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Energy Saving Potentials of Ventilation Controls Based on Real-time Vehicle Detection in Underground Parking Facilities

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Abstract

The main topic of this paper is to show a possibility of indoor air quality enhancement and the fan energy savings in underground parking facilities by applying the demand-controlled ventilation (DCV) strategy based on the real-time variation of the traffic load. The established ventilation rate is estimated by considering the passing distance, CO emission rate, idling time of a vehicle, and the floor area of the parking facility._However, they are hard to be integrated into the real-time DCV control. As a solution to this problem, the minimum ventilation rate per a single vehicle is derived in this research based on the actual ventilation data acquired from several existing underground parking facilities. And then its applicability to the DCV based on the real-time variation of the traffic load is verified by simulating the real-time carbon monoxide concentration variation. The energy saving potentials of the proposed DCV strategy is also checked by comparing it with those for the current underground parking facility ventilation systems found in the open literature.

Keywords: Demand controlled ventilation, Energy conservation, Underground parking facilities, Vehicle detection system

1. Introduction

DCV has been widely acknowledged based upon indoor occupant demand for last 30 years and DCV-applied automatic ventilation control system has been developed according to the rapid technology development of CO_2 sensor in the 1990s (Stipe, 2003). DCV is applied indoor building space by detecting the density of strong pollutants thus several advantages occurred as a result such as energy savings, improved indoor air quality and occupancy information (Fisk and De Almeida, 1998; Schell and Inthout, 2001). It is important to know the changing level of occupancy for the potential benefits of DCV application, thus real-time data collection of the indoor occupancy level is being carried out (Johansson et al., 2011; Li et al., 2012). Further the sensing systems and repeatability are key elements in measuring data to determine the success of DCV application (Dougan and Damiano, 2004).

DCV as a part of ventilation control system refers to the automatic control system of outdoor air inflow rate based upon the ventilation requirement and the real-time occupant number (Stipe, 2003). According to the ASHRAE Standard 62.1-2007, the minimum ventilation rates are defined according to indoor pollution factors divided by people and building components and the occupant number and unit floor area are applied to DCV (ASHRAE Standard 62.1 2007). There are few DCV researches regarding non-occupant spaces like parking area or industrial facilities whereas many DCV-related researches are being conducted including simulations and experiments for the occupant spaces such as public assembly space, office buildings, residential area, schools or sports facilities (Chao and Hu, 2004; Jeong et al., 2010; Lu et al., 2011; Mysen et al., 2005; Nassif, 2012; Owen Ng et al., 2011). According to the report of ITA Working Group in 1995, however, underground parking facilities are expected to be increased in population area (Godard, 1995), thus DCV researches are required to be carried on parking facilities as well.

According to established ventilation standards (Table 1), many countries defined the minimum outdoor air ventilation rate required for keeping the carbon monoxide (i.e., CO) concentration to a certain maximum allowable level (Krartiand Ayari, 2001; ASHRAE, 2007). Each recommended ventilation rate is almost normalized for the unit floor area or unit volume of the facility, so applying current ventilation standard for parking facilities to the DCV control based on the real-time variation of the traffic load may be difficult.

In this research, a minimum ventilation air flow required for a single vehicle is derived based on ventilation rate for enclosed parking garages, which can be more easily integrated into the DCV control approach. Then the DCV applicability to the parking facilities is examined by prediction simulation of real-time ventilation adjustment and CO_2 concentration variation according to the ventilation system control strategy. Further application of varied DCVs to parking facilities, the possibility of indoor air

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Table 1. Ventilation rates for enclosed parking garages

	ASHRAE (USA)	Finland	France	Germany	Korea	Sweden	U.K
Period [h]	$8^a/1^b$	$8^a/0.25^b$	0.33^b (Ceiling)	-	8	-	$8^a/0.25^b$
CO [ppm]	$25^a/9^b$	$30^a/75^b$	$200^a/100^b$	-	25^b	-	$50^a/300^b$
Ventilation rate	27 [m^3/hr-m^2]	9.72 [m^3/hr-m^2]	594 [m^3/hr-car]	11.88 [m^3/hr-m^2]	27.4 [m^3/hr-m^2]	3.276 [m^3/hr-m^2]	6-10 ACH

Note: ^{a}Time weighted average concentration (TWA), ^{b}Short term exposure limit (STEL) (e.g., 8 hour exposure limitation is for 25 ppm, and 1hour exposure limitation is for 9 ppm on ASHRAE 2007)

quality (IAQ) enhancement and fan energy savings by the DCV strategy is also quantitatively analyzed by the simulation study.

2. Ventilation Mode

The existing operation modes of mechanical ventilation applicable to a parking facility are continuous operation and intermittent operation. CO-DCV belongs to the continuous operation mode supplying variable air volume according to the indoor CO density (Krarti et al., 1999). The accurate calibration of CO sensor is required as CO-DCV employs indoor CO density as ventilation control indicator. Thus in this research, we have applied VDS (Vehicle Detection System) monitoring real-time traffic load in addition to the existing CO Sensor-applied DCV. Initial installation cost might be reduced for the additional sensors as real-time vehicle monitoring system could be effectively connected to VDS-DCV in the large underground parking facilities.

