Standard 62.1-2004

System Operation: Dynamic Reset Options

By Dennis Stanke, Member ASHRAE

Seventeen years ago, the ventilation rates established by ANSI/ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality,* increased substantially over those previously required by the 1981 version of the standard. Fifteen years later, Standard 62.1-2004 (Standard 62.1) prescribed new minimum breathing zone ventilation rates and a new calculation procedure to find the minimum intake airflow needed for different ventilation systems. Described in previous articles,[1–4] these new rates and procedures must be used to find the design or "worst-case" outdoor air intake flow, which establishes the required capacity of mechanical system equipment. In this article, we turn from ventilation system *design* to *operation*.

Although ventilation systems must be designed to handle the highest minimum outdoor air intake flow expected, they often can be operated with less intake airflow (much less in some systems) while still complying with Standard 62.1 requirements. As conditions in ventilation zones change, the required intake airflow also changes. Standard 62.1-2004 recognizes this and allows for *dynamic reset* of intake airflow. Resetting intake airflow to match ventilation load can save outdoor air preconditioning energy while ensuring ventilation at or above the minimum required rates.

Dynamic Reset

Section 6.2.7 (see sidebar, *Dynamic Reset*) allows designs to include optional means to reset either the outdoor air intake flow or the breathing zone outdoor airflow, or both, in response to the current demand for ventilation resulting from current operating conditions. Without precluding other approaches, Section 6.2.7 lists three fluctuating conditions (variations in population, variations in ventilation efficiency, and variations in intake flow above minimum), which may be used as the basis for dynamic reset control approaches.

About the Author

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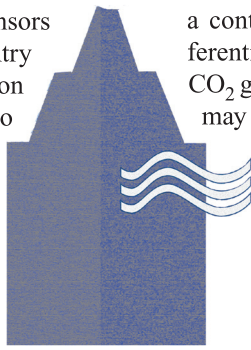
Variations in Occupancy or Ventilation Airflow

The number of occupants in many ventilation zones changes during normal operation. Actual zone population often falls short of the peak design population used to establish the highest zone outdoor airflow and outdoor air intake flow needed. Consequently, Standard 62.1 allows breathing zone and/or intake airflow to be reset in response to changes in zone population or the resulting changes in the zone ventilation airflow per person. To reset ventilation based on the current population within a zone requires a reasonably accurate estimate of population or breathing zone outdoor air rate (per person). Standard 62.1 lists four example measures used to estimate *variations in occupancy* and one measure to estimate *variations in ventilation airflow*.

- **Direct Count of People.** In some zones, occupant entry and exit may be orderly (e.g., through a set of turnstiles or a single set of doors). Using appropriate sensors and counting controls, the difference between entry and exit events can be used to estimate population based on a direct "count." Ticket sales might also be used as an estimate of population. Some retail stores or auditoriums may be configured to use these approaches. Sensors that actually sense individual occupants also might be used, although such sensors are not common.



- **Presence of People.** A variation to counting occupants directly involves simply sensing the presence of occupants. Motion detectors can sense human activity in offices, conference rooms and so on. Upon detecting motion, the control system assumes (estimates) that the zone is occupied at peak population and calls for ventilation accordingly.
- **Time-of-Day Schedule.** In some zones, population can be predicted based on time-of-day (TOD). For instance, the population in a given classroom in an elementary school may be estimated quite accurately during any given hour of the day. The daily schedule for Mr. Brown's fifth graders (25 students this year) places them in Mr. Brown's classroom from 8 a.m. until 10 a.m., in the art room from 10 a.m. until 11 a.m., then back in the classroom from 11 a.m. until noon, and so on. If the building control system includes an occupancy schedule for the classroom, current population can be estimated and outdoor airflow can be reset to match prescribed ventilation airflow to current population.
- **Estimate of Occupancy Based on CO_2 and Airflow.** As Mumma has shown,[5] in a single-zone system, zone and outdoor CO_2 level along with intake airflow could be sensed and, assuming an occupant activity level, used to estimate the current population. At steady-state CO_2 concentration (see Equation 1 in sidebar, *Equations and Variables*) zone population could be found (Equation 2), but in practice, zones seldom reach steady-state conditions. So, in addition to accurate CO_2 and airflow sensors, this approach requires a controller capable of solving a non-steady state (differential) equation. And, since occupant activity level and CO_2 generation rate can vary widely, calculated population may not be accurate. Due to its cost, its complexity and its potential for poor accuracy, not many designers use this approach. However, don't confuse this CO_2-based "people counting" measure with our next topic: traditional CO_2-based "demand-controlled ventilation."
- **CO_2-Based Estimate of Current Outdoor Airflow per Person**. Since changes in population change ventilation "demand," any dynamic reset approach that responds to zone population could be referred to as demand-controlled ventilation (DCV). However, this acronym has been used for years to refer specifically to control measures that sense CO_2 concentration as a surrogate for the concentration of human bioeffluents. The most popular dynamic-reset approach to part-load ventilation, DCV controls adjust outdoor airflow rate to maintain zone CO_2—and thereby bioeffluents—at levels that would result from ventilating at, or above, prescribed minimum outdoor airflow rates. As explained by Taylor,[6] CO_2-based

Dynamic Reset

Excerpt from Standard 62.1-2004:

6.2.7 ***Dynamic Reset.*** *The system may be designed to reset the design outdoor air intake flow (V_{ot}) and/or space or zone airflow as operating conditions change. These conditions include but are not limited to:*

