gravel material at culvert outlets begin to increase our knowledge of scour at culvert outlets. The Bohan and the Fletcher and Grace equations have provided conservative estimates of scour in uniform noncohesive materials that have d_{50} > 0.22 mm. Opie's results have not been used previously in the form presented in this paper to estimate scour in uniform gravel. This is partly because of the different objectives of his study and partly because there were no scour data for sand or gravel materials that approached the size of particles he used.

The equations presented herein for the scour-hole characteristics of depth, length, width, and volume provide a refinement in the estimation of these parameters. Improved evaluations of alternative methods of scour protection or energy dissipators can be obtained by using these new estimates.

The magnitudes of the scour cavity vary in relation to the mean grain diameter and the discharge intensity, as shown in Figure 5. Therefore, if the culvert diameter, design discharge, and median diameter of the channel-bed uniform material are known, all scour-hole characteristics can be determined.

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Test Simulations of a Single-Track Subway Environment

NEIL MELTZER

The Subway Environment Simulation (SES) Computer Program was developed to analyze flows of air and heat in complex subway networks. As part of a recent effort to enhance its cost-effectiveness, the SES was reworked to operate on the central computer facility at the Transportation Systems Center in order to provide project administrators with real-time access capabilities. To demonstrate these capabilities, a series of test cases was devised that illustrated the transformation of data from input to output that would characterize more-detailed simulations. A single-track, two-stop route was selected for a base that allowed for the introduction of variable scheduling, track alignment, speed restrictions, coasting, distributed heat sources, blockage ratios, head losses, station impedances, vent shafts, and fans. Data were derived from prior sample problems described in the Subway Environmental Design Handbook. The requirements for input verification and computational execution of each case are described. The program output details, at user-specified intervals, the train's position and speed, heat rejection, induced airflow, system air velocities, temperature, and humidity. Data are summarized and compared by using baseline time-location profiles. These results are contrasted with alternative methods for quantifying the subway environment, including a model of propulsive force estimated by linear regression of the manufacturer's data. Further analysis provides insight into the development of design strategies through basic simulation. In conjunction with piston action, the tunnel-vent configuration has a predictable effect on resulting patterns of airflow. Fundamental parametric relationships are evaluated, and implications for environmental control in stations are discussed.

The Subway Environment Simulation (SES) Computer Program was developed as an end product of the Subway Environmental Research Project. Organized in 1969 and administered by the Transit Development Corporation under a grant from the Urban Mass Transportation Administration (UMTA), the project produced extensive methodologies for evaluating strategies for environmental control in underground rapid transit systems.

As discussed at length in the Subway Environmental Design Handbook (1, Part 1.3, pp. 1-13 to 1-20), computer simulation was used to overcome the deficiencies of closed-form analytic techniques so that the patterns of air flow and heat transfer associated with complex subway networks could be predicted with accuracy. Accordingly, a comprehensive research program was structured to develop and validate (by using scale models and field testing) the SES as a valuable analysis tool. Since its release in 1975 (2), numerous systems in the United States and abroad have been subjected to SES analysis in applications ranging from concept development to final design evaluation.

When the time came to revise the SES to include major enhancements, experienced users were sought for further technical direction. Largely for this reason, the current version of the SES was reworked to operate on the central computing facility at the Transportation Systems Center (TSC) in Cambridge, Massachusetts, where U.S. Department of Transportation (DOT) project administrators could use direct machine access to develop real-time familiarity with the computer program. In order to demonstrate an emerging analytic capability, a series of test cases was devised to illustrate the transformation of data from input to output that would characterize more detailed simulations.

Data were generated for testing the program operation by using a wide range of computational possibilities. Cases evolved from the most basic aboveground, single-train route to an underground system that had multiple routes, a tunnel that had a

Figure 1. Basic route and track profile.