2.1. Continuous mode operation

Continuous operation mode is the constant or fixed volume supply of the ventilation air. The continuous operation mode of constant volume control requires no complicated control logics and automatic operation is available by entering a simple schedule data. It is appropriate for parking facilities with the high usage (or circulation) rate. Because of the continuous operation of ventilation units, relatively high fan energy consumption is inevitable. As for this case, two different DCV approaches; CO-concentration based DCV (CO-DCV) and DCV with vehicle detection system (VDS-DCV) are proposed to reduce the fan energy consumption.

2.1.1. CO-DCV

The CO-DCV uses CO detection system for estimating real-time variation of the traffic load by monitoring the indoor CO concentration variation, and modulating the ventilation rate. The number of vehicles in the facility can be estimated indirectly from the transient variation of the CO concentration. Recently, the use of CO sensor in underground parking facilities has been widely induced due to cost-effective sensors available. There are previewed limits in applying CO-DCV to the underground parking space as change of pollutants is not big for CO in the air and the resolution of CO sensor is small.

2.1.2. VDS-DCV

The VDS-DCV is based on the actual number of vehicles monitored by the detecting sensors (or cameras) installed at the entrance and the exit of the parking facility. Based on the real-time variation of the traffic load, one can adjust the ventilation rate. The most important point of VDS-DCV is that the entire traffic load is considered as potential cause of pollution as the regular driving patterns of real-time traffic load could not be predicted likewise men's behavior pattern.

2.2. Intermittent mode operation

In the intermittent operation mode for the underground parking facilities is the simple on/off (or binary) control of the mechanical ventilation system. The simple binary control of intermittent operation mode is considered to be a sort of DCV for the underground parking facilities (Martin, 2001) and we have applied VDS-DCV to the intermittent operation mode in this research.

2.2.1. Simple binary control

When the indoor CO concentration reaches at its upper limit level, constant volume ventilation units are activated and supply design flow until the CO concentration is back to normal. This simple approach is suitable for the facility with insignificant fluctuation of entering and leaving vehicles. Control logic and energy consumption are operated by a simple on/off control which is regarded to be the most practical control system. Simple binary control is, however, restricted to provide maximum ventilation airflow rate only when indoor CO is detected over the upper limit level.

2.2.2. VDS-DCV

VDS-DCV, which supplies ventilation required according to the real-time traffic load, was connected to the intermittent operation mode in order to compensate the restrictions of simple binary control. In VDS-DCV, VDS monitors the number of vehicles in the facility. Many different vehicle detection sensors are adopted such as electrical, magnetic, optical, acoustic or video detector for vehicle detection system (Han et al., 2011). The VDS-DCV control logic flow-chart in the intermittent operation mode is shown in Fig. 1. Threshold indoor CO limit, minimum ventilation rate per a single vehicle, real-time traffic load and minimum operating hours are 4 major variables in operation of VDS-DCV. When CO concentration increases over the upper limit, the ventilation units begin to supply exact amount of ventilation air determined based on the number of vehicles detected at that moment.

3. DCV Simulation

The simulations of ventilation airflow rate variation and transient variation of CO concentration have been conducted in random model spaces according to the ventilation mode of underground parking facilities. The transient CO concentration variation inside the facility is expressed by Eq. 1. By rearranging the governing equation for the transient variation of the number of vehicles (i.e., N_e/dt), and then discretizing the equation by hour (Eq. 2), one may estimate the number of vehicles based on the CO concentration variation. The predicted number of vehicles is a critical input parameter in the CO-DCV operation. The discrete governing equation has been solved numerically using a commercial equation solver program.