1. *Variations in occupancy or ventilation airflow in one or more individual zones for which ventilation airflow requirements will be reset.* ***Note:*** *Examples of measures for estimating such variations include: occupancy scheduled by time-of-day, a direct count of occupants, or an estimate of occupancy or ventilation rate per person using occupancy sensors such as those based on indoor CO_2 concentrations.*
2. *Variations in the efficiency with which outdoor air is distributed to the occupants under different ventilation system airflows and temperatures.*
3. *A higher fraction of outdoor air in the air supply due to intake of additional outdoor air for free cooling or exhaust air makeup.*

Equations & Variables

Equations:

$$(C_r - C_{oa}) = \frac{k \cdot m}{V_{bz} / P_z} \tag{1}$$

$$P_z = (C_r - C_{oa}) \cdot \frac{V_{bz}}{k \cdot m} \tag{2}$$

$$V_{ot} = \frac{R_a \cdot A_z}{E_z - \frac{R_p \cdot (C_r - C_{oa})}{k \cdot m}} \tag{3}$$

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \tag{4}$$

(See Standard 62.1, Equation 6-1)

$$V_{oz} = \frac{V_{bz}}{E_z} \tag{5}$$

(See Standard 62.1, Equation 6-2)

$$V_{ot} = V_{oz} \tag{6}$$

(See Standard 62.1, Equation 6-3)

$$V_{ot} = \left(\frac{V_{otdes} - V_{ot\,min}}{C_{r\,max} - C_{r\,min}}\right) \cdot (C_r - C_{r\,min}) + V_{ot\,min} \tag{7}$$

$$V_{ot} = 0.392 \cdot (C_r - 400) + 60 \tag{8}$$

(zero-to-peak controller)

$$V_{ot} = 0.894 \cdot (C_r - 780) + 130 \tag{9}$$

(minimum-to-peak controller)

Variables:

- A_z = zone floor area, ft^2 (m^2)
- C_{oa} = CO_2 concentration in outdoor air, ppm
- C_r = CO_2 concentration in breathing zone, ppm
- $C_{r\,max}$ = highest CO_2 concentration in breathing zone, ppm
- $C_{r\,min}$ = lowest CO_2 concentration in breathing zone, ppm
- E_z = zone air distribution effectiveness (See Standard 62.1, Table 6-2)
- k = CO_2 generation rate, 0.0084 cfm per met per person (0.0040 L/s per met per person)
- m = activity level of occupants, met
- P_z = zone population, persons
- R_a = area outdoor air rate, cfm/ft^2 (L/s per m^2)
- R_p = people outdoor air rate, cfm/person (L/s per person)
- V_{bz} = breathing zone outdoor airflow, cfm (L/s)
- V_{ot} = outdoor air intake flow, cfm (L/s)
- V_{otdes} = outdoor air intake flow at design population, cfm (L/s)
- $V_{ot\,min}$ = outdoor air intake flow at minimum population, cfm (L/s)
- V_{oz} = zone outdoor airflow, cfm (L/s)

DCV assumes that people produce both odors and CO_2 in proportion to their activity level, that occupant activity level in a zone (in terms of metabolic rate, *m*) can be estimated with reasonable accuracy, and that steady-state equations can be used to estimate ventilation load, much the same as steady-state equations can be used to estimate heating/cooling load. For single-zone systems, the minimum required outdoor air intake flow can be related to the difference between indoor and outdoor CO_2 level (Equation 3). Taylor goes on to explain how differential CO_2 level can be incorporated in one possible DCV approach—also discussed in the 62.1 User's Manual[7] and detailed below as one of several approaches—to control intake airflow to equal or exceed the minimum required ventilation rate.

The population estimate resulting from any of the first four measures can be used to recalculate the minimum breathing zone outdoor airflow (Equation 4) required by Standard 62.1 for the current population. This new outdoor airflow value then can be used to find the current minimum zone outdoor airflow (Equation 5) needed. For single-zone systems, the zone outdoor airflow requirement equals the intake airflow (Equation 6). Any controller used to implement these four reset approaches must be capable of doing some simple calculations, since the population estimate must be translated to a current outdoor airflow setpoint, and must include means to adjust outdoor airflow to maintain the current setpoint.

The fifth measure described earlier can be used to control intake airflow directly, without actually calculating either current population or the minimum outdoor air intake flow currently required by Standard 62.1. In a sense, any DCV approach that maintains CO_2 level (at or above the levels that would result at prescribed minimum outdoor airflow) controls bioeffluents *directly* in response to both current population and current intake airflow. DCV approaches need controls that sense differential CO_2 and maintain it by adjusting outdoor airflow incrementally without (necessarily) sensing it. We discuss several possible DCV implementations below.

Variations in Efficiency

The second operating condition listed in Section 6.2.7 relates to ventilation efficiency. Standard 62.1 requires accounting for both *zone air-distribution effectiveness* (E_z) and *system ventilation efficiency* (E_v). Zone air-distribution effectiveness applies to all ventilation zones in any system and indicates the fraction of outdoor air delivered to a zone (at the diffusers, for instance) that actually enters the breathing zone. System ventilation efficiency, on the other hand, only applies to multiple-zone recirculating systems and indicates the fraction of outdoor air entering the system (at the intake) that actually dilutes contaminants in the breathing zone. Changes in these efficiency values during operation effectively change ventilation "demand," not as a result of varying population but as a result of varying zone and system airflow at different load conditions.