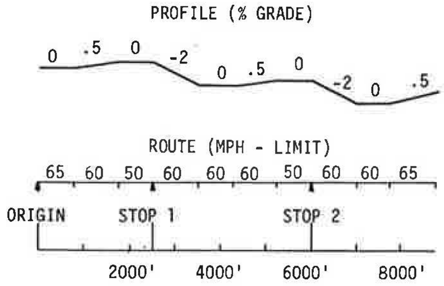
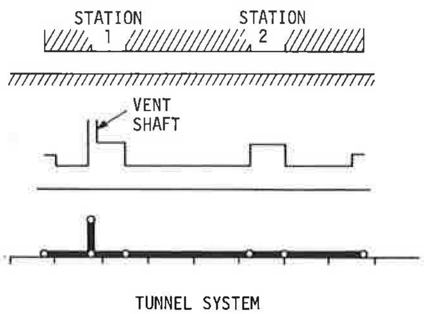


Figure 2. Tunnel system and ventilation network.



varying cross section, and vent shafts that had fan operations. In each case the emphasis was placed on producing acceptable program execution and results that were feasible, consistent, and explainable.

This paper does not chronicle those cases per se, but rather describes the data, both input and output, as they relate to the elements of subway environmental design. It is designed to further an understanding of the state of the art and to orient future research and applications at DOT.

DATA REQUIREMENTS

The main objective in testing the operation of the SES program was to integrate progressively more complex design factors onto the basic input in order to obtain an increasingly broad range of environmental performance measures. These include train movement, heat release, bulk airflow, air velocity, temperature, and humidity--instantaneous and average values and extremes--at multiple locations and times within a tunnel-vent system. Once enumerated, this output was then subjected to comparison with other models of environmental performance, to parametric analysis, and to evaluation of design alternatives.

Input data were drawn principally from the SES Sample Problems (2, Chapter 13, pp. 13-5 to 13-193). These files contain realistic values for system geometries, surface characteristics, train routing, propulsion data, and heat and humidity sources. Also illustrated are the file structure and proper digital alignment. [Complete listings are available from the author.]

The scenario employed for the full set of design options depicts a simple west-to-east route (Figure 1) that runs through a two-station tunnel-ventilation system (Figure 2). This design scenario considers groups of four-car trains dispatched at 90-s intervals along 10 interconnected track sections that alternate in length between 750 and 1000 ft at the grades indicated. Trains accelerate to the posted speed limit, automatically coasting and braking to stop at points 2500 and 6000 ft from the origin. Passengers board trains at the rate of 150 per 180-s stop at each station, including the origin; 50 and 100 riders disembark at successive stops.

The tunnel-vent system (Figure 2) is based on a single 300-ft^2 bore that extends from points 750 to 7750 ft along the route. Stations are carved out between 1750 and 2500 ft and between 5250 and 6000 ft. Cross-sectional areas vary from the portals (300 ft^2) through midtunnel (225 ft^2) to the stations (450 ft^2). Each segment is further divided to contain steady-state heat sources that vary from 7 to 727 Btu/h•ft. The vent shaft that connects the station tunnel to the atmosphere is located at the west end of the first station (1750 ft) and has a grate-free area of 150 ft^2, a stack height of 50 ft, and a maximum outflow of 1000 ft/min. It accommodates an exhaust fan set for positive flow.

The transformation of input to output is the first-order result of simulation. When adjusted properly, the program performs the detailed calculations necessary to evaluate the given design scenario. Listed for each train are instantaneous values for location, speed, acceleration, air drag, tractive effort, motor current, horsepower, grid temperature, power loss, and heat rejection. Airflow and air velocities are printed for each segment; temperatures and humidities are printed for each subsegment. The system summary provides maximum, minimum, and averages for each parameter within a segment, as well as heat-balance totals. These statistics are particularly helpful in referencing the critical elements of environmental control.

