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Real-world exhaust temperature profiles of on-road heavy-duty diesel vehicles equipped with selective catalytic reduction

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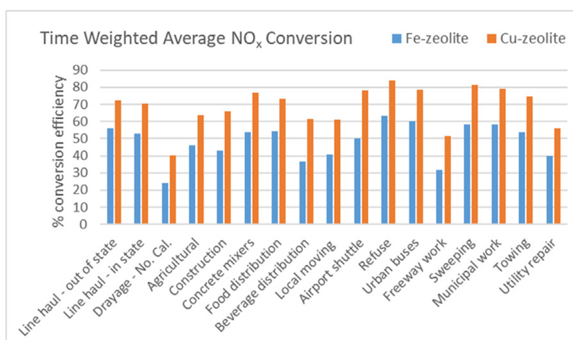
HIGHLIGHTS

- Real-world exhaust temperature data of 90 heavy-duty diesel vehicles (HDDVs) show high variability by vocational use.
- Exhaust temperature at selective catalytic reduction (SCR) inlet is found to be lower than 200 °C for 11-70% of the time.
- Copper zeolite SCR would be more effective at controlling NO_x emissions from HDDVs than Iron zeolite SCR.
- NO_x emissions from HDDVs equipped with SCR could be higher than expected for a significant part of their operations.

GRAPHICAL ABSTRACT



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ABSTRACT

On-road heavy-duty diesel vehicles are a major contributor of oxides of nitrogen (NO_x) emissions. In the US, many heavy-duty diesel vehicles employ selective catalytic reduction (SCR) technology to meet the 2010 emission standard for NO_x. Typically, SCR needs to be at least 200 °C before a significant level of NO_x reduction is achieved. However, this SCR temperature requirement may not be met under some real-world operating conditions, such as during cold starts, long idling, or low speed/low engine load driving activities. The frequency of vehicle operation with low SCR temperature varies partly by the vehicle's vocational use. In this study, detailed vehicle and engine activity data were collected from 90 heavy-duty vehicles involved in a range of vocations, including line haul, drayage, construction, agricultural, food distribution, beverage distribution, refuse, public work, and utility repair. The data were used to create real-world SCR temperature and engine load profiles and identify the fraction of vehicle operating time that SCR may not be as effective for NO_x control. It is found that the vehicles participated in this study operate with SCR temperature lower than 200 °C for 11–70% of the time depending on their vocation type.

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This implies that real-world NO_x control efficiency could deviate from the control efficiency observed during engine certification.

1. Introduction

On-road heavy-duty diesel vehicles are a major source of nitrogen oxides (NO_x) emissions in the United States (US), accounting for about 16%–18% of total NO_x emission inventory from all sources in the past decade (US Environmental Protection Agency, 2016). To help reduce NO_x emissions from this source, the US Environmental Protection Agency (EPA) and the California Air Resources Board (ARB) have adopted new diesel engine exhaust emissions standards that require model year (MY) 2010 and later on-road heavy-duty diesel vehicles to meet a NO_x emission standard of 0.20 g/bhp-hr over the transient Federal Test Procedure (FTP) engine dynamometer cycle. This is a 90% reduction from the previous standard for MY 2007–2009 engines. In addition, emissions from the engines are required to be within not-to-exceed (NTE) limits while operating within a specific engine operating region defined by a series of engine torque and speed conditions (US Environmental Protection Agency, 2004). This is intended to demonstrate in-use compliance under a wide range of driving conditions with a particular focus on highway driving.

Heavy-duty diesel engines in the US market have in most cases been using advanced engine exhaust aftertreatment, specifically selective catalytic reduction (SCR), to meet the 2010 NO_x emission standard (Jääskeläinen and Majewski, 2016). In SCR, NO_x is converted into nitrogen and water by the reaction with ammonia over a special catalyst. Typically, the exhaust gas temperature at SCR inlet (referred to as SCR temperature hereinafter) needs to be at least 200 °C for a significant level of NO_x conversion to occur (Slimarik et al., 2014; Cavataio et al., 2007). Heavy-duty diesel engines tested on the FTP cycle generally produce SCR temperature between 250 and 350 °C during the majority of the cycle (DieselNet, 2017). In addition, the NTE NO_x emission limits do not apply when the SCR temperature is lower than 250 °C (US Environmental Protection Agency, 2004). Thus, SCR has been widely used to meet the 2010 NO_x emission standard and achieve the in-use compliance.

However, a number of researchers have found that real-world NO_x emissions from SCR-equipped heavy-duty diesel vehicles can vary significantly, depending on the operating profile of a vehicle (Miller et al., 2013; Kotz et al., 2017). While SCR systems can generally provide good NO_x conversion efficiencies under highway driving conditions where engine load and SCR temperature are high, researchers have observed higher NO_x emissions under conditions where engine load and SCR temperature are relatively low such as during cold starts, long idling, and low speed driving (Misra et al., 2013; Thiruvengadam et al., 2015; Misra et al., 2016; Yoon et al., 2016; Carder et al., 2014). Remote sensing studies have also found SCR-equipped heavy-duty diesel trucks at weight scales and at ports to have high NO_x emissions when operating under these conditions (Bishop et al., 2012, 2013; Dallmann et al., 2011).

The operating conditions under which today's SCR-equipped heavy-duty diesel vehicles emit higher real-world NO_x emissions are associated with low SCR temperature (Misra et al., 2013). The frequency of these operating conditions, and thus the SCR temperature profile of a vehicle, could vary greatly by vocational use. For example, one would expect a drayage truck to have more idling time than a line haul truck. However, there is very little public data on in-use activity of heavy-duty diesel vehicles. Most of the data in literature do not differentiate vehicles by vocation (Boriboonsomsin et al., 2012). On the other hand, the data that do differentiate vehicles by vocation only contain vehicle activity data but have no engine activity data (Battelle, 1999; Jack Faucett Associates, 2002). In recent work, both vehicle and engine activity data were collected from 125 conventional diesel and diesel hybrid electric trucks in four vocations—beverage delivery, parcel delivery, linen delivery, and food distribution—but only a small fraction of these trucks were equipped with SCR (Thornton et al., 2015).

Therefore, it is important to collect new vehicle and engine activity data from today's SCR-equipped heavy-duty diesel vehicles in a variety of vocations, and then examine their real-world SCR temperature profiles to identify the fraction of vehicle operation with low SCR temperatures where SCR may not be as effective for NO_x control. This will lead to a better understanding of the potential impact of vocation-specific activity patterns on the effectiveness of current implementations of SCR in vehicles meeting the 2010 NO_x emission standard and on NO_x emission inventories of these vehicles. In this article, we describe the collection of real-world vehicle and engine activity data from a large number of heavy-duty diesel vehicles in California in a variety of vocations, and examine their SCR temperature profiles by vocation.

2. Material and methods

A large-scale data collection program was conducted in which vehicle and engine activity data were collected from 90 heavy-duty vehicles in California that make up 19 different groups defined by a combination of vocational use and geographic region. These include line haul, drayage, construction, food distribution, refuse, and utility repair, among others. Almost all of the vehicles have engine MY 2010 or newer and are equipped with SCR. The data were collected using advanced data loggers that recorded vehicle speed, position, and >170 engine parameters at the frequency of 1 Hz. The data collection effort spanned from November 2014 to September 2016, but was intermittent depending on when the participating fleets were successfully recruited and when the vehicles and data loggers were available. For each vehicle, the data were collected for a minimum period of one month with many vehicles having data collected for several months. Details of the data loggers and vehicles are described below.

2.1. Data loggers

Since the late 1990s, GPS data loggers have increasingly been used in vehicle activity studies as their cost has become lower and their accuracy continued to improve. In GPS-based vehicle activity studies, GPS data loggers are instrumented on vehicles to record the vehicles' position (latitude, longitude, and altitude), speed, and the associated timestamp. These data are recorded at high frequency, typically ranging from 0.5 to 10 Hz. Since a GPS data logger can be powered by the vehicle, either through the cigarette lighter or the on-board diagnostic (OBD) port, it can record vehicle activity data for a long period of time (several months). Recently, on-board engine control unit[1] (ECU) data loggers have emerged as a useful tool for vehicle and engine performance studies. Once connected to the vehicle's Controller Area Network (CAN) bus through the OBD port (for most light-duty vehicles) or the J1939 port (for most heavy-duty vehicles), an ECU data logger can record engine parameters such as wheel speed, engine speed, fuel rate, etc. at a high frequency.[2] Since the data logger is powered through

[1] Sometimes also known as electronic control unit.

