behind the last truck happens to be located outside the domain, resulting in a lower TKE value. This could have affected the values of the slope and y-intercept of the equation.

6.3.3 Effect of Traffic Composition in the Domain

While the cases in section 6.3.2 treated different type of vehicles separately; this section analyzes the effect of traffic mix, or traffic composition, on the volume-averaged TKE in the domain. The number of trucks in the domain was increased from 0 to 3 while the number of passenger vehicle was decreased from 8 to 5, thus keeping the total number of vehicles constant at 8.

Figure 6.11 is the TKE contour of the case where there are 2 trucks in the domain. There is a zone of high TKE created behind the first truck, same as the case with a single truck. TKE decays down with the distance behind the first truck as expected, then increases to a certain extent, affected by the two passenger vehicles, and there is a zone of relatively low TKE before the second truck drives in. Behind the second truck, there is a zone of high TKE created.

Figure 6.11 TKE contour on XZ-plane for two trucks and multiple passenger vehicles
Not much can be said from the contour alone; therefore the volume-averaged TKE values are compared. Since there are trucks in addition to passenger vehicles, a mixing height of 4m was also considered as well as the usual 3m. The two results are plotted on the same axis as shown in Figure 6.12.

![Volume-averaged TKE for Different Traffic Compositions](image)

Figure 6.12 Volume-averaged TKE for different traffic compositions in the domain under mixing height of 3m and 4m

The two graphs for different mixing heights show similar results, with only a small difference in values. Mixing height of 4m was able to capture some of the high-rising TKE wake zones, resulting in a higher average TKE values than that under a mixing height of 3m. These two graphs both show that there is a large increase in volume-averaged TKE when the first truck is added, however, additional increments in the number of trucks do not cause as a large increase in TKE as the first truck does.

To predict the change in the volume-averaged TKE with a change in traffic composition, the equations from section 6.3.2 relating the number of vehicles to the volume-averaged TKE in the domain are used. Assuming independent contribution from the passenger...
vehicles and the trucks, the equations are simply superimposed. The y-intercept value for passenger vehicles and the y-intercept value for trucks are averaged, to represent the “average” RIT, and the slope for each type of vehicle was used.

The resulting equation is:

\[
TKE_{vol, avg} = (VIT_{passenger\ vehicle}) + (VIT_{truck}) + RIT
\]

\[
= 0.20(\text{number of PV}) + 1.21(\text{number of truck}) + \left(\frac{1.59 + 2.45}{2}\right) \\
= 0.20(\text{number of PV}) + 1.21(\text{number of truck}) + 2.02
\]

Using this equation, the volume-averaged TKE values are calculated for different traffic compositions, and the calculated values are compared to the simulated values in Figure 6.13.

![Volume-averaged TKE for Different Traffic Compositions: Simulated vs. Calculated](image)

Figure 6.13 Simulated vs. Calculated volume-averaged TKE for different traffic compositions in the domain under mixing height of 3m
Overall, the simulated values and the calculated values are reasonably close in values. For the case with 7 passenger vehicles and 1 truck, the calculated value is 9% lower than the simulated value, which could be due to an error introduced from using the average RIT value. For the case with 5 passenger vehicles and 3 trucks, the calculated TKE is about 16% higher than the simulated TKE. This difference could be due to, in addition to the error from the RIT value, the limit in the size of the computational domain. As the traffic density increases in the domain, some of the vehicles are located too far back in the domain, and the TKE regions created behind them are not fully captured in the calculation as they happen to be located outside the domain. This error could be reduced if a larger domain size is used.

Despite the difference, it seems that the independent contribution from each type of vehicles may be added together to yield a reasonable estimation of the overall volume-averaged TKE in the domain when there are different traffic compositions on road.