TRAIN POSITION AND TRACTIVE FORCE

Whereas heat release and piston action are byproducts of train propulsion, motion along the route is the intended result, and the one most basic to understanding the differential loading on the subway environment. If speeds were constant at the limit, location could then be predicted as a product of these speeds and time. This, of course, does not account for the variations induced by train operating modes.

To more closely approximate the motion simulated by the program, one could presume uniform acceleration to the limit and deceleration to a stop thereafter. However, there are other factors to consider. In operation, forces are applied to overcome the inertia established by the bulk of the train, its equipment and moving parts, and its passengers. Tracking these forces over time and distance without the computational advantages of a simulation model is, at very least, problematical.

Suppose that propulsive force is equated to the train's tractive resistance as described by the manufacturer's data (2, Chapter 13, pp. 13-5 to 13-193). Derived through linear regression, force is related to speed by the equation

$$F = (W/g)(K_1 - K_2 U) \quad (1)$$

where

F = force (lb),
U = train speed (mph),
W = train weight (lb),
g = gravitational constant = 47.18, and
K_1, K_2 = coefficients determined by linear regression (K_1 = 7.011 and K_2 = 0.069).

Equation 1 can then be subjected to Newton's law of motion, resulting in the nonhomogeneous linear differential equation

$$d^2S/dt^2 = (K_1 - K_2)(dS/dt) \quad (2)$$

where

S = position (ft),
t = time (s),
(d^2S/dt^2) = acceleration (mph/s), and
(dS/dt) = U = train speed (mph).

The solution to Equation 2 with appropriate boundary conditions for position S(t = 0) and velocity U(t = 0) is described by a trajectory whose acceleration decreases as an inverse exponential

$$S = (K_1/K_2)(t) - [(K_1/K_2)^2]\,[1 - \exp(-K_2t)] \quad (3)$$

Of note are the following observations:

1. Speed increases with time. Tractive force is always applied in the forward direction, producing positive acceleration.
2. Speed is limited asymptotically to a maximum (K_1/K_2) = 101.61 mph. This result is implicit in the tractive performance data and is not restricted by train coasting or braking.
3. To reach the halfway point on a trip of 3000 ft requires less than 30 s. However, the speed limit of 65 mph is exceeded in less than 15 s.

Figure 3 demonstrates how the application of train-speed control mentioned earlier might effect the velocities predicted by tractive force.

Although the consideration of tractive force alone is insufficient, that methodology illustrates the manner in which the SES calculates the implicit train performance. In essence, the total complement of propulsive and resistive forces is added to the equation of motion to account for the following factors:

1. The effective mass of the train vehicle is augmented by the rotational inertia of moving parts and the weight of passengers and ancillary equipment.
2. Cam controllers reduce current through the motors during acceleration by sequentially varying the circuit resistance, and hence power is lost to the resistor grids.
3. Curves and grades associated with the system profile deflect inertial forces so as to alter the vehicle kinematics.
4. Mechanical resistances induced by friction on the motor and wheels can be enumerated, thus providing better correlation between motion and tractive force.
5. Air drag on the surfaces of the vehicle, which increases roughly as the square of the velocity, is considered.
6. The disengagement and regeneration of tractive effort associated with coasting and braking, respectively, are simulated; the SES Train Performance Subprogram (2, Section 2.1, pp. 2-4 to 2-8) performs computations more sophisticated than those from a single differential equation.

The results of the simulated route are presented in Figure 4.

Figure 3. Theoretical train performance.

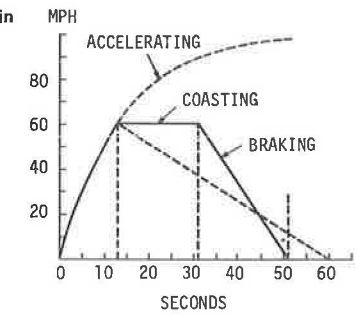
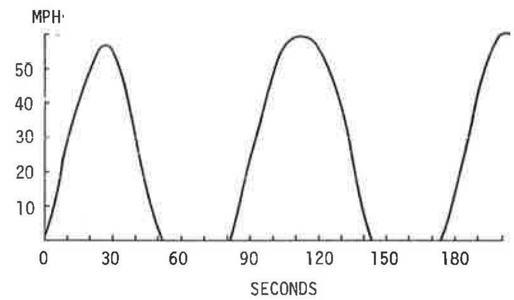


Figure 4. Simulated train performance.