[2] The frequency of the logged data for each parameter depends on the broadcasting rate of the respective parameter on the CAN bus. If the data logger requests data at a higher rate than broadcast on the CAN bus, the data will be interpolated to the logger-requested frequency.

Fig. 1. Data logger used in this research.

this connection, it can record vehicle and engine activity data for a long period of time and either store the data in local memory or transmit the data to a remote server.

The research team surveyed the market for a combined GPS and ECU data logger that would be capable of collecting both types of data simultaneously. Following this survey, the J1939 Mini Logger™ (HEM Data, 2017) was selected on the basis of capabilities and cost. It incorporates a CAN reader capable of acquiring CAN bus data in SAE J1939 standard and is equipped with on-board data storage. A GPS receiver and antenna as well as communication modems (cellular and/or WiFi) can be added as options. The data logger can be configured to acquire any number of J1939 parameters on a vehicle's J1939 network. In this data collection effort, the research team used two versions of the J1939 Mini Logger™. One was equipped with a WiFi modem, which was used mostly in the initial stages of the data collection when a version with cellular modem was not yet available. The WiFi version was also used on trucks whose owners requested not to be tracked in real time. Although the WiFi-capable data loggers can transfer recorded data to the data server over a WiFi connection, we did not utilize that feature as there was often not a free WiFi connection available at the fleet locations. These data loggers were exclusively used to store the recorded data on-board for later download after they were retrieved. The other version of J1939 Mini Logger™ that was used in this research was equipped with a cellular modem and was set up to transfer recorded data over a cellular network to a data server periodically during the data collection period. Fig. 1 shows the J1939 Mini Logger™ used in this research.

2.2. Vehicle samples

The research team targeted data from 100 vehicles, and designed a vehicle sample matrix that balanced between the number of vocations and the number of vehicles in each vocation. The targeted vehicles are from commonly found vocations that, collectively, represent the majority of the NO_x emission inventory of heavy-duty diesel vehicles in the state of California (Boriboonsomsin et al., 2017). Due to various reasons, such as not being able to recruit vehicles (or a specific number of vehicles) in some groups, lost data loggers, etc., the final dataset includes 90 vehicle samples in 19 groups as listed in Table 1. The third column in Table 1 shows the number of fleets from which the vehicle samples in each group were recruited, and the fourth column shows whether each of the fleets is located in the northern or southern part of California. There is a good balance between vehicle samples from both regions of the state when considering the overall vehicle samples as a whole, although not every vehicle group includes vehicle samples from both regions of the state.

All of the 90 vehicles are either commercial class 7 (GVWR 26,001–33,000 lbs) or class 8 (GVWR > 33,000 lbs). All the vehicles run on conventional diesel engines except the six urban buses (diesel hybrid electric) and the five express buses (compressed natural gas). Most of the vehicles have engine MY 2010 or newer and are equipped with SCR. Vehicles for which SCR temperature data was not obtained, either because they had no SCR or because the temperature data was not available, are asterisked in the engine ID column. For instance, no SCR temperature data was available for any of the vehicles in Group 2b (Drayage–Southern California). This is because one of them is MY 2008 and not equipped with SCR. While the other four vehicles have MY 2012 MACK MP8-415C engine with SCR, it was discovered after the data collection had been completed that MACK is one of a few engine manufacturers that use the J1962 connector and J1979 messages on ISO15765-4 CAN protocol for mandatory ECU information broadcasting instead of the more widely-used J1939 connector and J1939 messages on J1939 CAN protocol. As the data loggers used for the data collection effort were not configured to support the ISO15765-4 CAN protocol, data of certain ECU parameters including SCR temperature were not obtained from these vehicles.

3. Theory/calculation

SCR reduces NO_x in the exhaust stream by converting NO_x to nitrogen gas (N_2) and water (H_2O) through catalytic reactions with a reductant supplied as ammonia or urea. Most heavy-duty diesel engines in the US have relied on urea-based SCR technology to comply with the 2010 NO_x emission standard (Jääskeläinen and Majewski, 2016). In urea-based SCR systems, a urea solution or diesel exhaust fluid (DEF) is injected into the hot exhaust gas and then passively decomposed to ammonia and carbon dioxide by the heat of the exhaust gas. In modern applications, the urea injection and dosing strategy is controlled electronically based on several parameters such as NO_x concentration upstream of the SCR, SCR temperature, engine load, etc. in order to maximize the NO_x conversion efficiency while minimizing the amount of urea solution used and avoiding practical limitations like excessive urea solid deposits or nitrate formation on the SCR catalyst. For instance, some SCR systems only inject the urea solution once the SCR temperature reaches 190 °C with the engine torque of at least 20% (Slimarik et al., 2014) to avoid incomplete decomposition of the urea solution under low temperatures.

Table 1
Information about vehicle samples in each group.

Vehicle group					Engine				
ID	Name	No. of flt.	Fleet location[a]	No. of veh.	ID	Make	Model	Model year	HP
1a	Line haul-out of state	1	North	3	18	Cummins	ISX15 450	2012	450
					19	Cummins	ISX15 450	2013	450
					20	Cummins	ISX15 450	2014	450
1b	Line haul-in state	1	South	3	114	Detroit Diesel	DD15AT	2015	505
					116	Detroit Diesel	DD13	2015	500
					117	Detroit Diesel	DD13	2015	500
2a	Drayage-northern California	1	North	1	99	Cummins	ISX15 450	2012	450
2b	Drayage-southern California	1	South	5	73[b]	MACK	MP8-415C	2012	415
					75[b]	MACK	MP8-415C	2012	415
					76[b]	MACK	MP8-415C	2012	415
					78[b]	MACK	MP8-415C	2012	415
					79[b]	Detroit Diesel	Series 60	2008	n/a
3	Agricultural	1	South	8	85[b]	Paccar	MX	2010/11	n/a
					86[b]	Paccar	MX	2010/11	n/a
					87[b]	Paccar	MX	2012	455
					88	Paccar	MX-13	2014	455
					89[b]	Mercedez-Benz (Detroit Diesel)	OM 460 LA CID 781	2009	450
					90[b]	Mercedez-Benz (Detroit Diesel)	OM 460 LA CID 781	2009	450
					91	Paccar	MX-13	2014	455
					92	Paccar	MX-13	2014	455
4a	Construction	3	Both	6	1	Cummins	ISB6.7 240	n/a	240
					55	Cummins	ISL 300	n/a	300
					56	Cummins	ISL 300	n/a	300
					80	Cummins	ISX15 485	2011	485
					81	Cummins	ISX15 550	2015	550
					82	Cummins	ISX15 550	2015	550
4b	Concrete mixers	2	Both	5	83	Cummins	ISL9 350	n/a	350
					84	Cummins	ISL9 350	n/a	350
					111	Cummins	ISL9 370	2013	370
					112	Cummins	ISL9 370	2013	370
					113	Cummins	ISL9 370	2013	370
5a	Food distribution	1	South	5	50	Detroit Diesel	DD13	2013	500
					51	Detroit Diesel	DD13	2013	500
					52	Detroit Diesel	DD13	2013	500
					53	Detroit Diesel	DD13	2013	500
					54	Detroit Diesel	DD13	2013	500
5b	Beverage distribution	1	South	6	9	Paccar	PX-9	2003	n/a
					10	Cummins	ISX11.9 370	2011	370
					13	Paccar	PX-9	2013	n/a
					14	Paccar	PX-8	2012	n/a
					16	Paccar	PX-9	2013	n/a
					17	Paccar	PX-8	2012	n/a
5c	Local moving	1	South	1	49	Navistar	A410	2013	410
6	Airport shuttle	1	North	5	57	Cummins	ISL	2012	n/a
					58	Cummins	ISL	2012	n/a
					59	Cummins	ISL	2012	n/a
					60	Cummins	ISL	2012	n/a
					61	Cummins	ISL	2012	n/a
7	Refuse	1	North	6	24	Cummins	ISL	2010	380
					25	Cummins	ISL	2010	345
					26	Unknown	n/a	n/a	n/a
					102	Cummins	ISL	n/a	n/a
					103	Cummins	ISL	2010	380
					104	Cummins	ISL9	2013	345
8a	Urban buses	1	North	6	68	n/a	n/a	n/a	n/a
					69	n/a	n/a	n/a	n/a
					70	n/a	n/a	n/a	n/a
					108	n/a	n/a	n/a	n/a
					109	n/a	n/a	n/a	n/a
					110	n/a	n/a	n/a	n/a
8b	Express buses	1	South	5	93[b]	Cummins	ISL G280	2013	280
					94[b]	Cummins	ISL G280	2013	280
					95[b]	Cummins	ISL G280	2013	280
					96[b]	Cummins	ISL G280	2013	280
					97[b]	Cummins	ISL G280	2013	280
9a	Freeway work	1	Both	5	3	Cummins	ISB6.7 260	2012	260
					4	Cummins	ISB6.7 260	2012	260
					37	Cummins	ISB6.7 260	2012	260
					38	Cummins	ISB6.7 260	2012	260
					62	Cummins	ISB6.7 260	2012	260
9b	Sweeping	1	Both	5	40	Cummins	ISB6.7 280	2012	280
					41	Cummins	ISB6.7 280	2012	280
					42	Cummins	ISB6.7 280	2013	280