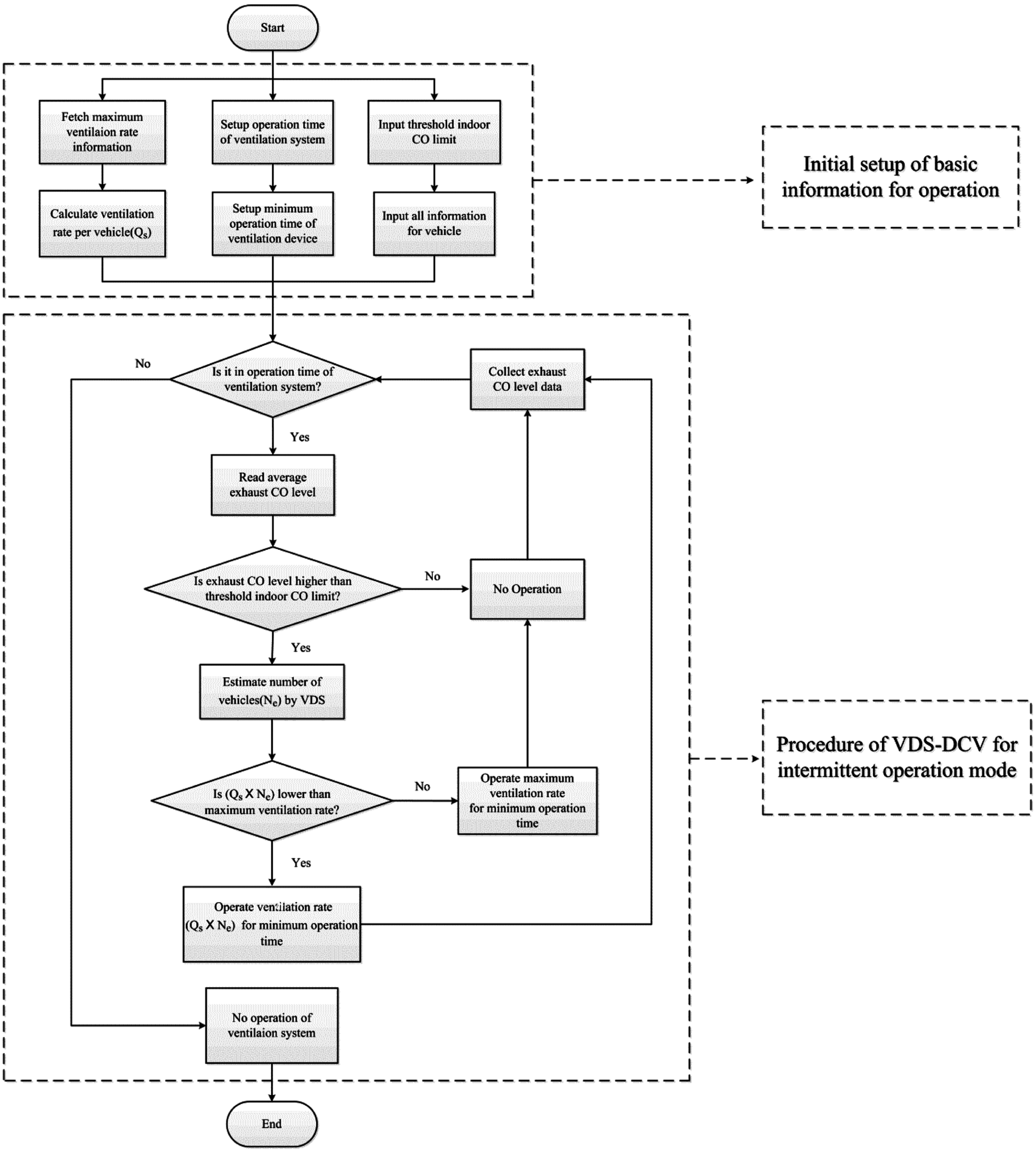


Figure 1. The flow chart of VDS-DCV for intermittent mode operation.

$$V\frac{dC}{dt}=-Q_S(C-C_S)+\left(E\times\nu\times\theta\times\frac{N_e}{dt}\right) \tag{1}$$

$$\left(\frac{N_e}{dt}\right)^n=\frac{1}{(E\times\nu\times\theta)}\left[V\frac{(C^n-C^{n-1})}{dt}+Q_S^n(C^n-C_S^n)\right] \tag{2}$$

Where,

V : the space volume, m^3

dC/dt : the time variant change of CO concentration, 1/min

Q_S : the ventilation airflow rate, m^3/min

C : the indoor CO concentration, m^3/m^3

C_S : the CO concentration of supply air, m^3/m^3

E : the average CO emission for a typical car, g/min-car

ν : the specific volume of CO, m^3/kg

θ : the average length of operation and travel time for a typical car, min

N_e/dt : the time-variant change number of cars, car/min

dt : the time interval, min

n, $n-1$: the current and previous time steps

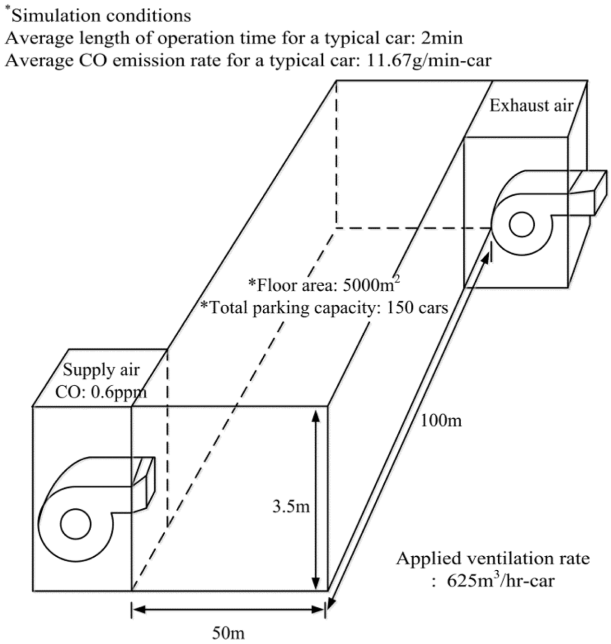


Figure 2. Model space.

