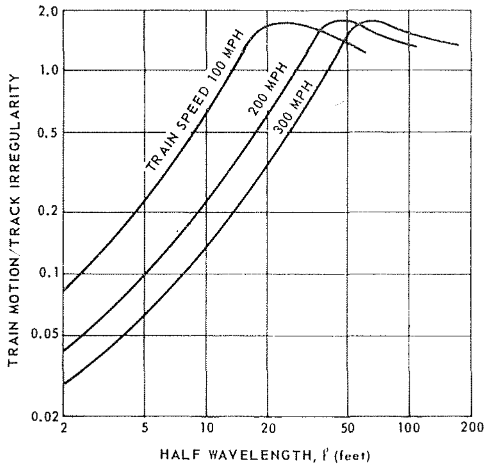

Fig. 12 Relationship between train motion and allowable track misalignment

train with respect to the rail will be less than those shown. It appears reasonable to assume that the track irregularities for the short half wavelengths will be adjusted by realigning the rail with respect to the tube while the longer wavelength irregularities will be in the tube with respect to the tunnel and will be controlled by adjustments of the tube position. It is interesting to note that for the short wavelength, high frequency disturbances, the dynamic displacement of the train relative to the rail is about the same amount as the allowable track irregularity. The amount of train-tube displacement allotted for vibration in the baseline definition is also shown.

For an insight into the relationship between the maximum train motion and the irregularity of the track when the track smoothness just satisfies the ride comfort requirements, the ratio of the train motion to the track irregularity is presented (Fig. 12) as a function of half wavelength for train speeds of 100, 200, and 300 mph. This presentation shows that at the shorter half wavelengths, the response is amplified. The point at which the train motion and track irregularity are equal represents a disturbance frequency of about 5.5 Hz and is independent of train speed.

Conclusions and Recommendations for Future Research

Success has been achieved in developing computer programs to evaluate the response characteristics of complex dynamic systems such as that of the Gravity-Vacuum-Transit System. The techniques employed as well as the programs themselves are considered to have general application to the analysis of ground transportation systems. The results of the studies show the influence of track irregularities on riding comfort and indicate that the track alignment requirement is about 25 times more stringent than that presently achieved on the Japanese Tokaido railroad. (This requirement on track alignment approximately matches that of the Baseline System Definition [1].) If this smoothness criterion cannot be met, it may be necessary to soften the wheel spring suspension and increase the clearance between the train and tube to provide acceptable comfort at high speed. An alternate solution might be the incorporation of an active and/or adaptive train suspension system.

Other conclusions include:

1 The proposed flexible mounting of the tube contributes no direct benefit in reducing periodic disturbances affecting passenger comfort, but may be useful in adjustment of the tube alignment.

2 The dynamic deflection of the train with respect to the tube is relatively small and within acceptable baseline tolerances.

3 Damping in the car suspension should be sufficient to eliminate the sharp resonance response; however, damping beyond this limited amount cannot be used to improve the critical alignment requirements.

4 Except in the vicinity of the train suspension natural frequency (3 to 5 Hz), the mass of the tube has little influence on the acceleration response of the train due to track disturbances.

5 The tube critical velocity is sufficiently high with respect to the train velocity so as to have little influence on the acceleration of the train due to track disturbances.

6 The damping characteristics of the flex joints connecting the cars have a strong influence on the dynamic response of the train.

Based upon the work described herein, recommended areas for additional analytical studies include:

1 The track alignment requirements as dictated by allowable periodic lateral accelerations of the passenger.

2 The vertical and lateral responses of the GVT train to nonperiodic track disturbances.

3 The longitudinal response of the train to pneumatic forces.

4 The interaction between the two tubes of the GVT system to assess the need and desirability of joining them together as proposed in the baseline definition.

References

1 Edwards, L. K., and Skov, R. E., "Baseline System Definition: Urban Gravity-Vacuum-Transit," Contractor Report APL/JHU BFM-097, May 1968. (Available from CFSTI as PB 179 157.)

2 Makofski, R. A., et al., "Performance Criteria and Technical Feasibility of the Urban Gravity-Vacuum-Transit System," APL/JHU TG 984, May 1968. (Available from CFSTI as PB 179 055.)

3 Matsudaira, T., "How High Can Train Speed Be Increased," *International Railway Congress Association Monthly Bulletin*, Vol. 44, No. 1, 1967, pp. 93–99.

4 Sato, Y., "The Tolerance of Track Longitudinal Level Irregularity Determined by Riding Quality," Japanese National Railway, *Quarterly Report of the Railway Technical Research Institute*, Vol. 8, No. 1, 1967.

5 Goldman, D. E., "A Review of Subjective Response to Vibrating Motion of the Human Body in the Frequency Range 1 to 70 Cycles Per Second," National Medical Research Institute Project MM 004001, Report No. 1, March 16, 1948.

6 "Survey of Technology for High Speed Ground Transport," M.I.T., June 15, 1965. (Available from CFSTI as PB 168 648.)