Table 1 (*continued*)

Vehicle group					Engine				
ID	Name	No. of flt.	Fleet location[a]	No. of veh.	ID	Make	Model	Model year	HP
					43	Cummins	ISB6.7 280	2012	280
					44	Cummins	ISB6.7 280	2012	280
9c	Municipal work	1	South	3	5	Detroit Diesel	DD13 12.8	2010	500
					6	Cummins	ISB6.7 240	2010	240
					7	Cummins	ISB6.7 240	2010	240
9d	Towing	2	Both	7	45	Cummins	ISX15 550	2012	550
					46	Cummins	ISX15 525	2014	525
					47	Cummins	ISX15 550	2014	550
					48	Paccar	PX-8	n/a	n/a
					105	Cummins	ISB6.7 260	2014	260
					106	Cummins	ISB6.7 280	2013	280
					107	Cummins	ISB6.7 281	2014	280
10	Utility repair	1	North	5	63	Detroit Diesel	DD13	2012	500
					64	Detroit Diesel	DD13	2012	500
					65	Detroit Diesel	DD13	2012	500
					66	Detroit Diesel	DD13	2012	500
					67	Detroit Diesel	DD13	2012	500
	Total	24		90					

[a] North = Northern California; South = Southern California.
[b] No SCR temperature data.

SCR requires adequate temperatures for the NO_x conversion to take place efficiently. While the term SCR temperature in this article is referred to the exhaust gas temperature at SCR inlet, it should be noted that SCR catalyst has a thermal mass resulting in a delayed catalyst temperature profile when compared to the exhaust gas temperature at SCR inlet. This can result in thermal conditions conducive to high NO_x conversion efficiency after the exhaust gas temperature at SCR inlet drops below a certain threshold. The same thermal lag effect applies in an opposite manner when heating up the SCR. The NO_x conversion efficiency also depends on the type of catalyst used. Zeolite SCR catalysts in combination with Copper (Cu) or Iron (Fe) are the most commonly used in heavy-duty diesel engines for on-road applications (Guan et al., 2014). Fig. 2 shows the NO_x conversion efficiency curves of a Fe-zeolite SCR catalyst and a Cu-zeolite SCR catalyst that have gone through hydrothermal aging equivalent to 120,000 miles of vehicle use (Cavataio et al., 2007). According to the figure, Cu-Zeolite SCR achieves significantly higher levels of NO_x conversion than Fe-Zeolite SCR at temperatures lower than 360 °C while Fe-Zeolite SCR performs better at temperatures higher than 360 °C. Both SCR catalysts perform poorly at low temperatures where about 77% NO_x conversion is achieved at 200 °C in the case of Cu-Zeolite SCR and only 27% in the case of Fe-Zeolite SCR.

Under real-world operations of heavy-duty diesel vehicles, there are times when SCR temperatures may be lower than 200 °C, such as right after engine start (cold start) and during low engine load operations experienced when the engine is idling or when the vehicle is moving slowly on flat terrain. As an example, Fig. 3 shows a vehicle speed profile (blue line) and the corresponding SCR temperature profile (red line) of a heavy-duty diesel vehicle during a trip. The green horizontal line represents a SCR temperature of 200 °C. As seen in the figure, there are multiple instances when the SCR temperature drops below 200 °C. This includes at the beginning of the trip where it takes about 30 min for the SCR temperature to climb up to above 200 °C. Also, as marked in the figure, there is a long period of idling (about 30 min) where the SCR temperature drops from 350 °C to around 120 °C. In addition, a sustained period of low engine load operation where the vehicle creeps mostly below 10 mph also causes a sharp drop in the SCR temperature from 400 °C to 200 °C. The frequency of engine starts (especially after a long soak period), long idling, and low engine load operations—which contribute to vehicles having low SCR temperatures—depends in large part on their vocational use. For instance, vehicles in line haul application would operate mostly at highway speeds, and thus would likely maintain high engine loads for most of their operation. On the other hand, vehicles in drayage application would operate with frequent stops and long idles, and thus would often experience low engine loads.

4. Results and discussion

4.1. SCR temperature and engine load profiles by vocation

The results of SCR temperature and engine load profiles are presented in this section in the form of frequency distribution and cumulative frequency distribution. These results are based on aggregated data from all vehicle samples that provide usable data throughout the entire data collection period of each vehicle sample. For conciseness of this article, the plots of SCR temperature distributions in Fig. 4 and engine load distributions in Fig. 5 are presented for only a subset of vocations in which the vehicle samples have large engines (with rated horsepower > 400). These include line haul–out of state, line haul–in state, drayage–Northern California, food distribution, and utility repair. Note that line haul–out of state trucks travel outside of California while line haul–in state trucks only service locations within California.

Fig. 4(a) and (b) show the SCR temperature profiles for vehicles in the same vocation (line haul) that use engines from different manufactures. The line haul–out of state trucks in Fig. 4(a) use MY 2012–2014

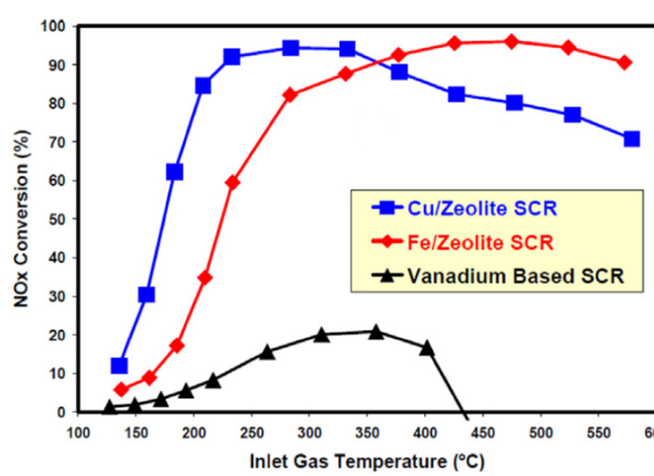


Fig. 2. NO_x conversion efficiency of different SCR catalysts (Cavataio et al., 2007).

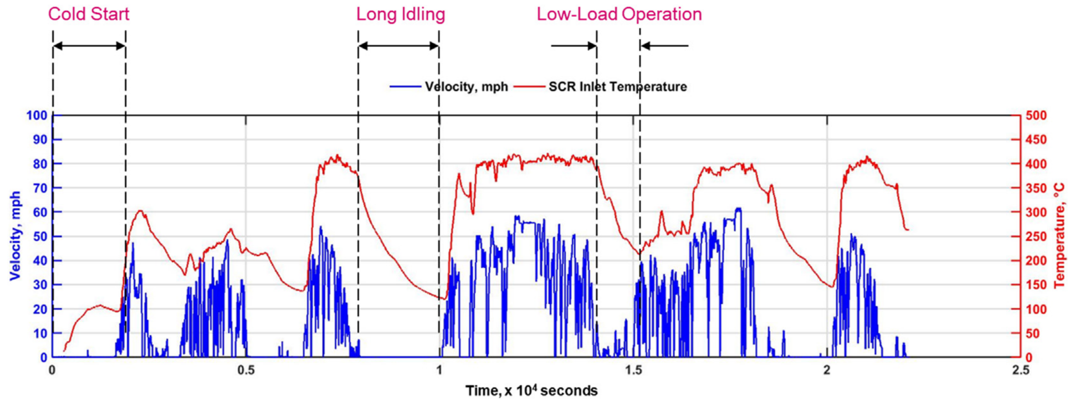


Fig. 3. Vehicle speed and SCR temperature profiles of a heavy-duty diesel vehicle during a trip.