3.1. Simulation conditions

A 5000-m^2 space (100 m × 50 m × 3.5 m) is defined as the model parking facility for ventilation control simulations. It is assumed that the model space is served by the supply and the exhaust air units with variable frequency drives (Fig. 2). The impact of the natural ventilation is not considered for simplicity. The design parking density is 3cars/100m^2, so the model space is able to accommodate

Table 2. Derived ventilation rates per a single vehicle for model space

	ASHRAE (USA)	Finland	France	Germany	Korea	Sweden	U.K
Ventilation rate	27 [m^3/hr-m^2]	9.72 [m^3/hr-m^2]	594 [m^3/hr-car]	11.88 [m^3/hr-m^2]	27.4 [m^3/hr-m^2]	3.276 [m^3/hr-m^2]	6-10 ACH
Derived Ventilation rate	900 [m^3/hr-car]	324 [m^3/hr-car]	594 [m^3/hr-car]	396 [m^3/hr-car]	913 [m^3/hr-car]	109 [m^3/hr-car]	700-1167 [m^3/hr-car]

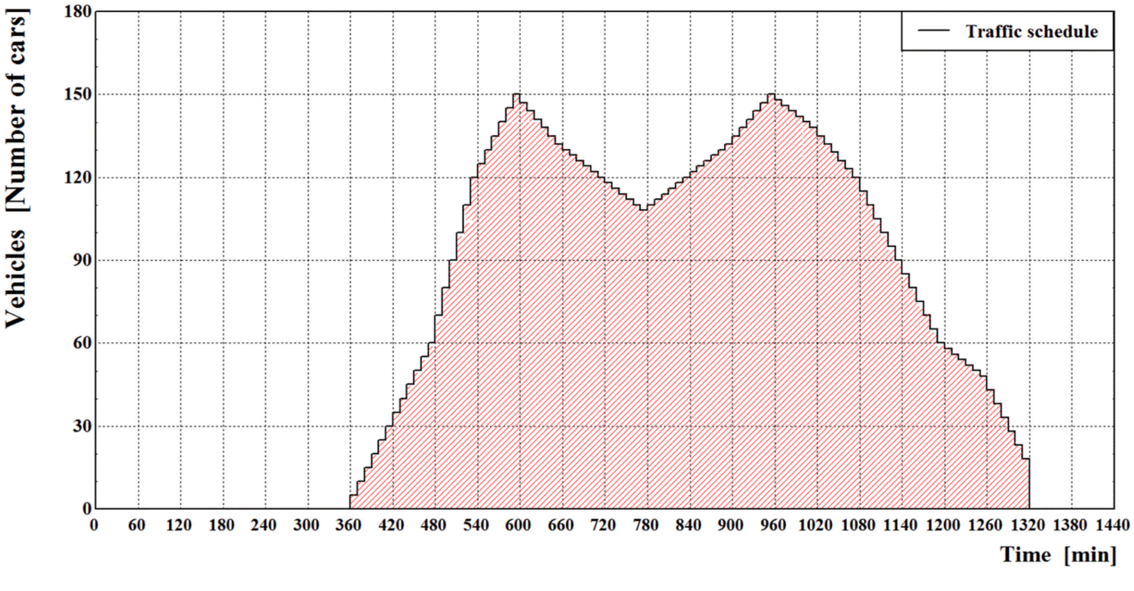
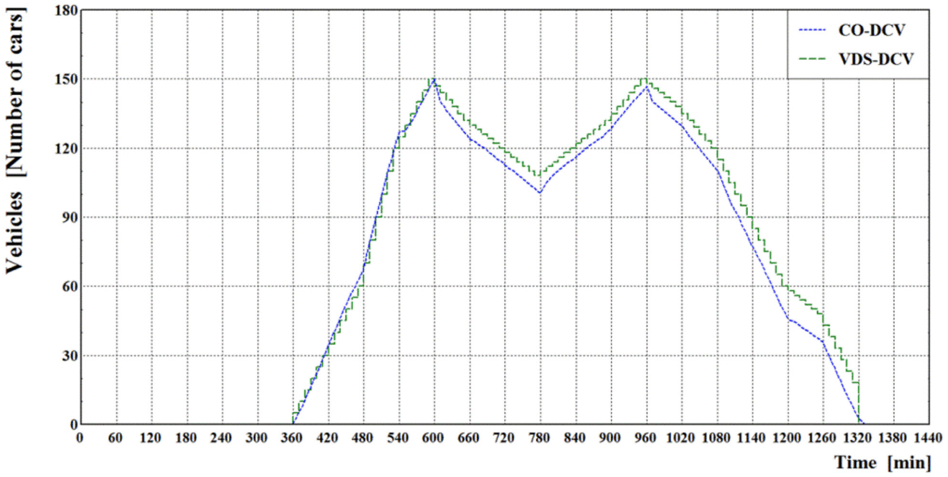


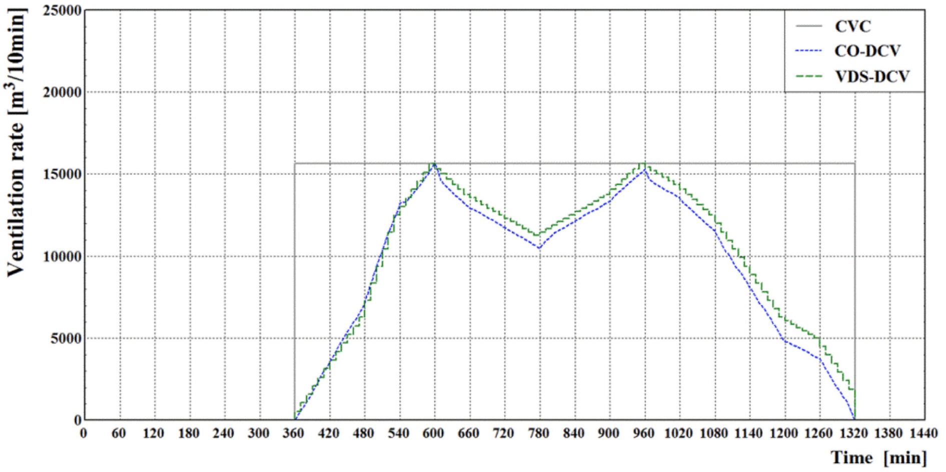
Figure 3. Traffic load schedule.