AIRFLOW AND VELOCITY CONTROL

Aerodynamic drag establishes a forcing function on the air confined within a tunnel (the piston effect). The surface of a train that moves through an air mass exerts pressure on that mass, inducing a pattern of flow restricted by the geometry of the containing surfaces and governed by principles of energy transfer. In particular, the SES Aerodynamic Subprogram (2, Section 2.2, pp. 2-9 to 2-13) calculates airflow in such a way that each line section defines a flow field that is one dimensional, unsteady, turbulent, and incompressible.

Velocities in a tunnel-vent system that has specified geometry and train characteristics are determined by equating the drag forces on the train with pressure losses in its vicinity, according to the Bernoulli equation. The computational procedures, further explained in the Subway Environmental Design Handbook (1, Part 3.1, pp. 3-24 to 3-51), account for the following:

1. Gradients in the pressure field drive air through openings in conduits to and from the atmosphere.
2. Pressure losses along the tunnel are additive and proportional to the air-velocity head times a friction factor determined by relative wall roughness, Reynolds number, area changes, protuberances, and vertical open areas.
3. Turbulent losses to surface angles, turns, and junctions are highly dependent on the geometry of the cross section, characterized by its aspect ratio.
4. Cross-flow splits at junctions converge for flow in either direction and aid in the calculation of total flow impedance in their vicinity.

Rather than by deriving the piston action in our tunnel system from the basic equations of motion, fundamental flow patterns can be understood by means of the simulation data.

Consider the tunnel system of Figure 2. Plotting train position as a function of time yields a baseline on which the airflow can be measured. Figure 5 details the periodic fluctuations between 0 ft^3/min and a maximum of approximately 411 300 ft^3/min. After an initial start-up time, the maximum velocity effected by the 225 ft^2 cross

Figure 5. SES airflow versus time profile for tunnel system.

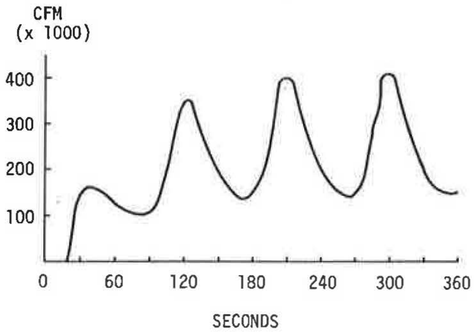


Figure 6. Instantaneous air velocities in entrance tunnel and vent shaft.