Cummins ISX15 450 engines with 450 hp. The line haul–in state trucks in Fig. 4(b) use MY 2015 Detroit Diesel DD15AT or DD13 engines with 500–505 hp. The frequency distributions of SCR temperature in both figures are similar where they have two peaks. One is around 260–290 °C, which is when driving at highway speeds. The other one is around 100–130 °C for the Cummins engines and 110–130 °C for the Detroit Diesel engines, which is when idling. It is interesting to observe in Fig. 5(a) and (b) that both sets of engines had about 50% of their time operated at engine loads lower than 10%. However, the Cummins engines spent a higher fraction of that time at engine loads between 0% and 5% while the Detroit Diesel engines spent more time at engine loads between 5% and 10%. This most likely contributes to high idling SCR temperatures observed for the line haul–in state trucks. The differences in SCR temperatures between the two groups of line haul trucks while operating with low engine loads are also due to the specific SCR technology and the associated SCR temperature management strategy used by the different engine manufacturers.

In contrast to the earlier comparison, Fig. 4(b) through Fig. 4(d) compare the SCR temperature profiles for vehicles in different vocations that use the same engine model but different model years. The engines for two out of three line haul–in state trucks in Fig. 4(b), all five food distribution trucks in Fig. 4(c), and all five utility repair trucks in Fig. 4(d) are Detroit Diesel DD13 model with MY 2015, 2013, and 2012, respectively. Compared to the SCR temperature frequency distribution for line haul–in state trucks, the SCR temperature frequency distribution for food distribution trucks has the major peak at a slightly lower temperature range of around 260–270 °C (versus 270–290 °C). While the SCR temperature frequency distribution for food distribution trucks has the minor peak at a slightly higher temperature range of around 120–150 °C (versus 110–130 °C), it also has an additional peak at very low temperatures of around 30–50 °C. These are partly a result of the line haul–in state trucks having a larger fraction of their operation time at medium and high engine loads as shown in Fig. 5(b) and (c). In comparison with these two vocations, the utility repair trucks have the lowest overall SCR temperatures. This is because they spend a significant amount of their operation time under low engine loads, especially when idling. Note that for food distribution trucks and utility repair trucks, there is no variability by engine manufacturer, model, and model year within each vocation. Thus, the differences in their SCR temperature distributions can be attributable solely to the operating characteristics specific to their respective vocation.

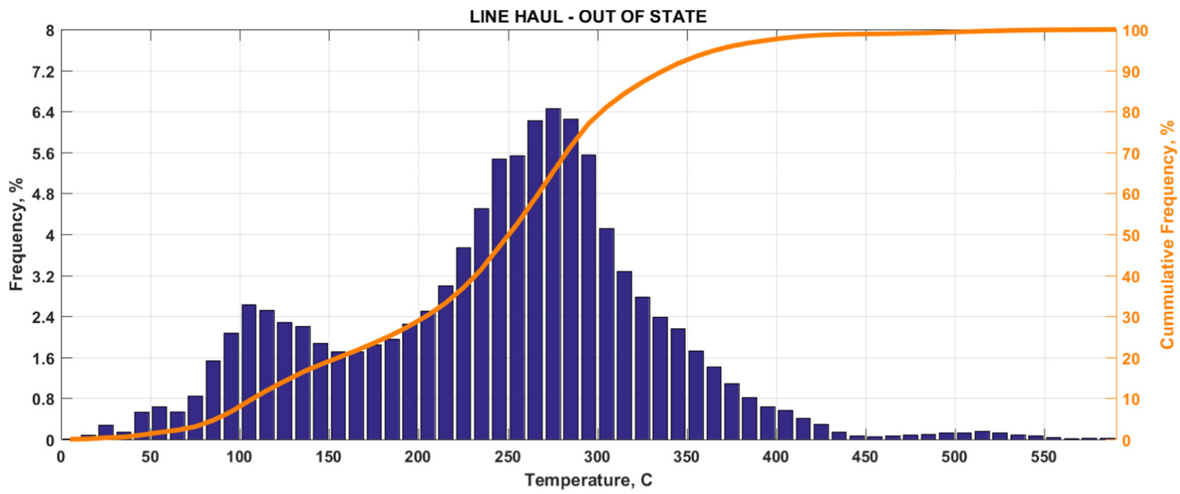
Fig. 4(e) shows SCR temperature distributions of Group 2a (Drayage–Northern California). This group consists of only one vehicle, which is from the same fleet as the vehicles in Group 1a (Line haul–out of state). This vehicle has a MY 2012 Cummins ISX15 engine with 450 hp, which is the same as one of the line haul–out of state trucks (Engine ID 18). The SCR temperature distributions of this truck are given in Fig. 4(f). Compared to Fig. 4(f), the SCR temperature distributions in Fig. 4(e) are significantly different, where the frequency distribution peaks at around 100–120 °C and skews right. This can be explained by the engine load distributions in Fig. 5(e) and (f) where the Drayage–Northern California truck barely has any activity at engine loads higher than 25% whereas the line haul–out of state truck spend a significant portion of its operation time at engine loads higher than that. This is strong evidence of how the differences in vehicle activity pattern can affect the engine load and SCR temperature of heavy-duty diesel vehicles, which could affect their real-world NO_x emissions.

Table 2 presents the information about the fraction of vehicle operating time that the SCR temperature was below certain thresholds. The selected thresholds were from 50 °C to 500 °C in 50 °C increments. Taking line haul–out of state trucks as an example, Table 2 shows that on average their SCR temperatures were lower than 200 °C for 27.7% of the total operating time and lower than 250 °C for 46.9% of the time. According to Table 2, it was found that on average the heavy-duty diesel vehicles in this study operated with SCR temperatures lower than 250 °C for 42–89% of the time, depending on their vocation. Given that heavy-duty diesel engines tested on the FTP cycle generally produce SCR temperature between 250 and 350 °C during the majority of the cycle (DieselNet, 2017), the results in Table 2 indicate that when these heavy-duty diesel engines are used in real-world applications, their real-world SCR temperatures are lower than the levels typically experienced during the FTP testing for a large fraction of their operation time. And as the NTE NO_x emission limits do not apply when the SCR temperature is lower than 250 °C (US Environmental Protection Agency, 2004), it means that a large portion of these engines' real-world operation would not be subject to the NTE requirements.

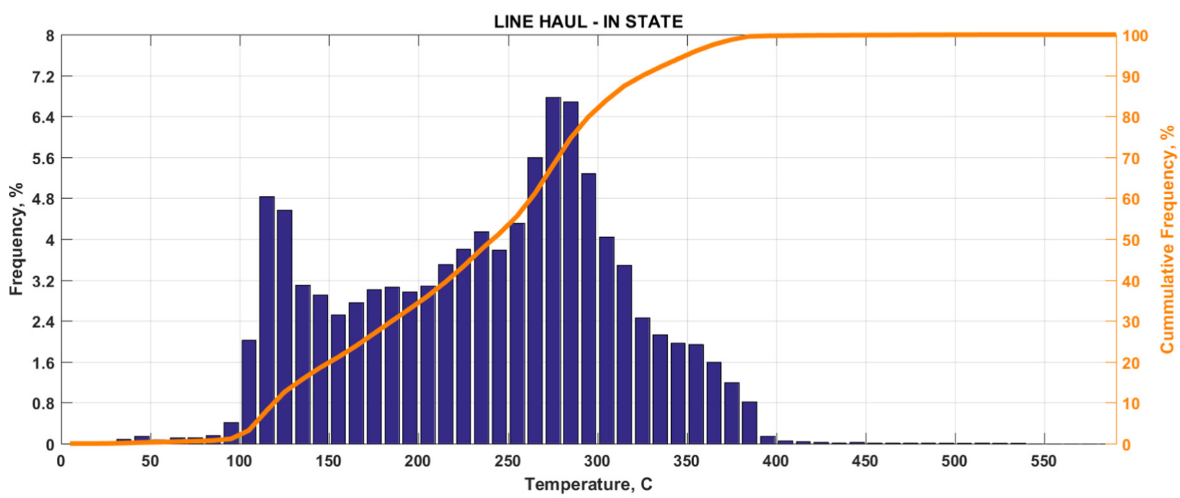
In addition, some SCR systems employ a urea control strategy that only injects the urea solution once the SCR temperature reaches a certain level such as around 190–200 °C (Slimarik et al., 2014). According to Table 2, the heavy-duty diesel vehicles in this study operated with SCR temperatures lower than 200 °C for 11–70% of the time, depending on their vocation. If these vehicles are equipped with such SCR systems, then the urea solution would not be injected for a significant portion of their operation time during which the full engine-out NO_x emissions could be emitted. This could have a significant implication on the vehicles' real-world NO_x emissions.