The default value (refer to Standard 62.1, Table 6-2) for zone air-distribution effectiveness can change during normal operation. For instance, if the same overhead diffusers deliver warm air during heating mode and cool air during cooling mode, the likelihood of air bypassing the breathing zone changes. When heating, warm discharge air tends to float above cooler zone air. If it's too warm (see sidebar, *Warm Supply Air*), a portion of it bypasses the breathing zone, in which case E_z = 0.8, according to Standard 62.1. When cooling, however, all of the discharge air drops into the breathing zone, so E_z = 1.0. For *design* purposes, zone outdoor airflow may need to exceed the breathing zone outdoor airflow by a factor of 1.25 in the heating mode. However, during normal *operation*, zone air-distribution effectiveness may increase from 0.8 when heating to 1.0 when cooling, so zone outdoor airflow could be reset downward to equal the required breathing zone outdoor airflow.

Variations in zone air-distribution effectiveness can be used to recalculate and dynamically reset zone outdoor airflow in *any* ventilation system, but single-zone heating/cooling systems are likely to benefit most from this reset approach. Single-zone systems with increased E_z need less zone outdoor airflow and less outdoor air intake flow (Equation 6) during cooling operation than during heating, which reduces cooling energy. Dedicated outdoor air systems supplying 100% outdoor air, on the other hand, usually deliver ventilation air at or below zone temperature, so E_z doesn't vary with load and intake airflow is usually constant—no dynamic reset opportunities. And, for multiple-zone recirculating systems, increased E_z *in the "critical zone"* during cooling can mean less intake airflow.

System ventilation efficiency (E_v)—the ratio of outdoor air used in all breathing zones to outdoor air intake for the system ($E_v = V_{ou} / V_{ot}$)—varies widely in VAV multiple-zone systems, since both zone and system airflow change in response to load. For *design* purposes, minimum outdoor air intake flow for these systems must be determined using the lowest efficiency and the highest outdoor air intake flow. For proper *operation*, however, minimum intake airflow may be determined using the system ventilation efficiency at current operating conditions. This article focuses on DCV for single-zone systems. A detailed discussion of dynamic reset approaches in multiple-zone systems is left for a future article.

Variations in Intake Airflow

Standard 62.1 cites a third condition that may be used as the basis for dynamic reset control. It relates to variations in the fraction of outdoor air in the primary airstream due to the introduction of excess ventilation air in the process of providing free-cooling with outdoor air (economizer cooling) or providing intake air to replace local exhaust air. This approach only applies to VAV multiple-zone systems since it allows resetting zone minimum primary airflow settings downward. Reducing zone minimum airflow settings can save local reheat energy in some systems at some load conditions. Since this approach would commonly be combined with "variations in efficiency" for multiple-zone systems, a more detailed discussion remains for a future article.

What Changed?

This article focuses on dynamic reset of outdoor air intake flow in response to variations in population in single-zone systems. Since 1989, Standard 62 has specified minimum ventilation rates in terms of outdoor airflow per person for most occupancy categories. This was handy for CO_2-based DCV because it allowed the ventilation rate per person to be held constant by simply adjusting zone outdoor airflow as necessary to maintain the sensed zone CO_2 level constant. Although not explicitly allowed by earlier versions of Standard 62.1, DCV has been used effectively by many system manufacturers and designers, and it was supported by several official interpretations of the standard.

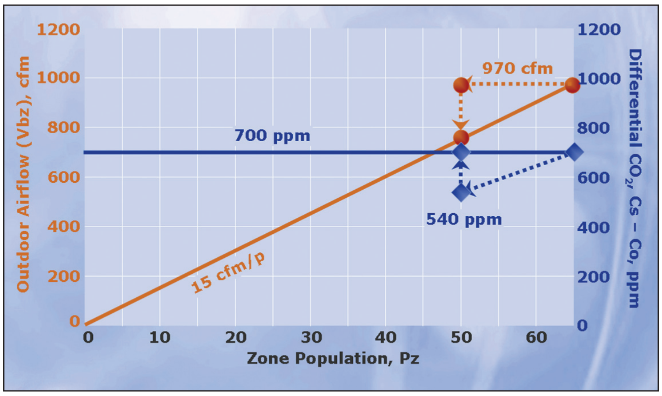
How did it work? For example, assume that a single-zone, constant-volume rooftop unit serves a 1,000 ft^2 lecture classroom designed for 65 people. Standard 62-2001 required a minimum breathing zone outdoor airflow of 970 cfm at design ($V_{bz} = 15 \times 65 = 970$ cfm). With zone air-distribution effectiveness of 1.0, zone outdoor airflow at design equaled breathing

Warm Supply Air

Although Table 6.2 shows lower zone air-distribution effectiveness with overhead heating, designers still have an opportunity to reduce outside air (ventilation air) when heating from the ceiling by meeting the discharge-to-room temperature difference and diffuser throw requirements outlined in the table. In other words, instead of concluding that discharge air temperature always exceeds zone temperature by 15°F when heating, designers can design for lower differential temperatures and comply with Table 6.2 requirements using E_z = 1.0.

In the *2005 ASHRAE Handbook—Fundamentals*, Chapter 33, indicates that differentials in excess of 15°F reduce the likelihood of achieving satisfactory occupant comfort, due to excessive stratification. ANSI/ASHRAE Standard 55-2004, *Thermal Environmental Conditions for Human Occupancy,* limits vertical stratification to 5°F in the occupied zone—a limit that may be violated when differential temperature exceeds 15°F. If too much stratification violates Standard 55-2004, it might also fail to comply with U.S. Green Building Council's LEED®-NC (New Construction) Indoor Environmental Quality (EQ) credit 7.1.

Suffice it to say that high differentials during overhead heating can lead to trouble while lower differentials can lead to many beneficial results.