150 vehicles. The ambient air CO concentration is set to 0.6 ppm (MEK, 2009). And the average length of operating time and the CO emission rate per a typical car are assumed as 2 minutes, and 11.67 g/min., respectively (ASHRAE, 2007).

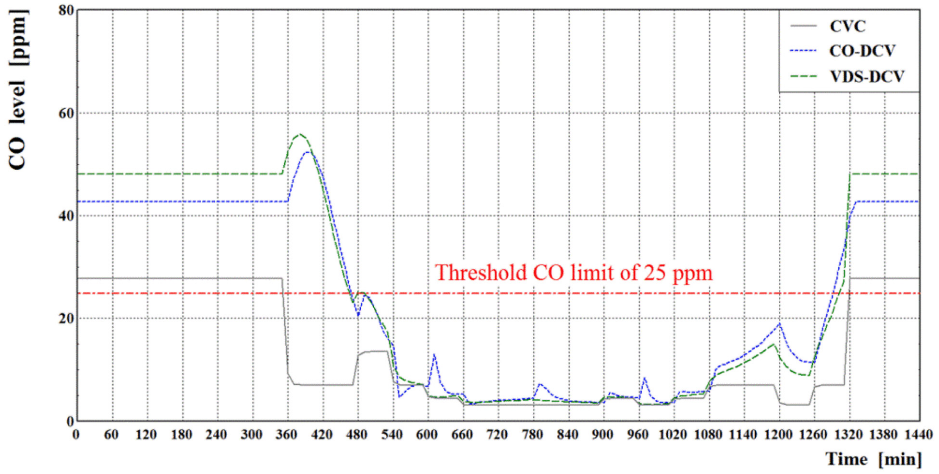
Table 2 shows the ventilation standard by nation converted into ventilation rate per a single vehicle in the target model space. In Table 2, the average 625 m^3/hr-car of



(a) Traffic load



(b) Ventilation rate



(c) CO concentration

Figure 4. DCV for continuous mode operation.

the required ventilation rate per a single vehicle is applied to the simulation except England and Sweden respectively representing the maximum and minimum ventilation rates. Fig.3 is the traffic load schedule defined for the simulation. It is assumed that ventilation system is operated from 6:00 AM to 22:00 PM, and deactivated for the rest of the time. The minimum operating hour is set to 10 min considering the ventilation overload due to frequent on/offs in intermittent operation mode. The static pressure for supply and exhaust fans is set to 500 Pa, and 1-kW power is required per 5000-CMH air supply.

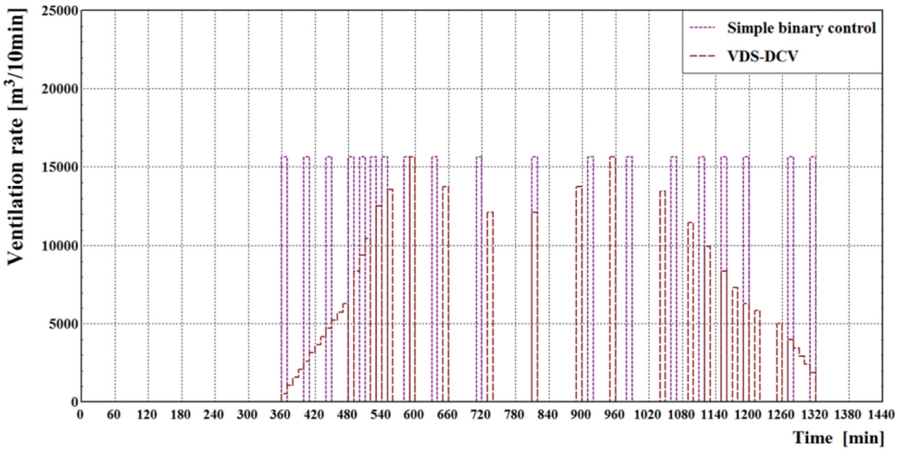
3.2. Simulation results

The DCV simulations are conducted for the continuous and the intermittent operations of the ventilation system of the model space. The CO-DCV and the VDS-DCV are applied to the continuous operation mode. As for the intermittent mode operation, to the simple binary control method and the VDS-DCV approach are considered.