4.2. NO_x conversion efficiency

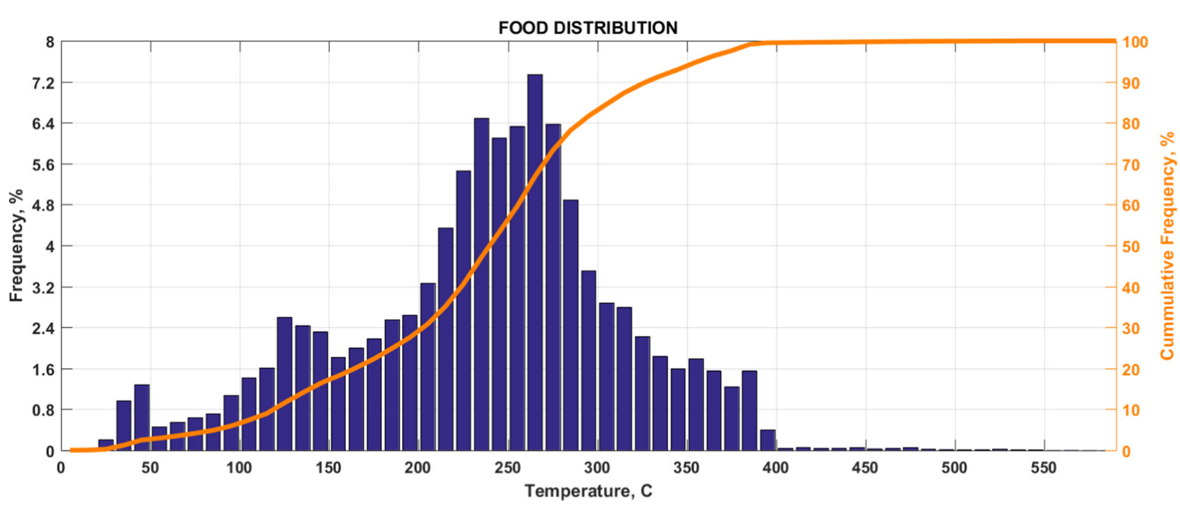
It is of interest to estimate how real-world SCR temperature profiles may affect the NO_x conversion efficiency of SCR. To estimate the potential impact of real-world SCR temperature of the vehicle samples in this research on the NO_x conversion performance of their SCR, we first determined the fraction of vehicle operation time that SCR temperature was within 11 different bins as shown in Table 3. For each vehicle group, the sum of the fraction values across the 11 bins equals 100.



(a) Group 1a (Line haul – out of state)

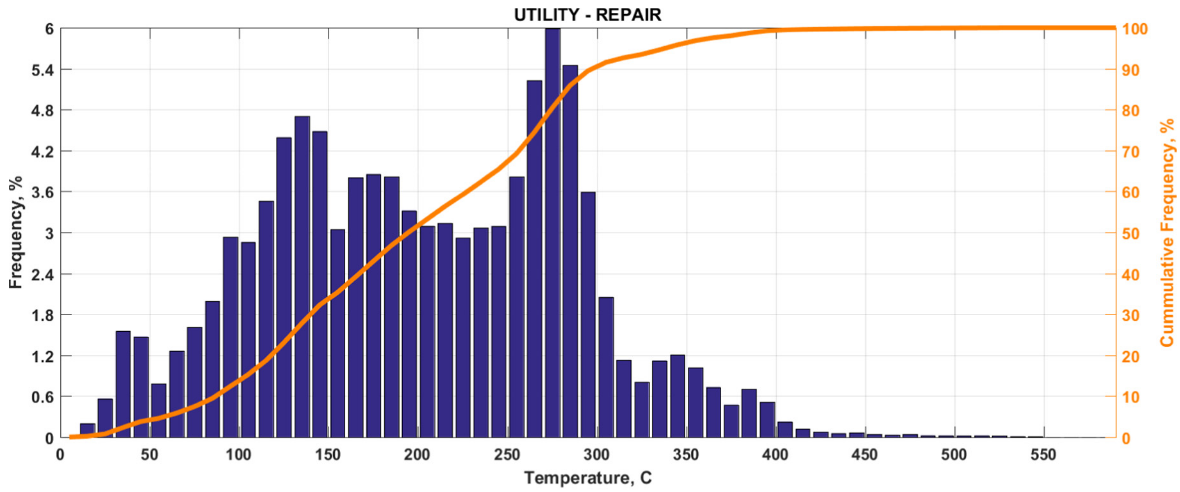


(b) Group 1b (Line haul – in state)

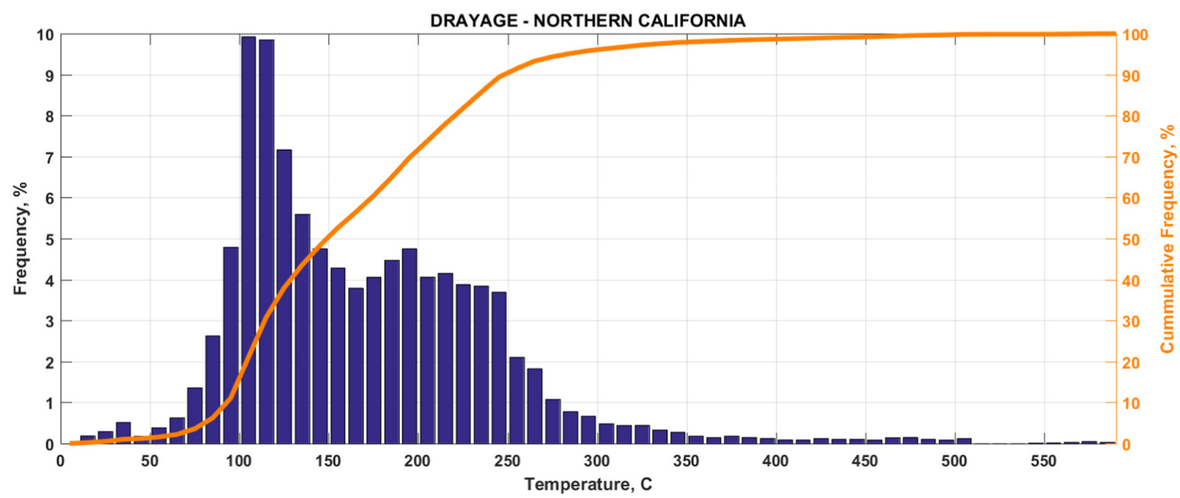


(c) Group 5a (Food distribution)

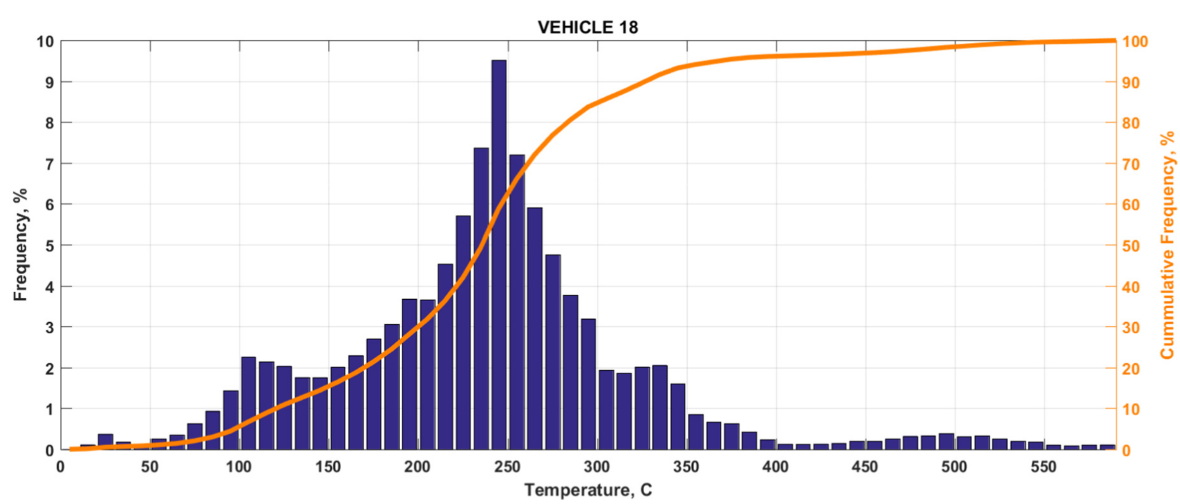
Fig. 4. Real-world SCR inlet temperature distributions.