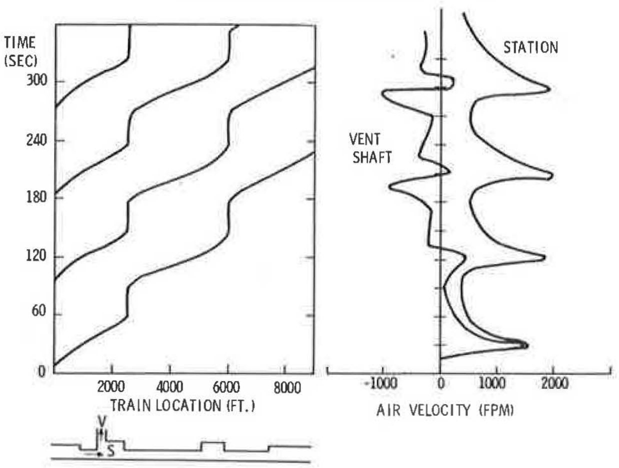
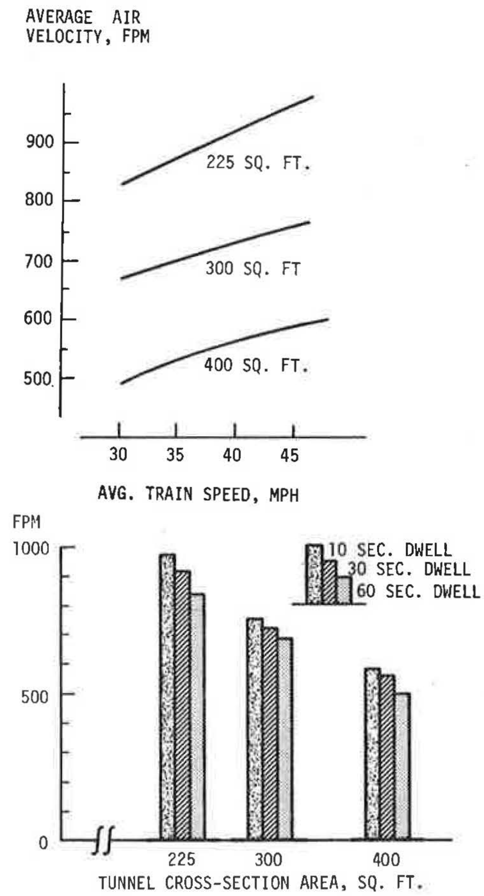


Figure 7. Average air velocity versus tunnel cross-sectional area for varied station dwell time.



section is 1828 ft/min at t = 300 s, or when the second train is leaving station 2, the third train is leaving station 1, and the fourth train is approaching station 1 in the entrance tunnel. Once the first train has left the first stop, flow is never again less than approximately 100 000 ft^3/min or 224 ft/min.

When the complete ventilation system--with vent shaft--is simulated, a more intricate pattern emerges. Airflow is split between the vent shaft and the remainder of the tunnel. As the train leaves the first station, flow induced behind it is likewise drawn from both the entrance tunnel and the vent shaft, reducing the longitudinal suction experienced at their juncture. Velocities in the entrance tunnel and vent shaft are plotted in Figure 6. For obvious reasons, train speed and blockage ratio are the primary determinants of air velocity in a tunnel. Their interrelationship can be derived by expressing the effective pressure drop in terms of the losses along the tunnel and equating this expression with the far-field drag force produced as the piston effect. Section 3 of the Subway Environmental Design Handbook (1) enumerates the parameters necessary to perform this formidable task. A more expedient, if less elegant, solution can be developed by exploiting the empirical relationship in the simulation data.

The tunnel diameter and the dwell time at station 1 can be varied in order to control average speed between the origin and station 2. Figure 7 summarizes the resulting interrelationship. As the diagrams suggest, air velocity varies directly with train speed and inversely with tunnel diameter. Within the limits of our simulation, the latter effect is much more pronounced; an increase in train velocity when the tunnel diameter is held constant produces a less-measurable increase in average air velocity than does an equal percentage of reduction in tunnel diameter.

These observations are reflected in Equation 4, estimated by log-linear regression, which expresses the relationship as multiplicative:

$$V = 1.05\,(U^{0.40}/C^{0.88}) \qquad (4)$$

where

- V = average air velocity in the tunnel (ft/s),
- U = effective train velocity (mph) over the first 6000 ft of the route, and
- C = average (constant) tunnel cross-sectional area (ft^2).

This estimate is for the particular tunnel network only. Note the relative sensitivity to the two independent variables. To realize equal percentage changes, train speed must be increased by more than a power of two above a corresponding decrease in tunnel area.