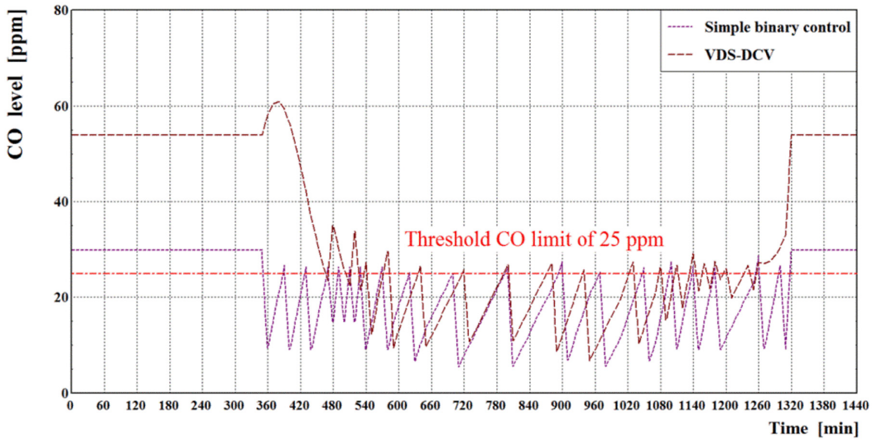
3.2.1. DCV for continuous mode operation

Fig. 4.1 shows the forecast of real-time variation of traffic load by CO-DCV detecting the measured CO concentration variation with CO Sensor and by VDS-DCV with vehicle detection sensor. In Fig. 4.1, one may see that the transient traffic load variation is predicted well in the CO-DCV case with ventilation rates per a vehicle. The number of cars estimated indirectly from the indoor CO concentration variation match very close to the exact numbers from the vehicle detecting system, while there is a little delay and under estimation. It may be normal because the CO concentration variation always follows the traffic load changes. Similar changes are appeared in DCV simulations using CO_2 concentration in the occupied space (Jeong et al., 2010).

The transient supply airflow rate variation estimated for each DCV strategy is presented in Fig. 4.2. The constant volume control-CVC is set to supply maximum outdoor air inflow of 93,750 m^3/hr during occupied hours regardless of vehicle access. While CO-DCV or VDS-DCV approach is applied, the ventilation airflow is modulated based on the expected or specific number of vehicles inside the model space. Consequently, the total amount of ventilation air supplied to the space (i.e., the area under the line) in



(a) Ventilation rate



(b) CO concentration

Figure 5. VDS-DCV for intermittent mode operation.

each DCV case is less than that for the constant volume control (CVC) case.

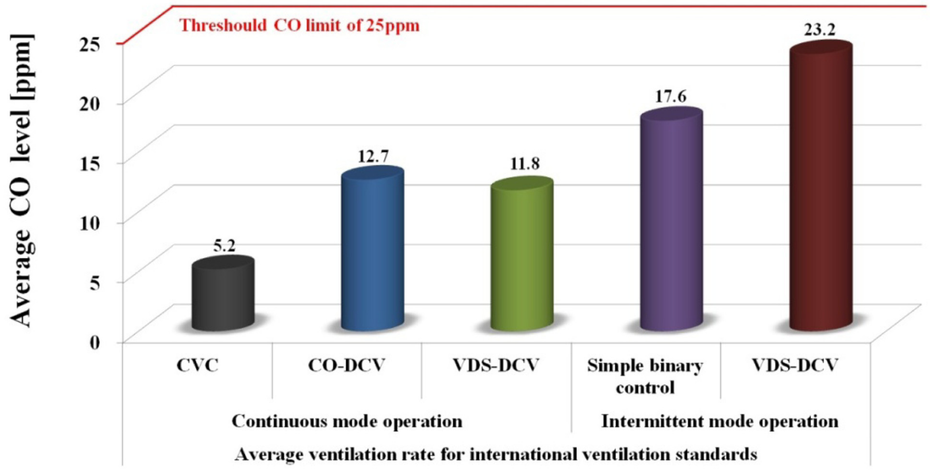
Fig. 4.3 depicts the variation of the CO concentration for each ventilation strategy. Whereas VDS-DCV shows slow change of concentration overall, CO-DCV shows momentarily increasing CO concentration at inflection point of vehicle changes which is because the traffic load is forecasted after the actual traffic load has occurred. All DCV cases are found to be able to maintain CO concentration below the threshold value (i.e., 25 ppm), while CVC operations lower the CO concentration somewhat quickly at the early stage of mechanical ventilation. It means that both CO-DCV and VDS-DCV approaches can avoid the over-ventilation occurring in CVC operation.