(d) Group 10 (Utility repair)

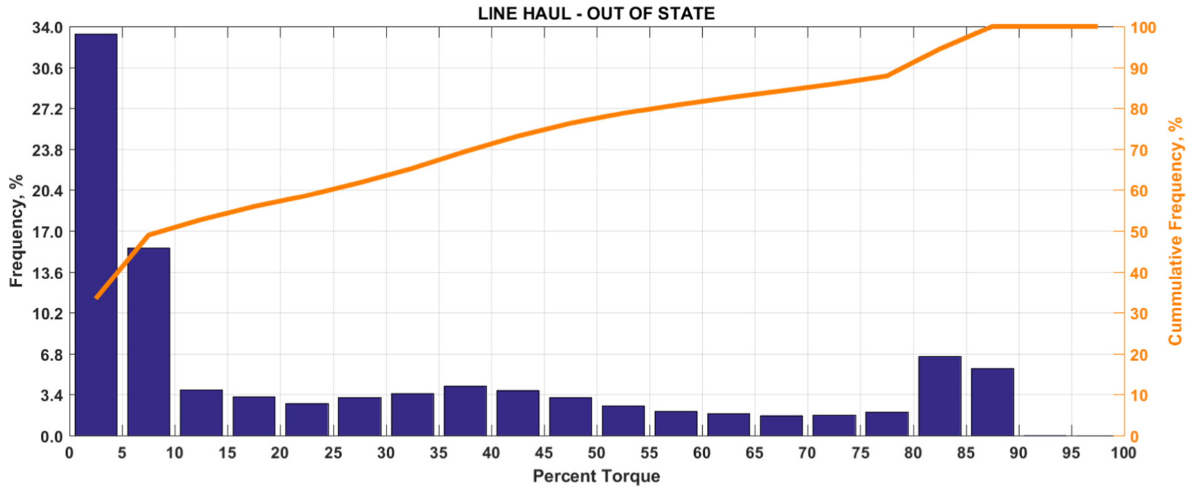


(e) Group 2a (Drayage – Northern California)

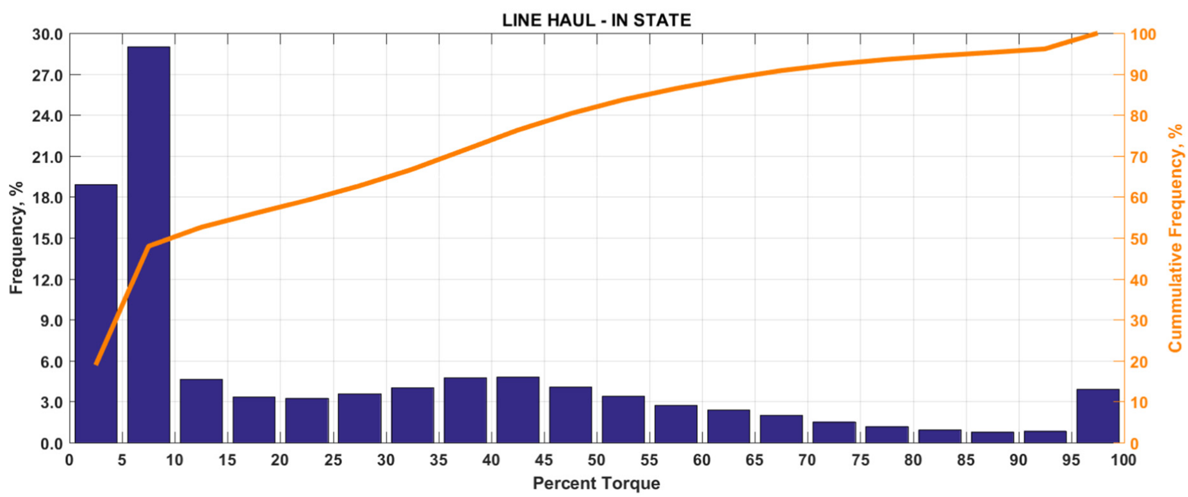


(f) Engine ID 18 (Line haul – out of state truck)

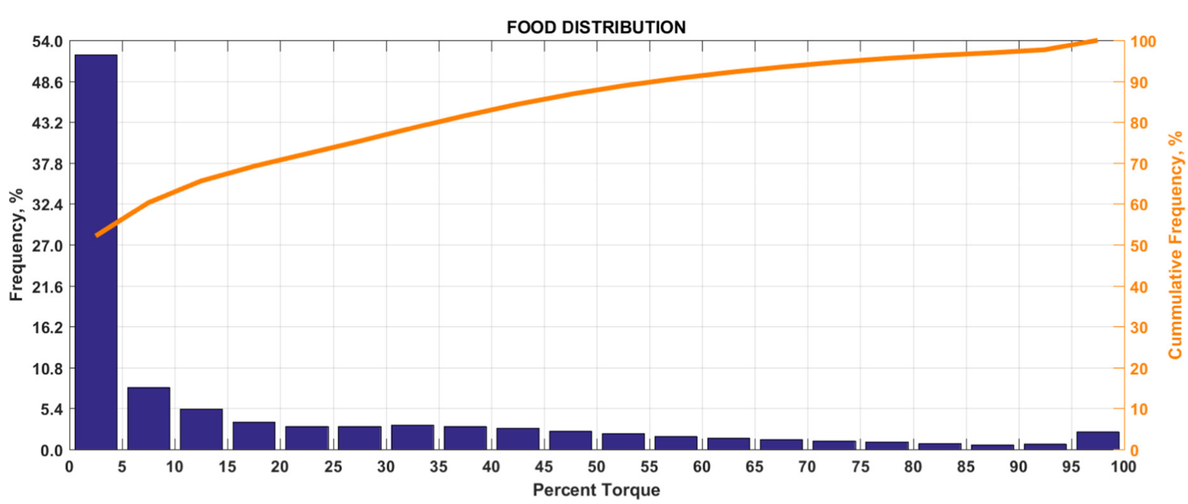
Fig. 4 (*continued*).



(a) Group 1a (Line haul – out of state)

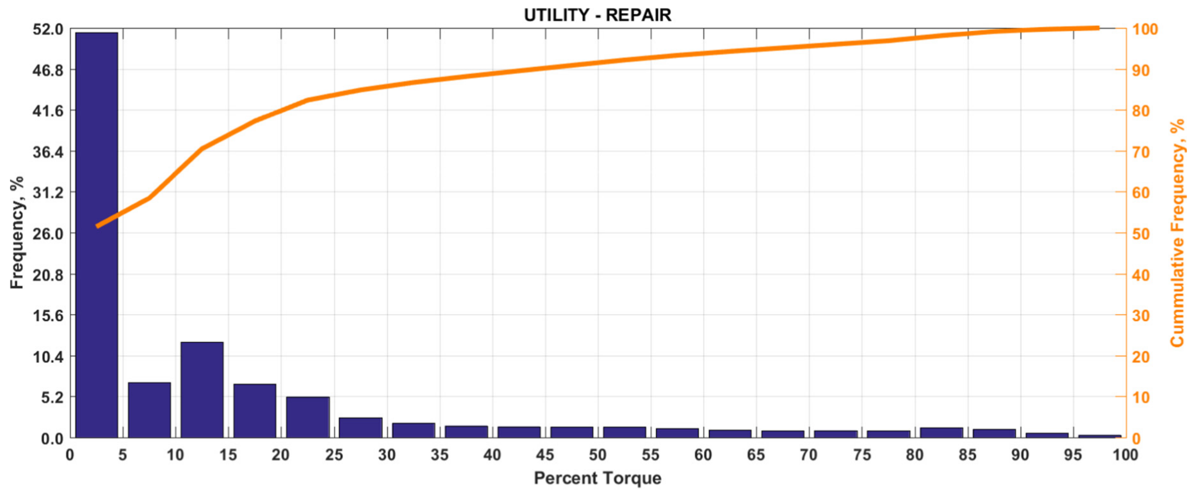


(b) Group 1b (Line haul – in state)