Even more difficult to surmise is the dependence of air velocities on the tunnel-vent configuration. The ventilation shaft depicted in Figure 2 is often called a blast shaft because it is thought to reduce peak velocities otherwise directed onto a station platform downstream from an approaching train. Although the effectiveness of this particular strategy can be questioned (1, Part 3.2, pp. 3-65 to 3-78), the placement of shafts is an important

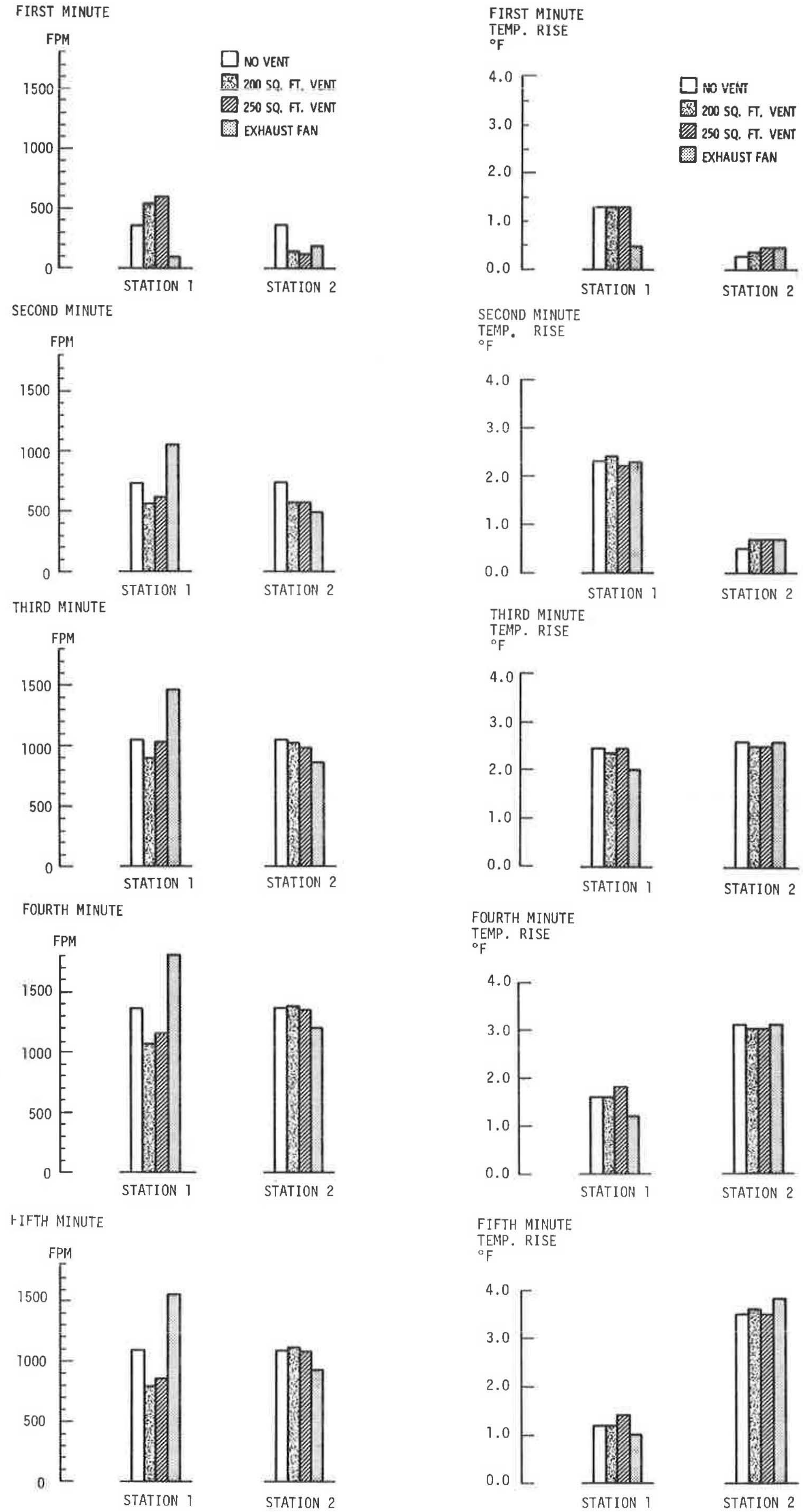


Figure 8. Average air velocity and temperature rise at each station.

design consideration, one that is well suited to simulation.