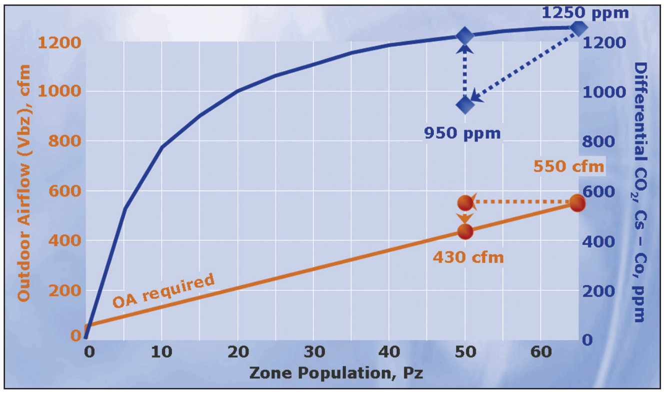
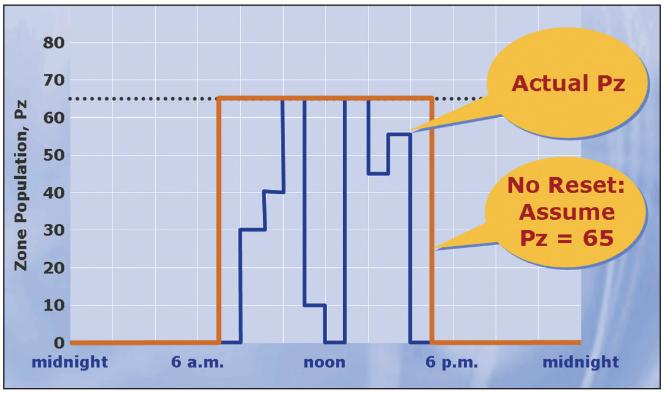


Figure 1 (left): Standard 62-2001: required OA flow and CO_2 level. Figure 2 (right): Standard 62.1-2004: required OA flow and CO_2 level.



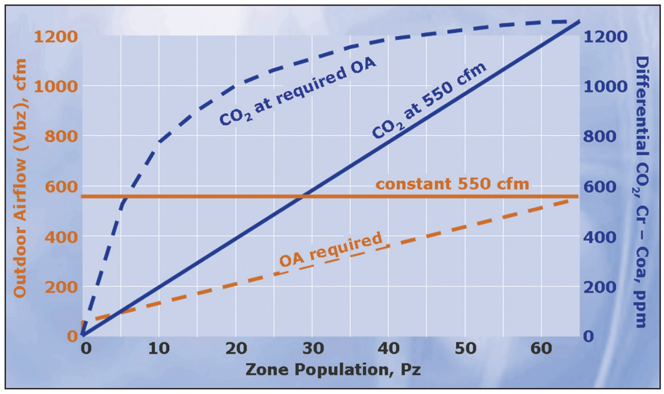


Figure 3 (left): Population profile. Figure 4 (right): Without dynamic reset: OA flow and CO_2 level.

zone outdoor airflow (Equations 5 and 6). Assuming average occupant activity level of 1.25 met and a typical CO_2 generation rate (k = 0.0084 cfm/person/met), the required rate of 15 cfm/person resulted in a differential (indoor-to-outdoor) CO_2 level of 0.000700 (or 700 ppm, see Equation 1). Without DCV, intake airflow would be maintained at 970 cfm regardless of changes in population. If population dropped to 50 people, differential CO_2 would drop to 540 ppm (*Figure 1*). But, 50 people required intake airflow of only 750 cfm. Introducing 750 cfm of outdoor air for 50 occupants again would have resulted in a differential CO_2 level of 700 ppm. Differential CO_2 level could be controlled to a constant value because it was related to the constant ventilation rate of 15 cfm/person. By sensing differential CO_2 level and adjusting intake airflow to maintain it at 700 ppm, a properly designed controller could maintain the zone outdoor airflow at the required per-person rate, without any knowledge of actual population or actual outdoor airflow.

But, Standard 62.1-2004 introduced a new way to find the minimum breathing zone outdoor airflow. Instead of prescribing a single per-person outdoor airflow rate, the standard prescribes both a per-person rate and a per-unit-area rate for each occupancy category. The per-person rate results in a minimum outdoor airflow rate intended to dilute contaminants generated by occupants and their activities, while the per-unit-area rate results in an outdoor airflow rate intended to dilute contaminants generated by the building, its finishes and furnishings. The sum of these airflow rates helps to establish the required intake airflow. The required "effective rate" per person varies with population.

The example lecture classroom now requires 7.5 cfm per person plus 0.06 cfm per ft^2 to comply with Standard 62.1-2004. According to Equations 4, 5 and 6, intake airflow must equal 550 cfm ($V_{ot} = V_{oz} = V_{bz} = 7.5 \times 65 + 0.06 \times 1{,}000$) at the design population of 65 people—a significant drop compared to the 2001 standard. Solving Equation 1, we see that steady-state differential CO_2 rises to 1,250 ppm at this effective rate. If population drops to 50 people and intake airflow remains at 550 cfm (no dynamic reset), differential CO_2 drops to 950 ppm (*Figure 2*). But, Standard 62.1 requires only 430 cfm intake airflow—a slight increase in effective rate cfm/person—which would result in a slight drop in differential CO_2 to 1,220 ppm. In this case, the differential CO_2 level drops as population drops because the effective rate per person rises. Differential CO_2 level could be sensed and maintained at some level by adjusting intake airflow, but at what level? The "target" CO_2 level varies with population, because the effective rate per person varies with population.