6.4 Conclusions and Implications

In this study, CFD tools were employed to simulate the TKE production from vehicles travelling in series and side-by-side in adjacent lanes both in the same direction and in the opposite directions; and the effects of traffic density and fleet composition on TKE have been modeled. Parameterizations were developed wherever applicable, and insights were provided as to which parameters are more important in estimating the volume-averaged TKE in the domain of interest. Findings from this study are listed below:

1. It was shown for the first time through simulation that the overall VIT from multiple vehicles travelling in series can be estimated by superimposing the VIT of each vehicle, without considering the distance between them while the distance is greater than one vehicle length. This finding is particularly significant since it enables a new approach to VIT simulations where the overall VIT is calculated as a function of number of vehicles, regardless of the distance between them.
2. Since the TKE wake does not extend very far horizontally, the interactions between vehicles travelling next to each other in adjacent lanes are not significant. This applies regardless of the directions of the traffic flow. Consequently, simulations of different traffic scenarios can be substantially simplified by treating two-way traffic as one-way traffic, which would result in less than 5% difference in the overall volume-averaged TKE.

3. For any single type of vehicles, the volume-averaged TKE in the mixing zone can be expressed as a linear function of the number of vehicles in the domain. The following equation can be used to relate the number of passenger vehicles or trucks to the volume-averaged TKE under a mixing height of 3m.

\[
\text{TKE}_{\text{vol.avg, PV}} = 0.20 \times (\text{number of passenger vehicles}) + 1.59
\]

\[
\text{TKE}_{\text{vol.avg, Truck}} = 1.21 \times (\text{number of trucks}) + 2.45
\]

4. With different types of vehicles in the domain however, the relationship between the volume-averaged TKE is no longer linear with an increase in the total number of vehicles. The contribution from each vehicle type needs to be treated separately, and the linear expression for each vehicle is summed up to yield the total volume-averaged TKE. For the traffic composition case of trucks and passenger vehicles, volume-averaged TKE was estimated by the following equation:

\[
\text{TKE}_{\text{vol.avg}} = \text{(VIT}_{\text{passenger vehicle}}) + \text{(VIT}_{\text{truck}}) + \text{RIT} \\
= 0.20(\text{number of PV}) + 1.21(\text{number of truck}) + 2.02
\]

The current study provides insights into what factors are important in estimating TKE in the domain of interest. Since the horizontal interactions between vehicles in adjacent lanes are insignificant and their VIT can be superimposed when they are travelling in series, the overall volume-averaged TKE can be estimated as a function of the number and the type of vehicles in the domain.
7 Conclusions and Recommendations

7.1 Conclusion
The aim of this study was to simulate the turbulence induced by moving vehicles under different conditions representing realistic highway conditions. The approach used was first to simulate turbulence around a single vehicle to determine which factors are important, then to validate the result by comparing with the results from other studies and field measurements, and then to move onto more complex cases to obtain useful insights and empirical parameterizations for different traffic conditions. The investigations in this study lead to the following conclusions:

1. Vehicle shapes and sizes have a substantial effect on the magnitude of TKE generated, and the decay characteristics. The decay of TKE with increasing distance behind the vehicle can be fitted using a power-law equation; the decay power law exponents obtained from this study are -0.34 for passenger vehicles, -0.36 for SUVs, and -0.94 for heavy-duty trucks. These decay exponents values compare reasonably well with previous studies and with field measurements.

2. Vehicle speeds have a direct impact on the volume-averaged TKE in the computational domain. The average TKE can be expressed as a linear equation in terms of vehicle velocity using the following equation within the computational domain used in this study:

\[ TKE_{vol.avg@3m} = 0.057(velocity) + 0.005 \]

3. Thermally induced turbulence and any buoyant effect due to hot exhaust or hot road surfaces are relatively small in magnitude, compared to the mechanically generated VIT. Unless the thermal effects are rigorously introduced as a change in atmospheric stability and resulting ambient wind, thermal induced turbulence is not significant on roadways.
4. Regardless of the direction, the impact of external winds on both the shape and location of the TKE wake region is significant. Perpendicular winds shift the location of the TKE wake region down the wind, and increasing wind speed results in higher TKE in the domain. Parallel to the traffic flow, the wind blowing from the front increases the magnitude of TKE generated behind the vehicle. On the other hand, the wind blowing from behind reduces the TKE right behind the vehicle by causing resistance in flow in the opposite direction, but increases the width of TKE wake region behind the vehicle. Consequently, the overall volume-averaged TKE increases in the presence of external wind from any direction.