In the simulated system, air velocities follow a general cyclic pattern, as can be seen in Figure 6 (right side). Velocities evolve over a start-up period, thereafter oscillating between local maxima and minima. Venting has both mean and amplitudinal effects. Using the SES on variations of the basic design produces such results as the following:

1. Increasing the cross-sectional area of the vent 25 percent reduces fluctuation by 5 percent but raises slightly the mean velocity. The resulting maximum velocity decreases by 1-2 percent.
2. Displacement of the vent to the forward (downstream) end of the station substantially reduces the mean velocity and the fluctuation. This is contrary to expectations on the "proper" location of a blast shaft.
3. The addition of a second, identical vent shaft at the opposite (forward) end of the station has the same result as that expected as a result of inserting a larger shaft midway, i.e., reduced mean velocity and fluctuation.
4. A typical exhaust fan of capacity 220 000 ft^3/min increases the average flow by approximately 25 percent.

DESIGN STRATEGIES

All these data are important when circumstances that arise in subway stations are considered. The station environment is characterized by transient airflow, as examined above, and by measures of air quality. Masses of air that surround station surfaces are subjected not only to piston action but also to excessive releases of heat from trains, resistor grids, rails, other equipment, and people. During peak summer rush hours, temperatures on station platforms can rise by more than 20-30°F over the ambient. Hence a need for some control.

Ventilation for draft relief has been designated the airflow management policy central to the design of environmental control systems (3). Within this notion is a recognition that a heat balance that would otherwise be unacceptable for reasons of extreme temperature, humidity, velocity, etc., can be improved by strategic use of natural piston-action ventilation. The use of computer simulation is one way of evaluating such control.

At each instant of observation, at both stations, an associated matrix evaluates air velocity and temperature rise (i.e., increase over ambient). Figure 8 summarizes the average measures of the station environments during the first 5 min of simulation. In particular, differences attributable to ventilation capacity are exhibited. And as an approximation, data for the analysis of alternative environmental control systems are presented.

Clearly such evaluation must account for trade-offs between resulting velocities and temperature at the prospective stations. For example, to increase vent size at station 1 reduces temperatures at station 2, at less extreme velocities, but at the price of aggravating both velocities and temperatures at station 1 for all time intervals.

Alternatively, the provision of mechanical ventilation to supplement that available through piston action is effective in reducing temperatures at station 1 but contributes to further deterioration of the thermal environment at station 2. Furthermore, to the extent that high temperatures are preferable to high velocities, ventilation might be reduced rather than supplemented.

This analysis is intended only to illustrate the thrust of subway environment simulation from a design-oriented stance. In more practical situations, similar information on a variety of parameters is developed into engineering concepts and is further exploited in the validation of final designs.

CONCLUSIONS

The test simulations reported in this study demonstrate a capability to execute the SES Computer Program by using design data. In addition, they provide a framework for analyzing the subway environment in its entirety. Within this framework, system design is seen as a process by which ventilation elements are integrated onto a basic structure. Such integration requires the enumeration of track profile and scheduling data, the specification of the tunnel network, and calibration of surface dimensions and angularities. At appropriate stages of formulation, the systems are validated by using SES subroutines.

The simulation data detail not only the resulting flows of air and heat but also the factors underlying environmental performance. Train positioning and the dynamics of propulsion are the key to understanding heat release and air drag, which constitute the major loads on the subway environment.

Environmental control is established according to patterns of airflow determined by the piston effect. To a certain degree, air velocities can be controlled through variation of station dwell times and the tunnel-vent geometry. Exhaust fans can provide an additional measure of control. The simulation data have been used to quantify the basic relationships and to explore design strategies for regulating the station environment.

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