7 Carstens, et al., "Literature Survey of Passenger Comfort Limitations of High-Speed Ground Transports," United Aircraft Report D-910353-1, June 1965. (Available from CFSTI as PB 167 171.)

DISCUSSION

Bruce E. Skov[3]

The purpose of this discussion is not to criticize the excellent work reported in the paper, but rather to describe certain changes that have been incorporated in the GVT suspension systems since that analysis and to present results of recent analyses of the revised configuration. This discussion will also summarize progress made in certain areas that are recommended for further study in the paper.

Changes to GVT Suspension

Most of the work reported in this paper was accomplished and documented, in reference [2] of the paper by APL in early 1968 and based on material supplied by Tube Transit Corp. (TTC) in late 1967. TTC has subsequently refined the Urban GVT design, relying on the APL analysis as a very useful guide. Changes in the design are summarized in Table 1.

As reported in the paper, APL found that the flexible support of the tube has little effect on the dynamic response of the train to

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[4] Numbers in brackets designate Additional References at end of discussion.

track irregularities. While flexibility of the support is important in providing adjustability of tube alignment, a stiffer support has greater stability. For these reasons, TTC has increased the stiffness of the tube support by a factor of $2^1/_2$ which is still sufficiently flexible for adjustment purposes [8].[4] Analysis by Aerotherm Corp. [9] shows a critical speed of approximately 1400 mph for the coupled pair of tubes.

APL also recommended a lower natural frequency for the train suspension and increased dynamic freedom in order to reduce the rail alignment accuracy necessary for passenger comfort. A major step in this direction has been accomplished by incorporating a semiactive suspension unit that serves as a load leveler as well as providing spring and damper functions. The use of a load leveler increases the dynamic freedom by eliminating static deflections caused by changes of load within the train. Such deflections would be large for the relatively soft springs implied by the recommended natural frequency.

The springing of the suspension was softened by a factor of 20 which along with a small increase in the mass supported by each wheel resulted in a natural frequency of approximately 1 hertz. The dynamic freedom was also increased from ± 0.2 in. to ± 0.3 in. by reconsideration of the budget of clearance between the train and tube.

Several factors have led to a reduction in the maximum design speed for Urban GVT trains from 300 mph to 250 mph. The main factors were:

1 Speeds above 250 mph were only encountered in stages longer than about $3^1/_2$ miles.

2 Reduction of the maximum slope from 25 percent to 20 percent was desirable.

3 The 900-ft maximum depth consistent with 250 mph maximum was attractive compared to the 2000 ft used for 300 mph.

4 Lower speeds would reduce the required track alignment accuracy and increase confidence in wheel integrity.

Consequently, Urban GVT systems now are limited to 250 mph, 20 percent slope and 900-ft depth. Many systems, such as that proposed for the New York metropolitan area by Reginal Plan Association would have little or no mileage where speeds exceeded 200 mph.

Analysis of Train Dynamics

TTC and Aerotherm have analyzed dynamic responses of the train to track irregularities using the refined configuration. Two coordinated models were used which are in certain respects more sophisticated than those used by APL. Both models considered finite-length trains up to 20 cars long, treated end cars accurately, and included the flex-joints located near the wheels. Roll, pitch, and vertical motions of each element of the train were considered in the models. Care must be used in characterizing the flex-joints because they have a virtual center of rotation which is located a considerable distance from the plane of the joint. This consideration was not included in the finite-length model reported by APL in the paper.

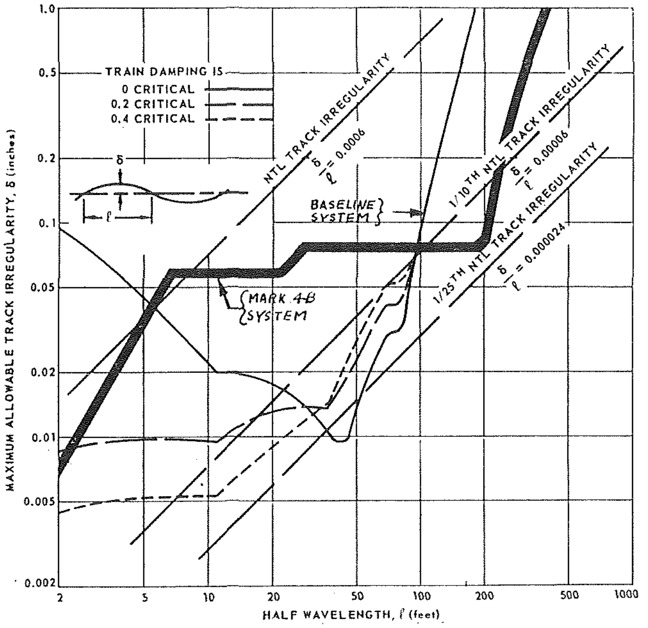


Fig. 13 Rail alignment requirements

Good correlation was obtained between the two models used by TTC and Aerotherm. The rail alignment necessary for passenger comfort with the new suspension concept is shown in Fig. 13 superimposed on the curves of Fig. 10 of the paper. The curve also reflects the constraints of limited freedom and the requirement that dynamic variation of contact force between the wheel and rail be limited to 2000 lb. Damping was selected to give the best tradeoff between high-frequency acceleration responses and displacement responses at the natural frequency. The results of the Aerotherm and TTC work are documented in reference [10].