5. Volume-averaged TKE generated by vehicles travelling in series may be estimated without considering the distance between them, while the distance is greater than one vehicle-length. This is because the TKE induced by the vehicles are linearly superimposed when a vehicle moves into the TKE wake region created by the previous vehicle.

6. Side-by-side interactions between two vehicles travelling in adjacent lanes at distance more than one vehicle width apart are not significant regardless of the traffic direction, since the TKE wake does not extend very far horizontally. Consequently, simulations of different traffic scenarios can be greatly simplified by treating two-way traffic as one-way traffic.

7. Considering a single type of vehicle only, the average TKE in the domain for different traffic density can be expressed as a function of the number of vehicles. The equations for the case with passenger vehicles and the case with trucks are:

\[
\text{TKE}_{\text{vol,avg,PV}} = 0.20 \text{ (number of passenger vehicles)} + 1.59
\]

\[
\text{TKE}_{\text{vol,avg,Truck}} = 1.21 \text{ (number of trucks)} + 2.45
\]
8. The equation relating TKE to the traffic density may be modified to account for the change in the traffic composition, by superimposing the linear expressions describing the contribution from each vehicle.

\[
TKE_{vol.avg} = (VIT_{passenger\ vehicle}) + (VIT_{truck}) + RIT \\
= 0.20\ (number\ of\ PV) + 1.21\ (number\ of\ truck) + 2.02
\]

Obtaining empirical parameterizations for different traffic densities and fleet compositions may be made easier with the results from this study. Such insights from this study could also allow some savings in the computational expense while providing increased flexibilities in incorporating various traffic scenarios into pollutant dispersion modeling.
7.2 **Recommendations on Future Research**

To better understand the magnitude, generation and decay characteristics of turbulence on roadways, the following suggestions should be considered in future research:

1. The current study was not able to reproduce the horizontal decay of TKE that was observed in field measurements. Processes that would enhance the horizontal distribution of TKE wake region should be investigated and included, in which case it would be necessary to increase the domain size in the horizontal direction.

2. For some of the high traffic density cases, especially with multiple trucks, it would be required to increase the domain size behind the vehicles to capture the entire TKE wake region behind the last vehicle.

3. Use of symmetric planes may be adopted where possible to save computational expense.

4. The effect of different wind velocities and angles on the TKE generation needs to be further investigated. Also, wind-direction-frequency-weighted approach used in pollutant dispersion studies may be taken to simulate TKE on real roadways. User-defined wall functions can be used to describe the fully developed vertical profile of inlet wind, instead of a simple profile.

5. Although the majority of CFD studies have been using the closure parameter values given in FLUENT code, it may be worthwhile to investigate in the costs and benefits of modifying the closure empirical parameters used in k-ε turbulence model. Its potential importance was highlighted in this study but rigorous investigation was beyond the scope of this study and was left for future study.
8 References


9 Appendices

Appendix A: Different k-epsilon model constants

Appendix B: ICEM-CFD Mesh Setup Procedure

Appendix C: FLUENT Simulation Setup Procedure

Appendix D: CFD-Post Procedure
Appendix A: Different k-epsilon model constants

Although most studies adopt the values in FLUENT codes (Kim et al. 2001; Wang et al. 2006; Di Sabatino et al. 2007; Yassin et al. 2009), some studies have suggested these constants be altered to better represent the values that they observed.

Wang and Zhang modified the value of $C_{\mu}$ and $\sigma_\varepsilon$ their study, following the work of Richards and Hoxey (Richards and Hoxey 1993; Wang and Zhang 2009). Another study altered the dispersive parameters $\sigma_k$ and $\sigma_\varepsilon$, while keeping the other constants the same as the values used in FLUENT code (Solazzo et al. 2008). The effect of these two different sets of model constants is compared with the result from the base case used in this model. These results are not rigorously investigated in this study but the purpose is to highlight the possible importance.

Table A.1 lists the different values of constants used in each study.