3.2.2. DCV for intermittent mode operation

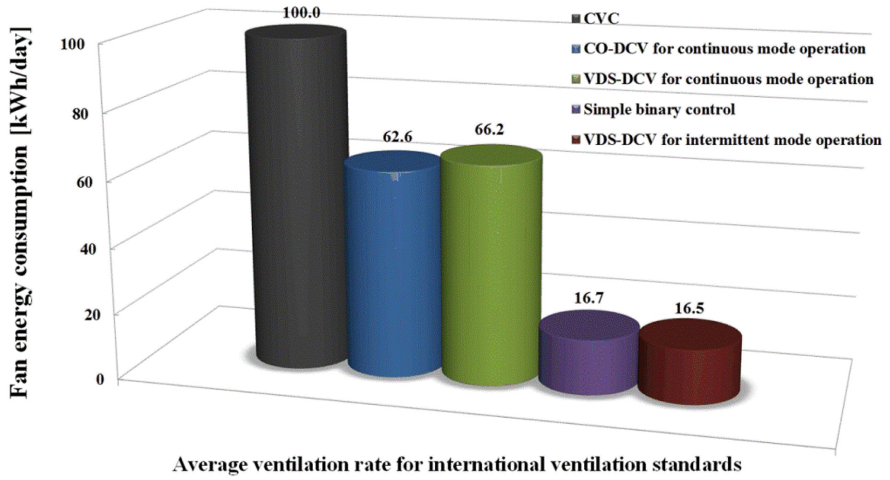
Fig. 5 shows the results of the simple binary control and VDS-DCV simulations for the intermittent operation. The simple binary control supplies the design ventilation flow when the indoor CO concentration exceeds the threshold level (Fig. 5.1), so the CO concentration drops quickly below the upper limit (Fig. 5.2). However, it seems that the indoor CO concentration may also be maintained at acceptable level with less ventilation air by combining the VDS-DCV approach with the simple binary control. As shown in Fig. 5a, the VDS-DCV adjusting the ventilation airflow based on the real-time traffic load whenever the indoor CO concentration is higher than its upper limit. Although the indoor CO concentration under the VDS-DCV control is a little higher than the simple binary control case (Fig. 5.2), it is still acceptable level.

3.2.3. Impact of DCV controls

Fig. 6 shows the average CO concentration and the fan energy consumption estimated for each DCV operation during the day. As expected, the average indoor CO concentrations of intermittent mode operation cases are higher than those of the continuous mode operation cases (Fig.



(a) Average CO concentration



(b) Fan energy consumption

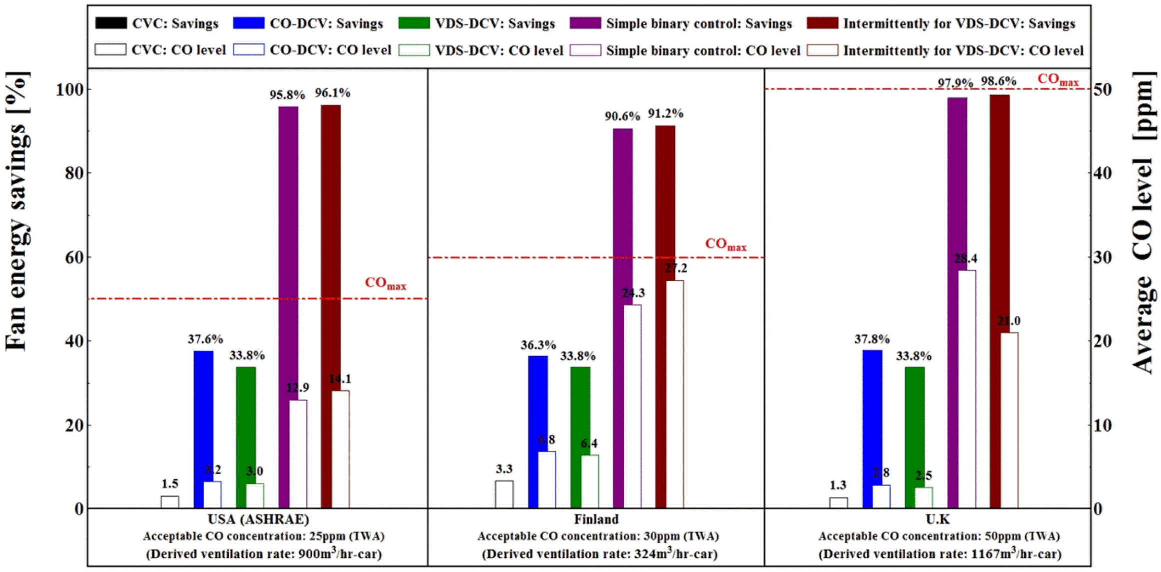
Figure 6. Impact of DCV controls.

6.1). In addition, the lowest CO concentration is observed under the CVC operation in both continuous and intermittent mode operations, while the VDS-DCV cases combined with the simple binary control show the highest indoor CO concentration. However, the threshold concentration of 25 ppm has not been violated even in the worst average CO concentration case.