At this realization, some designers may conclude that CO_2-based DCV cannot be used to comply with Standard 62.1-2004. Of course, that isn't the case. Controls can still adjust zone outdoor airflow as population changes. These controls

				Estimate of Population			CO_2-Based Estimate of Demand*		
	Actual Zone Population	Min. Required Outdoor Air Intake Flow	No Reset	Direct Count Of People	Presence Of People	TOD Schedule	Fixed CO_2 Setpoint With Base Intake Flow	Proportional CO_2 from Zero-To-Peak Population	Proportional Min.-To-Peak Population
Hour	P_z	V_{ot}	V_{ot}	V_{ot}	V_{ot}	V_{ot}	V_{ot}	V_{ot}	V_{ot}
7 a.m.	0	60	550	60	60	130	280	60	130
8 a.m.	30	280	550	280	550	430	280	380	320
9 a.m.	40	360	550	360	550	430	380	440	390
10 a.m.	65	550	550	550	550	550	620	550	550
11 a.m.	10	130	550	130	550	130	280	230	130
Noon	0	60	550	60	60	130	280	60	130
1 p.m.	65	550	550	550	550	550	620	550	550
2 p.m.	45	400	550	400	550	510	430	460	430
3 p.m.	55	470	550	470	550	510	520	510	490
4 p.m.	0	60	550	60	60	130	280	60	130
Hourly Avg.	—	290	550	290	400	350	400	330	325

* For CO_2-based approaches, the values listed correspond to assumed steady-state CO_2 levels each hour to allow for simple comparison of approaches. In practice, most zones require more than an hour to reach steady-state conditions.

Table 1: Hourly intake airflow required (cfm).

must result in differential CO_2 at or below the "required maximum" (blue line in *Figure 2*), so that the resulting breathing zone outdoor airflow always exceeds the "required minimum" (yellow line in *Figure 2*).

The following paragraphs show several alternative methods for implementing the dynamic reset approaches mentioned previously in single-zone systems (and perhaps, dedicated outdoor air systems with VAV fans). Multiple-zone systems can be designed to use dynamic reset, too, but discussion of these more involved systems deserves a separate, focused article on this subject.

Single-Zone Lecture Classroom

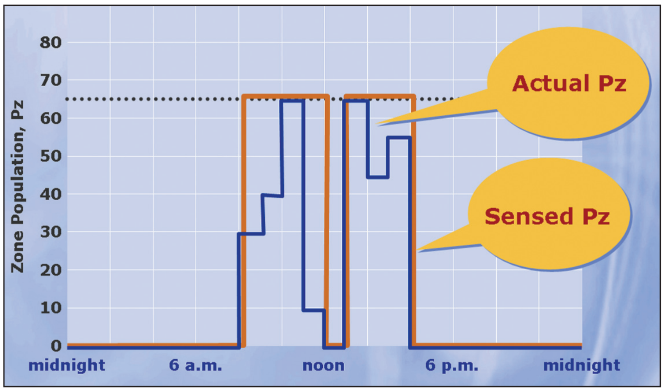
Let's look at different dynamic reset approaches applied to our example lecture classroom. If actual zone population varies throughout a given day as shown in *Figure 3,* the minimum *required* zone outdoor airflow varies from hour to hour as shown in *Table 1* (per Equations 4, 5 and 6). If the controls could bring in exactly the minimum required outdoor airflow for each hour, system intake airflow could be reduced to an average 290 cfm for each hour.

Without dynamic reset control, we must assume that zone population remains at the design value during all occupied hours (65 people each hour for 10 hours, see *Figure 3*). Consequently, the *actual* average outdoor airflow must be 550 cfm during each occupied hour (*Table 1*) regardless of zone population. With constant outdoor airflow, differential CO_2 level varies in direct proportion to population (*Figure 4*). Compliance with Standard 62.1 would have been possible with controls designed to operate the system at reduced zone outdoor airflow—only 290 cfm on average for each hour—but without such controls, the system operates with 550 cfm of intake airflow during all occupied hours. Clearly, some form of dynamic reset could reduce operating costs during non-economizer operation by reducing the intake airflow below its design minimum setting.

Estimate of Population

Dynamic reset based on estimated population allows calculation of current minimum outdoor airflow prescribed by Standard 62.1. It resets intake airflow but it neither senses nor controls actual indoor contaminants directly. It simply assumes that acceptable indoor air quality (IAQ) results from ventilation at the prescribed minimum airflow rates. In that sense, dynamic reset of intake airflow, based on estimated population, controls intake airflow *directly* but IAQ *indirectly*.

Changes in population change the demand for ventilation in occupied zones. Population-based dynamic reset approaches relate intake airflow requirements to estimated population. The following paragraphs describe four such approaches that comply with Standard 62.1-2004 requirements.



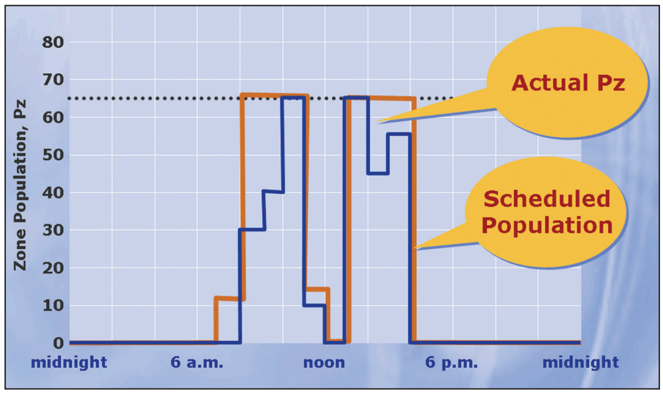
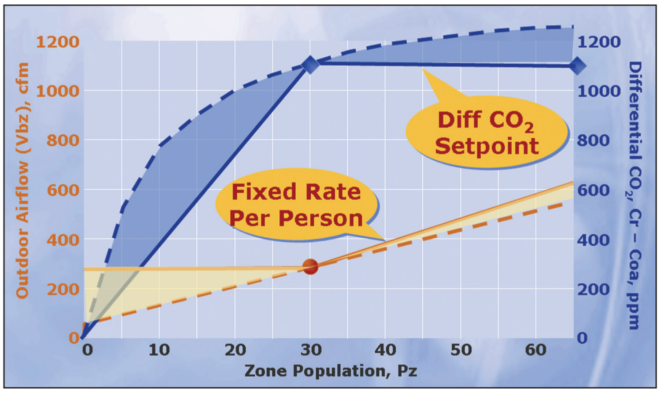