Table A.1. Different model constants used in each study

<table>
<thead>
<tr>
<th></th>
<th>$C_{\mu}$</th>
<th>$C_{1\varepsilon}$</th>
<th>$C_{2\varepsilon}$</th>
<th>$C_{3\varepsilon}$</th>
<th>$\sigma_k$</th>
<th>$\sigma_\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>0.09</td>
<td>1.44</td>
<td>1.92</td>
<td>1.44</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Wang and Zhang</td>
<td>0.013</td>
<td>1.44</td>
<td>1.92</td>
<td>1.44</td>
<td>1.0</td>
<td>3.22</td>
</tr>
<tr>
<td>Solazzo et al.</td>
<td>0.09</td>
<td>1.44</td>
<td>1.92</td>
<td>-</td>
<td>0.53</td>
<td>0.55</td>
</tr>
</tbody>
</table>

The resulting volume-averaged TKE under the mixing height of 3 m, and the percent difference are listed in Table A.2 for comparison.

Table A.2. Volume-averaged TKE and % difference for different studies

<table>
<thead>
<tr>
<th></th>
<th>Volume-averaged TKE ($m^2/s^2$)</th>
<th>% difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>1.65</td>
<td>-</td>
</tr>
<tr>
<td>Wang and Zhang</td>
<td>2.45</td>
<td>+48</td>
</tr>
<tr>
<td>Solazzo et al.</td>
<td>1.51</td>
<td>-8.5</td>
</tr>
</tbody>
</table>
The differences in TKE contours are shown in Figure A.1.

The modification by Wang et al. resulted in a rather remarkable change of 48% increase in the volume-averaged TKE in the domain, compared to the base case. This change also had an impact on the shape of TKE contour: the TKE zone extends further back while maintaining its high value. Also, right behind the vehicle near the tailpipe, there is a higher TKE region.

The modification by Solazzo et al. resulted in 8.5% lower volume-averaged TKE compared to this study. A significant difference was not seen in the shape of the TKE contours.

Although the differences are presented, these results are not investigated any further in this work. The purpose was to highlight the differences, and to suggest the need for future investigations in this area. One should be cautious to maintain consistency and closure of the equations, as these constants are not independent of each other.
Appendix B: ICEM-CFD Mesh Setup Procedure

1. Load ICEM

2. Create project: *.prj

3. Import geometry created from other CAD software or create a geometry file: *.tin

4. Modify geometry by:

   Creating point, line, surface, and volume

   Transforming geometry by using translate, rotate, mirror, and scale options

5. Repair geometry by building Diagnostic Topology

   Match surfaces

   Fill gaps
Close/remove holes

6. Delete unattached curves and points to clean up unwanted curves/points

7. Create density to refine mesh size around the vehicle

   Set 8, 1.2, 10 for size, ratio and width for the inner mesh density

   Set 16, 1.3, 10 for size, ratio, and width for the outer mesh density

   Size specifies the local maximum size within the density region

   Ratio specifies the growth ratio away from the density region

   Width specifies the number of layers of the specified element size away from the density region that has a constant expansion ratio

8. Create mesh

   1) Global Mesh setup: Set Global Element Scale Factor to 1 (used for scaling the entire mesh size up or down) and Max Element size of 0 (allows the implementation of the Automatic Sizing feature, in which the largest surface mesh size becomes the global max element size)

   2) Surface Mesh setup: Select Quad-dominant mesh type (quad-dominant but allows for several transitional triangles: useful in meshing complicated surfaces where a pure quad mesh may produce poor mesh quality) and Patch-dependent mesh method (gives the best quad dominant quality while capturing surface details)

   3) Volume Mesh setup: Select Tetra/mixed mesh type, Robust (Octree) mesh method (ensures refinement of the mesh where necessary, but maintains larger elements where possible, allowing faster computation), and allow 5 iterations with minimum quality of 0.4 to smooth mesh

   4) Part Mesh setup: define the max size element to each part in the domain
0.4 for exhaust pipe, 4 for vehicle surfaces, 60 for ground, 80 for the surrounding walls and top surface (units in inch)

5) Compute mesh

9. Edit mesh

1) Run Check Mesh to locate problem elements and errors

2) Smooth Mesh Globally: Improve the quality of the mesh elements by smoothing iterations up to a certain quality level. The criterion used is mesh quality (Histogram shows how many elements are at each quality bin)