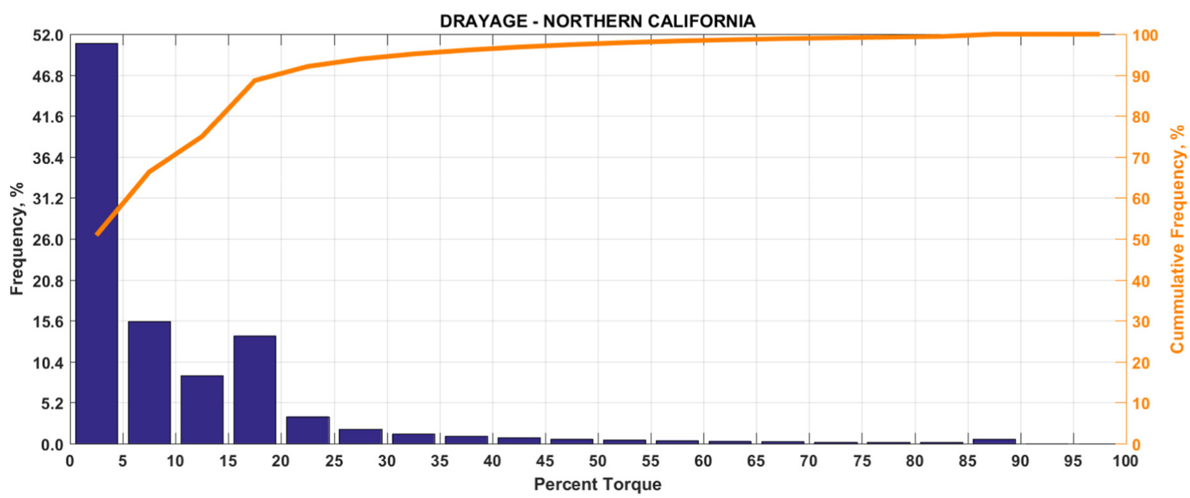


(c) Group 5a (Food distribution)

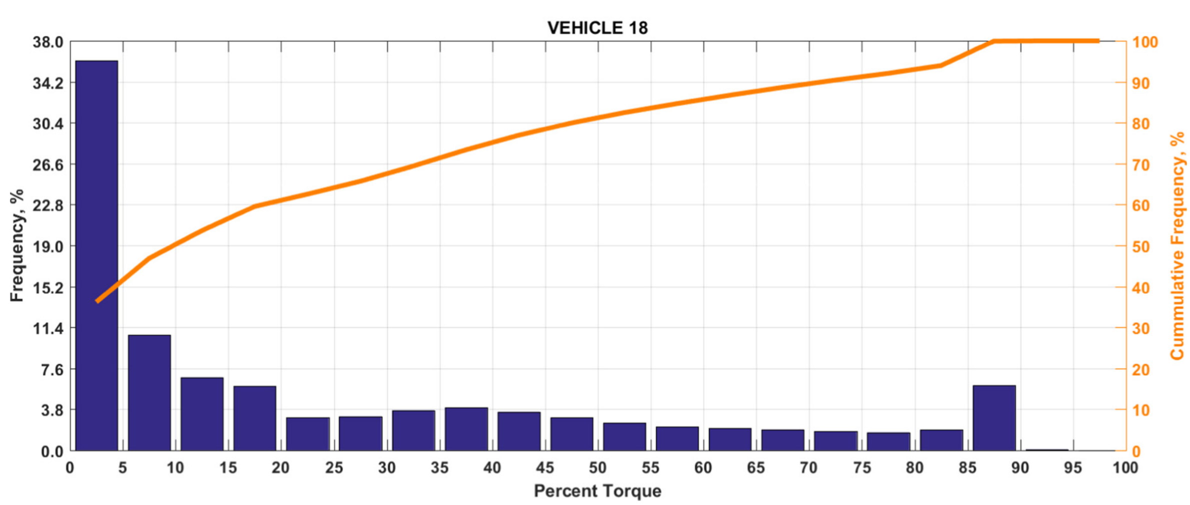
Fig. 5. Real-world engine load distributions.



(d) Group 10 (Utility repair)



(e) Group 2a (Drayage – Northern California)



(f) Engine ID 18 (Line haul – out of state truck)

Fig. 5 (*continued*).

Table 2
Percentage of vehicle operation time with SCR temperature below certain thresholds.

No.	Vehicle group	Fraction with SCR temperature (°C) lower than									
		50	100	150	200	250	300	350	400	450	500
1a	Line haul-out of state	1.0	6.7	18.2	27.7	46.9	76.9	91.7	97.4	98.8	99.3
1b	Line haul-in state	0.3	1.2	18.6	32.9	51.2	79.9	94.0	99.7	99.9	100
2a	Drayage-No. Cal.	1.2	11.0	48.3	69.7	89.3	95.8	97.8	98.6	99.1	99.7
3b	Agricultural-So. CV	0.4	5.5	25.9	40.1	58.8	91.8	95.4	97.6	98.6	99.1
4a	Construction	0.6	3.9	15.1	44.4	70.5	86.0	93.7	98.3	99.5	99.7
4b	Cement mixers	0.3	2.3	8.9	26.2	59.9	80.2	94.2	98.6	99.3	99.6
5a	Food distribution	2.5	5.9	16.3	27.5	53.2	81.6	93.0	99.5	99.7	99.9
5b	Beverage distribution	2.1	12.2	24.7	43.7	83.4	97.6	98.8	99.2	99.5	99.8
5c	Local moving	2.3	14.3	27.1	42.6	72.4	92.7	96.4	97.3	97.7	98.3
6	Airport shuttle	0.6	2.0	8.6	22.4	70.7	97.2	98.8	99.0	99.4	99.9
7	Refuse	0.8	3.5	7.1	11.2	47.2	75.5	91.5	94.4	97.1	99.8
8a	Urban buses	0.6	6.4	12.5	19.8	42.3	83.2	97.3	99.0	99.4	100
9a	Freeway work	2.6	16.8	33.6	58.0	81.8	92.8	98.0	99.3	99.5	99.8
9b	Sweeping	1.5	4.4	7.6	15.8	56.9	80.1	89.5	95.3	98.8	99.6
9c	Municipal work	1.4	3.8	10.2	20.7	48.4	83.2	94.7	98.8	99.6	99.9
9d	Towing	0.7	3.4	12.0	28.8	54.2	82.2	94.6	98.5	99.3	99.8
10	Utility repair	3.8	12.4	32.3	50.1	65.4	89.5	95.8	99.2	99.8	99.9

Note: Data for Group 2b (Drayage–Southern California) and Group 8b (Express buses) are not available.

Since the vehicle samples in this research are made up of a variety of engine manufacturers, engine models, and engine sizes, it is not possible to obtain NO_x conversion efficiency information for each of the vehicles. Also, such information is often not publicly available. Therefore, we assumed a % NO_x conversion efficiency value for each of the 11 SCR temperature bins based on the NO_x conversion efficiency curves in Fig. 2. One set of NO_x conversion efficiency values is obtained for the Fe-zeolite SCR and another set for the Cu-zeolite SCR. The values are given in the last two rows of Table 3. Using these values, we calculated the time weighted average % NO_x conversion efficiency for each vehicle group using the fraction of SCR temperature in the different bins as the weighting factor. The results are shown in Fig. 6.

According to the results in Fig. 6, the time weighted average % NO_x conversion efficiency of the Fe-zeolite SCR ranges from 24% for drayage trucks in Northern California to 63% for refuse trucks. The time weighted average % NO_x conversion efficiency of the Cu-zeolite SCR ranges from 40% for drayage trucks in Northern California to 84% for refuse trucks. Although the NO_x conversion efficiency varies greatly by vehicle group, the Cu-zeolite SCR consistently results in a higher NO_x conversion efficiency for all the vehicle groups. These results imply that Cu-zeolite SCR would be more effective at controlling NO_x emissions from heavy-duty diesel vehicles across various vocations, as its NO_x conversion efficiency characteristics are more conducive to the real-world SCR temperature profiles of these vehicles.