Figure 5 (left): Sensed presence profile. Figure 6 (right): Scheduled occupancy profile.



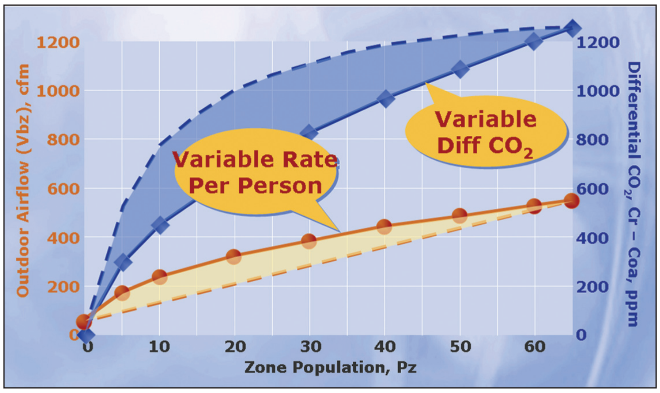


Figure 7 (left): Fixed rate per person (traditional DCV). Figure 8 (right): Zero-to-peak population (User's Manual).

• Direct Count of People

First, consider *direct count of people*. Any control system that accurately counts people can be used to find prescribed intake airflow. In this case, estimated population matches the actual zone population profile (*Figure 3*). The actual intake airflow (V_{ot}) needed for each hour can be determined and used as the new intake airflow setpoint. Both intake airflow and differential CO_2 levels match the design values (*Figure 2*) during all operating hours. With an accurate people count, intake airflow can be controlled to match the minimum required outdoor air intake flow exactly, resulting in an hourly average intake flow of 290 cfm per person in our example (*Table 1*), the lowest possible average rate.

This approach requires a people-counting sensor or sensing mechanism and a controller capable of determining the required intake airflow based on current population and providing this requirement as a new airflow setpoint. It also requires an intake airflow sensor, a modulating intake damper, and a controller capable of maintaining intake airflow at the current setpoint. Such controls may be beyond the budget for many single-zone systems.

• Presence of People

A control system that senses or otherwise determines the *presence of people* "estimates" population and can be used to determine current prescribed intake airflow. Estimated population is either zero or design (*Figure 5*). For each hour, the zone needs ventilation for either design population or for zero population. Intake airflow matches the "no reset" value (*Table 1*) with people present but drops to "zero population" level of 60 cfm with no people present during occupied hours. The intake airflow needed for each hour can be determined and used as the new intake airflow setpoint. Since only two population values can be sensed, only two intake airflow values are needed. Intake airflow control results in an hourly average intake flow of 400 cfm per person, using our example occupancy profile.

This approach requires a people-sensing device, like a motion detector or perhaps just a zone light switch. It also requires outdoor air damper control. A simple approach uses a multiple position OA damper that can be commanded to be closed, open to provide low airflow (no people present), or open to provide high (design minimum) airflow. Alternatively, it could be implemented using a controller capable of determining the required intake airflow based on current population, and providing this requirement as a new airflow setpoint. An intake airflow sensor, a modulating intake damper, and a controller capable of maintaining intake airflow at the current setpoint also would be needed in this case. It seems likely that, given single-zone system budgets, designers would choose a simple, multiple-position damper rather than a setpoint controller. Remember, these are minimum intake settings. During economizer operation, the outdoor air damper opens beyond minimum to increase the intake airflow for cooling.

• *Time-of-Day Schedule*

A control system with a time clock or building automation system, programmed with the expected occupancy during each hour of operation, can estimate current population based on the established *time-of-day schedule*. If programmed using conservatively high estimates of hourly population as shown (*Figure 6*) for our example classroom, the minimum required outdoor airflow for each hour can be determined based on the scheduled zone population. The intake airflow (*Table 1*) needed for each hour can be calculated and used as the new intake airflow setpoint. TOD schedule control for this example results in an hourly average intake flow of 350 cfm per person (*Table 1*).

This approach requires a programmable clock of some sort and a controller that can calculate an hour-by-hour minimum intake airflow setpoint based on scheduled population. It also requires an intake airflow sensor, a modulating intake damper, and a controller capable of maintaining intake airflow at the current setpoint.

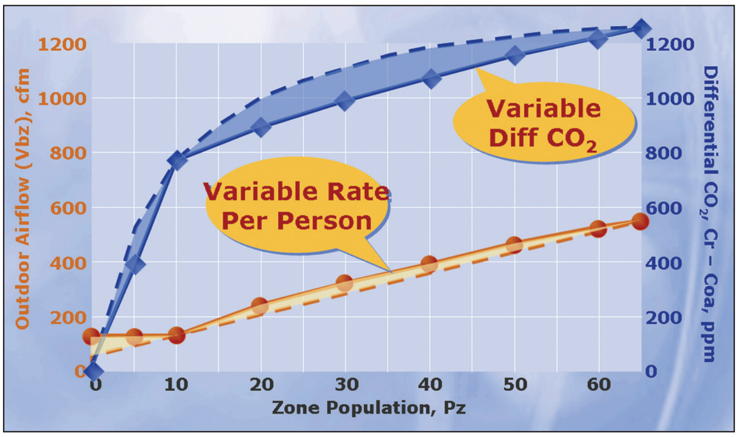


Figure 9: Minimum-to-peak population (modified User's Manual).