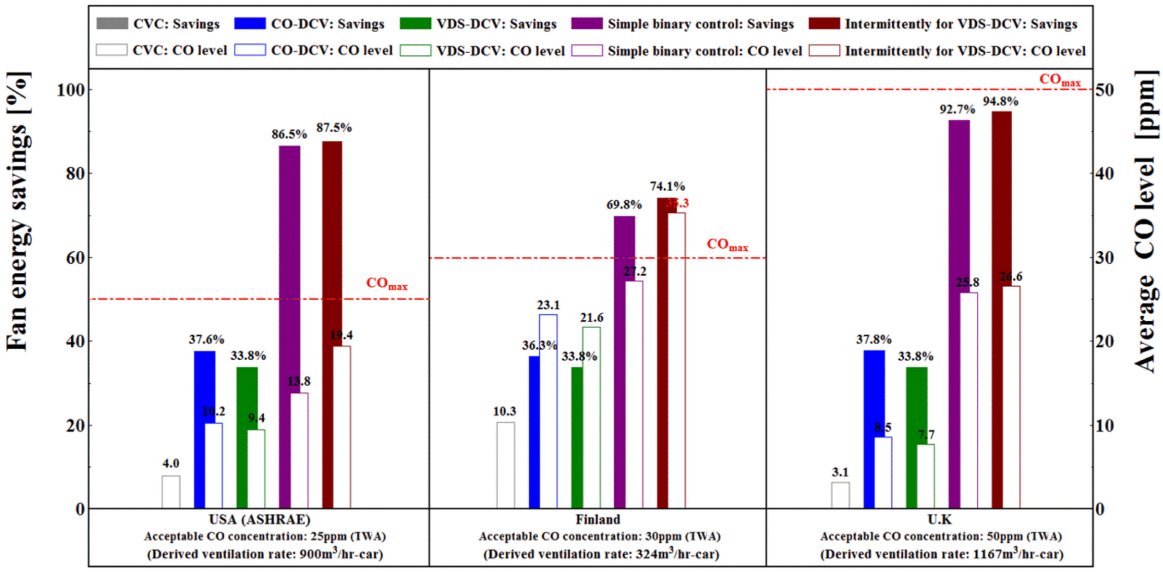
Fan energy was reduced 33~37% in continuous operation mode of DCV compared to the constant volume control-CVC operation by controlling the ventilation air flow according to the traffic load, the indoor contaminant source (Fig. 6.2). One may also see that significant fan energy saving is possible with the simple binary control and the VDS-DCV in the intermittent operation, while the indoor CO concentration is relatively high.

3.2.4. DCV controls for the other countries

ASHRAE Handbook 2007 forecasts different vehicle CO emissions for summer and winter. Simulations were carried out regarding fan energy savings by nation and average indoor CO concentration based upon ASHRAE manual according to the DCV application in underground parking facilities. Three countries were selected to conduct DCV simulations where time weighted average concentration and minimum ventilation standard are all presented (Krarti and Ayari, 2001; ASHRAE, 2007). The difference between actual weather data and applied simulation data of England and Finland was disregarded in order to review



(a) DCV strategies for the other countries in summer season (32°C, 3.09g/min)



(b) DCV strategies for the other countries in winter season (0°C, 11.67g/min)

Figure 7. DCV controls for the other countries.

DCV application according to multiple ventilation standards.

As appeared in Fig. 7, DCV application in continuous operation mode satisfies acceptable indoor air quality by nation as well as fan energy reduction. Fig. 7 also shows Finland has the highest CO concentration whereas the lowest for England. This is because the acceptable indoor CO concentration does not have a direct impact on the operation of ventilation system in continuous operation mode and the total ventilation amount is the biggest factor to determine indoor CO concentration.

Simple binary control & VDS-DCV show considerable fan energy saving rate with relatively higher indoor CO concentration in the intermittent operation mode compared to the constant volume control-CVC (Fig. 7). VDS-DCV exceeds standard indoor concentration during the winter time in Finland, which is because relatively higher acceptable-indoor-CO-concentration directly affects the average indoor CO concentration whereas lower design ventilation rate is designated than other countries (Fig 7.2). Whereas there exist no fan energy difference between summer and winter in the continuous operation mode, fan energy consumption varies according to seasons in the intermittent operation mode. It is because the ventilation system is operated according to the real-time traffic load measured by CO sensor, vehicle detection sensor in the continuous operation mode, however, in the intermittent operation mode, the ventilation system is operated according to the threshold indoor CO limit variables. Therefore fan energy consumption during the winter time is higher than summer due to the difference of CO emissions by seasons. The average CO concentration is higher in winter than summer due to the increasing CO emissions from vehicles. One notable thing is DCV spends 1/3 of fan energy in the continuous operation mode in summer compared to the existing CVC, however, average indoor CO concentration is maintained at the similar level to CVC.

4. Conclusion

For the parking facilities, existing ventilation requirements found in the literature are commonly derived as the outdoor air flow required for removing carbon monoxide generated by the vehicles. The ventilation standard is defined as air exchange rates per unit floor area in most countries. It is considered that the existing approach is hard to integrate into the DCV control on the real-time variation of the traffic load. Therefore, in this study, the current ventilation standards defined as the ventilation rate per floor area or air exchange rate in an underground parking facility was converted as a form of the ventilation rate per a single vehicle. And then the impact of several DCV strategies using the real-time traffic load on the indoor CO concentration and the fan energy consumption were quantitatively analyzed via a series of simulations. The simulation results indicate that a large amount of fan energy consumption can be reduced by the VDS-DCV method in continuous mode operations, in addition to the acceptable indoor air quality. The CO-DCV approach may also be a good choice in the continuous operation mode. DCV is applied more excellently in continuous operation mode in summer with higher outdoor air temperature. In case of the intermittent operation, significant fan energy savings were observed in both the simple binary control and the VDS-DCV, but one may experience the degradation of indoor air quality. Consequently, the continuous operation of ventilation units based on the CO-DCV or VDS-DCV may be a good choice for achieving energy savings and good indoor air quality simultaneously.

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