To date, studies have shown higher NO_x emissions from heavy-duty diesel vehicles under operating conditions where engine load and SCR temperature are relatively lower (Misra et al., 2013; Thiruvengadam et al., 2015; Misra et al., 2016; Yoon et al., 2016; Carder et al., 2014; Bishop et al., 2012; Bishop et al., 2013; Dallmann et al., 2011). However, these studies are based on emission measurements from a limited number of vehicles and for a limited amount of vehicle operation time. In this article, we have shown—based on the data collected from a large number of heavy-duty diesel vehicles in various vocations for several months—that such operating conditions account for a significant fraction of their operation time in real world. When put together, these findings point to a

Table 3
Percentage of vehicle operation time with SCR temperature in specific ranges.

No.	Vehicle group	Fraction with SCR temperature (°C) between										
		0–50	51–100	101–150	151–200	201–250	251–300	301–350	351–400	401–450	451–500	500+
1a	Line haul-out of state	1.0	5.7	11.5	9.5	19.2	30.0	14.7	5.7	1.5	0.5	0.7
1b	Line haul-in state	0.3	0.9	17.4	14.3	18.3	28.7	14.1	5.7	0.2	0.1	0.0
2a	Drayage-No. Cal.	1.2	9.8	37.3	21.4	19.7	6.5	2.0	0.8	0.5	0.6	0.3
2b	Drayage-So. Cal.	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
3	Agricultural	0.4	5.2	20.3	14.3	18.7	32.9	3.6	2.3	0.9	0.6	0.9
4a	Construction	0.6	3.3	11.2	29.3	26.1	15.5	7.7	4.6	1.2	0.2	0.3
4b	Cement mixers	0.3	2.0	6.6	17.3	33.7	20.4	14.0	4.4	0.7	0.3	0.4
5a	Food distribution	2.5	3.4	10.4	11.2	25.7	28.5	11.3	6.6	0.2	0.2	0.1
5b	Beverage distribution	2.1	10.1	12.5	19.1	39.7	14.2	1.2	0.4	0.3	0.3	0.2
5c	Local moving	2.3	12.0	12.8	15.5	29.9	20.3	3.7	0.9	0.4	0.6	1.7
6	Shuttle	0.6	1.4	6.6	13.8	48.2	26.6	1.5	0.3	0.3	0.6	0.1
7	Refuse	0.8	2.7	3.6	4.2	36.0	28.2	16.1	2.9	2.7	2.7	0.2
8a	Urban buses	0.6	5.8	6.1	7.3	22.5	40.9	14.0	1.7	0.5	0.5	0.0
8b	Express buses	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
9a	Freeway work	2.6	14.2	16.9	24.3	23.9	11.0	5.2	1.3	0.3	0.3	0.2
9b	Sweeping	1.5	2.9	3.2	8.3	41.1	23.2	9.4	5.8	3.5	0.9	0.4
9c	Municipal work	1.4	2.4	6.5	10.5	27.7	34.8	11.5	4.1	0.9	0.2	0.2
9d	Towing	0.7	2.7	8.7	16.7	25.5	28.0	12.4	3.9	0.9	0.4	0.2
10	Utility repair	3.8	8.6	19.9	17.8	15.3	24.1	6.3	3.4	0.5	0.2	0.1
NO_x conversion efficiency[a]	Fe-zeolite	0%	0%	5%	15%	50%	80%	87%	92%	95%	95%	94%
	Cu-zeolite	0%	0%	5%	50%	90%	95%	95%	88%	83%	80%	77%

[a] Source: Cavataio et al., 2007.

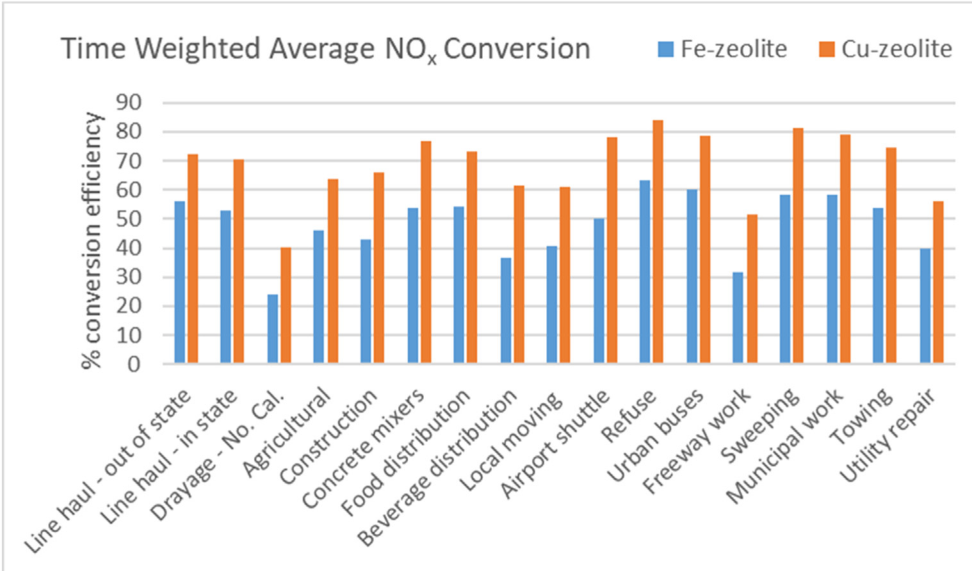


Fig. 6. Time weighted average NO_x conversion efficiency for each vehicle group.

hypothesis that real-world NO_x emissions from heavy-duty diesel vehicles equipped with SCR could be higher than expected for a significant part of their real-world operation.

5. Conclusions

On-road heavy-duty diesel vehicles are a major contributor of NO_x emissions. In the US, many heavy-duty diesel vehicles employ SCR technology to meet the 2010 emission standards for NO_x. Typically, SCR needs to be at least 200 °C before a significant level of NO_x reduction is achieved. However, real-world activity patterns of some of these vehicles may increase the likelihood that this SCR temperature requirement is not met, such as during cold starts, long idling, and low speed driving. The frequency of the activity patterns contributing to low SCR temperature varies partly by the vehicle's vocational use. In this study, detailed vehicle and engine activity data were collected from 90 heavy-duty vehicles involved in a range of vocations, including line haul, drayage, construction, food and beverage distribution, refuse, and utility repair. The data were used to examine real-world SCR temperature and engine load profiles to identify the fraction of vehicle operation time that SCR may not be as effective for NO_x control.

It is found that the vehicles in this study operate with SCR temperature lower than 250 °C for 42–89% of the time, depending on their vocation type. This large fraction of real-world operation, especially with low engine load, is not captured in the current FTP testing or the NTE requirements. It is also found that the vehicles in this study operate with SCR temperature lower than 200 °C for 11–70% of the time, depending on their vocation type. For some SCR systems, the urea solution would not be injected during those times and the full engine-out NO_x emissions could be emitted. This could have a significant implication on the vehicles' real-world NO_x emissions. An in-use emissions measurement study will be needed to quantify the impact of real-world activity patterns of heavy-duty diesel vehicles equipped with SCR on their real-world NO_x emissions.

The NO_x conversion efficiency of SCR depends partly on the type of catalyst used. Zeolite SCR catalysts in combination with Copper or Iron are the most commonly used in heavy-duty diesel engines for on-road applications. Laboratory test data from literature has shown that the optimal SCR temperature range for Fe-Zeolite SCR is between 350 and 575 °C whereas it is between 225 and 350 °C for Cu-Zeolite SCR. At low temperatures (<200 °C), Cu-Zeolite SCR is superior to Fe-Zeolite SCR where about 77% NO_x conversion is achieved at 200 °C as compared to 27% in the case of Fe-Zeolite SCR. Given these performance characteristics and the real-world SCR temperature profiles observed in this study, it appears that Cu-zeolite SCR would be more effective at controlling NO_x emissions from heavy-duty diesel vehicles across various vocations than its counterpart.

This article is focused on analyzing real-world SCR temperature data by vocation and pointing out the extent of low SCR temperature conditions during the vehicles' in-use operation. However, the number of vehicles sampled in this research, while substantial in aggregate, is still limited when considering it by vocation—there are no more than eight vehicle samples in a vocation and a few vocations only have one vehicle sample. Also, some vocations consist of vehicle samples with different engine manufacturers, models, and model years. This vehicle- and engine-level variability has not been fully characterized and can be a subject for future work. In addition, a minimum sample size for a vocation type can be established, considering the diversity of services performed, engine manufacturers, SCR catalyst technologies, and other factors within the vocation type. Then, additional vehicle and engine activity data can be collected accordingly.

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Disclaimer

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