3) Re-run until all meshes are above 0.35-0.4

10. Save geometry and project

11. Output to solver

1) Select Solver: FLUENT_V6

2) Select Common Structural Solver: ANSYS

3) Write input: *.msh
Appendix C: FLUENT Simulation Setup Procedure

1. Start FLUENT

2. Open a new case: *.cas

3. Import the mesh file created from ICEM

4. General
   
   Scale: convert units to match the mesh unit to the CFD domain unit

   Check: check the mesh to verify the validity of the mesh

   Choose Pressure-based solver type, absolute velocity formulation, and steady state solver

   Under Mesh menu, perform Reorder Domain using Reverse Cuthill-McKee method to reduce bandwidth usage

5. Models

   Multiphase: Off

   Energy: On

   Viscous model: Choose Standard k-epsilon (2eqn) with standard wall functions

   Enable species transport model with inert mixture, and select air and CO₂ as mixture materials to be included in simulation

   Enable inlet diffusion and diffusion energy source options

6. Materials

   Edit mixture, fluid, solid and inert materials

7. Cell Zone Conditions

   Choose moving reference frame at specified velocity for the cell zone air
8. Boundary conditions

Vehicles: Moving walls with absolute translational velocity, surface roughness height of 0.0015m, roughness constant 0.5, no slip condition, specified surface temperature

Ground: Stationary wall, surface roughness height of 0.01m, roughness constant 0.5, no slip condition, specified surface temperature

Tailpipe: Velocity inlet with specified velocity, specified temperature, species mole fraction of 1 for tracer species CO₂

Lateral side walls: Symmetry

Front wall: Velocity inlet with velocity of zero

Back wall: Outflow with flow rate weighting of 1

Top: Symmetry

9. Solution Methods

Scheme: SIMPLE

Spatial discretization:

Gradient- Least Squares Cell Based

Pressure- Standard

Momentum- Second Order Upwind

Turbulent Kinetic Energy- Second Order Upwind

Turbulent Dissipation Rate- Second Order Upwind

CO₂-Second Order Upwind

Energy- Second Order Upwind
10. Solution Controls Under-Relaxation Factors

Due the nonlinearity of the equation set being solved by FLUENT, it is necessary to control the change in the variable. This is typically achieved by under-relaxation of variables, also referred to as explicit relaxation. This reduces the change of the variable produced by multiplying the change by the under-relaxation factor when the variables are updated for every iteration. The factors used are:

- Pressure: 0.3
- Density: 1
- Body Forces: 1
- Momentum: 0.7
- Turbulent Kinetic Energy: 0.8
- Turbulent Dissipation Rate: 0.8
- Turbulent Viscosity: 1
- CO₂: 1
- Energy: 1

11. Monitors

Residuals: Conversion criteria are $10^{-3}$ for continuity, velocity components, k, epsilon, and species concentration and $10^{-6}$ for energy. Print and plot residuals on console.

12. Solution Initialization

Compute from vehicle, with absolute reference frame, specify initial values

13. Save Case: *.cas

14. Run Calculation
1) Check case for compliance in the mesh, models, boundary and cell zone conditions, material properties and solver choices

2) Run calculation for 5 iterations for a check

3) Run calculation until convergence is achieved

15. Save case and data file: *.cas and *.dat
Appendix D: CFD-Post Procedure

1. Start CFD-Post

2. Open FLUENT data file and save a new state: *.cst

4. To plot a chart
   1) Using locations menu, create a line along which the data will be collected
   2) Create a chart using Chart menu
   3) In the data series menu, select the line created
   4) Select X axis and Y axis variable
   5) Adjust data range
   6) Export data as a comma separated values file (*.csv) compatible with excel

5. To obtain a contour
   1) Using locations menu, create a plane
   2) Create a contour using Contour menu
   3) Under locations menu, select the plane created
   4) Select variable, adjust range and select color scale

6. To obtain a volume-averaged value
   1) Using locations menu, create a volume
      i) Select the domains for which the volume will be created
      ii) Choose isovolume method
      iii) Select the height Z as the variable and the mode as Below Value
   2) On Calculators tab, under function calculator menu, choose the volumeAvg function and select the location and variable