• *CO_2-Based Estimate of Occupancy*

Finally, some single-zone system designers may want to estimate current zone population based on sensed CO_2 level and sensed supply airflow, then adjust intake airflow to match that prescribed for the current population. This could probably be accomplished using any of several different approaches. The following illustrates one possible approach.

If intake airflow equals zone outdoor airflow, the current steady-state zone population could be found by sensing zone CO_2 level, sensing or assuming outdoor CO_2 level, sensing intake airflow rate, assuming an average activity level for occupants and solving Equation 2. Of course, zones seldom achieve steady state, so a differential equation (not shown here) must be solved to accurately estimate current population. In any case, with a population estimate in hand, the current outdoor air intake flow required can be found using Equations 4, 5 and 6. This intake flow value becomes the new setpoint for V_{ot}. Introducing outdoor air at this new flow rate changes indoor CO_2 level, even with constant population value. So, the differential equation must be solved continuously to find a steady calculated population value.

Estimating population based on CO_2 level requires sophisticated controls. This approach (which must not be confused with CO_2-based DCV, discussed next) requires at least a zone CO_2 sensor and an intake airflow sensor, along with a modulating outdoor air damper and a controller capable of processing the inputs (by solving a differential equation) to determine the currently required outdoor air intake flow setpoint. We didn't include a detailed controls description for this approach, and we didn't include it in *Table 1*; suffice it to say that if a controller can be designed to produce an accurate and speedy estimate of actual population, this estimate could be used to find the intake airflow prescribed at that population. The result would be identical to "direct count of people" mentioned earlier. However, controller design and tuning realities are likely to result in some "counting" inaccuracy and, therefore, some level of overventilation or underventilation.

CO_2-Based Demand-Controlled Ventilation

As an alternative to the population-based approaches described previously, dynamic reset based on CO_2 levels (and therefore, bioeffluent levels) adjusts intake airflow without attempting to determine the prescribed airflow currently required. It senses and controls one pollutant—CO_2 as a surrogate for human bioeffluent—and it allows intake airflow to vary, so long as it never falls below the prescribed minimum rates. In that sense, CO_2-based DCV controls intake airflow *indirectly* but it controls one component of IAQ *directly*.

CO_2-based DCV approaches have been used widely in the past to comply with Standard 62 during operation. With some small changes, illustrated later, similar approaches can be used to comply with Standard 62.1-2004. So far, we've used estimated population to determine the minimum prescribed intake airflow currently required and to control intake airflow directly based on that population estimate. Now, we'll look at three approaches using differential CO_2 levels to modulate intake airflow incrementally while sensing and controlling CO_2 (and, therefore, bioeffluents) directly, providing at least the minimum prescribed intake airflow without actually sensing intake airflow or maintaining it at a setpoint.

• *Fixed Rate per Person (Traditional DCV)*

The first CO_2-based DCV approach—very similar to traditional DCV approaches—uses a fixed CO_2 setpoint along with a relatively high intake airflow limit to provide outdoor airflow at a *fixed rate per person*. A controller senses indoor CO_2 level and either senses or estimates outdoor CO_2 level. The controller compares these CO_2 levels and as population changes, it adjusts the intake airflow to maintain a fixed differential CO_2 level, and thereby maintain a fixed outdoor airflow rate per person.

A minimum allowable intake airflow limit ensures dilution of contaminants from building sources.

For our example lecture classroom, we arbitrarily selected 30 people as a reasonable average population. With 30 people, Standard 62.1-2004 requires intake airflow of at least 280 cfm, which results in a differential CO_2 level of 1,100 ppm (per Equation 1). So, we set our differential CO_2 setpoint at 1,100 ppm. When population exceeds 30 people (*Figure 7*), the intake airflow needed to maintain 1,100 ppm exceeds the minimum airflow required by the standard. When population drops below 30 people, intake airflow is maintained at the fixed minimum—280 cfm—which results in decreasing differential CO_2 levels. This approach overventilates the classroom (the yellow shaded area) whenever zone population differs from 30 people. It should be evident that the intake airflow savings depend upon the "reasonable" average population used to find the CO_2 setpoint, and the actual population profile for the zone. With the actual population profile used in our example, the "traditional" approach results in hourly average intake airflow of 400 cfm per person (*Table 1*).

This approach requires an indoor CO_2 sensor, either an outdoor CO_2 sensor or a conservatively high estimate of peak outdoor CO_2, and a controller to compare CO_2 levels and incrementally change the position of the outdoor air damper in response to current CO_2 differential. It also requires a modulating intake damper.

• Zero-to-Peak Population (62.1 User's Manual)

The next DCV approach, discussed by Taylor[6] and ASHRAE,[7] varies intake airflow in direct proportion to the actual differential CO_2 level from *zero-to-peak population*. The 62.1 User's Manual explains this approach for single-zone systems in detail. Using the steady-state CO_2 level expected with required minimum outdoor intake flow for both zero population and design (peak) population, the controller is calibrated and outdoor air damper is adjusted to deliver the lowest required intake airflow at zero population (lowest differential CO_2) and highest required intake airflow at design population (highest differential CO_2 level). As population and intake airflow vary, the controller adjusts intake airflow in direct proportion to the sensed differential CO_2 level, in accordance with Equation 7.

Our example lecture classroom requires 60 cfm of outdoor air at zero population and 550 cfm at design population (see Equations 4, 5 and 6). According to Equation 1, differential CO_2 level is zero with zero population and proper ventilation (since the only source of CO_2 is outdoors) and at design population, it's 1,250 ppm. For our example controller, intake airflow follows Equation 8. Using a spreadsheet at each given zone population, we assumed an initial value for zone CO_2 level (C_r), solved Equation 8 for intake airflow, then solved Equation 2 for the differential CO_2 expected for the given zone population and calculated intake airflow. This process was repeated until the expected CO_2 level matched the initially assumed level. The entire process was repeated for several different zone populations to construct the plots in *Figure 8,* which show both the steady-state differential CO_2 level and the intake airflow that would result using the proportional controller described by Equation 8. Minimum intake airflow matches the Standard 62.1 requirement at both zero and design population, but it exceeds the minimum requirement at all other populations. The yellow line indicates the resulting V_{ot} and the blue line indicates corresponding differential CO_2 level. The yellow shaded area represents excess ventilation and the blue shaded area represents lower-than-maximum differential CO_2 level. As above, intake airflow savings depend upon the actual population profile for the zone. For this example, an hourly average intake airflow of 330 cfm per person results (*Table 1*).

This approach requires an indoor CO_2 sensor, either an outdoor CO_2 sensor or a conservatively high estimate of peak outdoor CO_2, and a controller to compare CO_2 levels and incrementally change the position of the outdoor air damper in response to current CO_2 differential. It also requires a modulating intake damper.

• Minimum-to-Peak Population (Modified 62.1 User's Manual)

A slight variation on the zero-to-peak-population approach, *minimum-to-peak population* uses a non-zero minimum population. This DCV approach also varies intake airflow in proportion to the actual differential CO_2 level, but in this case we find the steady-state CO_2 level expected at an assumed *minimum population* and at design (peak) population. Again, the intake damper is controlled to deliver the lowest required intake airflow at the assumed minimum population and highest required intake airflow at design population. The controller adjusts intake airflow in direct proportion to the sensed differential CO_2 level as population (and differential CO_2 level) varies, in accordance with Equation 7.

Our example lecture classroom requires 130 cfm of outdoor air for an assumed minimum population of 10 occupants and 550 cfm at design population (Equations 4, 5 and 6). According to Equation 1, differential CO_2 level is 780 ppm with 10 occupants present and 1,250 ppm at design population. In this case, our example controller follows Equation 9 to find intake airflow. Again, using a spreadsheet and the procedure described previously, we constructed the plots in *Figure 9.* Minimum intake airflow matches the Standard 62.1 requirement with 10 occupants and with design population, but it exceeds the minimum requirement at all other populations. As above, intake airflow and the corresponding differential CO_2 level are shown by the yellow line and blue line, respectively. The yellow shaded area represents excess ventilation, and the blue shaded area represents lower-than-maximum differential CO_2. Again, intake airflow savings depend upon the actual population profile for the zone. For this example, an hourly average intake airflow of 325 cfm per person (*Table 1*) results.

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As with the previous approach, minimum-to-peak control requires an indoor CO_2 sensor, either an outdoor CO_2 sensor or a conservatively high estimate of peak outdoor CO_2, and a controller to compare CO_2 levels and incrementally change the position of the outdoor air damper in response to current CO_2 differential. It also requires a modulating intake damper.

Building Pressure

Don't forget about building pressure! Building pressure responds to changes in intake airflow. During economizer cooling operation, when intake airflow exceeds the minimum airflow needed at design conditions, most systems must include provisions to increase relief airflow to avoid overpressurizing the building. Excessive positive pressure makes the doors stand open.

During heating or mechanical cooling operation with intake airflow at design minimum, the air balancer typically adjusts central relief airflow so that relief, local exhaust and exfiltration balance with intake airflow and maintain a neutral or slightly positive building pressure. Any dynamic reset approach that reduces intake airflow below the minimum required at design conditions must include provisions to ensure proper building pressure. As minimum intake airflow drops, central relief airflow must also drop to avoid negative building pressure. Mandatory local exhaust airflow coupled with building pressure requirements usually limit the relief airflow reduction permitted. So, intake airflow may be reduced by dynamic reset controls, but it cannot be reduced below a low limit, usually determined by the net sum of local exhaust airflow and the infiltration/exfiltration airflow resulting at the required building pressure.

In other words, be aware that building pressure considerations often limit the ability of the dynamic reset control system to reduce intake airflow. This can limit DCV energy savings unexpectedly.

Summary

Standard 62.1-2004 establishes new breathing zone outdoor airflow rates and new calculation procedures to determine *design* outdoor air intake flow rates (which in many cases are significantly lower than those previously required). It also allows optional dynamic reset approaches that may be used to determine intake airflow required during actual *operation*. Many designers have questioned whether the new rates and procedures are compatible with traditional demand-controlled ventilation approaches. To help answer this question, we investigated various control approaches for single-zone systems. These approaches vary intake airflow either directly based on changes in estimated population or indirectly based on changes in sensed CO_2 level. Systems designed to operate using any of these dynamic reset approaches would save intake airflow (and operating energy) and would comply with Standard 62.1. The "best" choice—the one that reduces intake airflow to the lowest achievable level—depends on the HVAC system, the expected population profile for the zone, the cost of sensors and the cost and desired sophistication of the controller.

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