TTC is now in the process of documenting plans for laying tracks to the accuracy requirements predicted from these analyses. Reference [8] shows analytically and experimentally that for half-wavelength greater than about 75 ft the flexibly supported tube can be adjusted to these accuracies. For shorter half-wavelengths it seems clear that the rail can be laid to the required accuracy.

It should be emphasized that the alignment requirement curve shown in Fig. 13 is for a region where the train is traveling at the maximum speed of 250 mph. For lower speeds the curve shifts to the left and the requirements are less stringent in terms of the ratio of irregularity to halfwavelength. As previously noted, most systems would have little mileage where speed would exceed 200 mph. (Stage length must be greater than about 2.5 miles before speed reaches 200 mph.)

Comments on Recommended Additional Studies

The paper recommended additional studies in several areas.

1 **Lateral Track Alignment.** It is agreed that this is a desirable area of endeavor, but analogy to the vertical dynamics suggests that there should be no problems.

2 **Vertical and Lateral Responses of Train to Nonperiodic Track Irregularities.** This is a desirable subject for further study, but is not considered as essential early work.

3 **Longitudinal Responses of the Train to Pneumatic Forces** This is considered to be unnecessary since experimental and analytical studies reported by Mr. Dahm have shown that no significant dynamic disturbances exist.

4 **Interaction Between Tubes.** Analytic studies of this subject have been conducted by Aerotherm Corp. subsequent to preparation of the paper and are documented in reference [9]. The analysis shows that there is no problem with the coupled pair of tubes and that the critical speed is about 1400 mph, well above operational speeds.

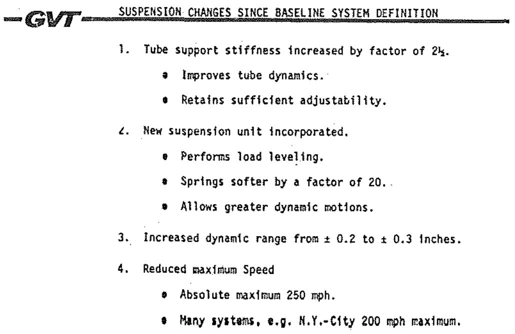
Airport Access and Corridor GVT

No conclusions can be drawn from the analysis presented in the paper or that of reference [10] concerning the dynamic responses of the airport access or corridor versions of GVT which have maximum speeds in the 300 to 400 mph region. These trains have no flex-joints at the wheel wells that tend to isolate sections of the train. Curves are negotiated by bending of the entire train. Thus a large portion of the track disturbances will be accommodated by letting the train behave as a continuous beam with numerous supports.

Conclusions and Summary

1 The work described in the paper has been a very useful guide to TTC in refining the system design.

Table 1



—GVT— SUSPENSION CHANGES SINCE BASELINE SYSTEM DEFINITION

1. Tube support stiffness increased by factor of 2½.
    - Improves tube dynamics.
    - Retains sufficient adjustability.
2. New suspension unit incorporated.
    - Performs load leveling.
    - Springs softer by a factor of 20.
    - Allows greater dynamic motions.
3. Increased dynamic range from ± 0.2 to ± 0.3 inches.
4. Reduced maximum Speed
    - Absolute maximum 250 mph.
    - Many systems, e.g. N.Y.-City 200 mph maximum.

2 Significant changes (summarized in Table 1) in the urban configuration have been made based in part on the work described in the paper.

3 Tube Transit Corp. and Aerotherm Corp. have analyzed the modified system with respect to dynamic responses of the train to track irregularities and show alignment requirements considerably less stringent than those reported in the paper.

4 Dynamics of the cross-coupled tubes have been shown to be very satisfactory by Aerotherm Corp.

5 Tests and analysis show that the train should have no longitudinal dynamic problems because virtually no pressure pulsations exist in the pneumatic cycle.

Additional References

8 Rodriguez, D. A., Weiler, F. C., and Dahm, Thomas J., "GVT Tube Adjustment Capability," Report No. 69-58, Aerotherm Corp. September 19, 1969, reviewed by Lloyd H. Donnell, prepared for Tube Transit Corp.

9 Rodriquez, D. A. and Varoglu E. L., "Dynamics of Coupled, Flexibly Supported Tubes," Report No. 69-59, Aerotherm Corp., September 19, 1969, reviewed by Lloyd Donnell, prepared for Tube Transit Corp.

10 Skov, Bruce E., Rodriguez, David, and Weiler, Frank, "Preliminary Dynamic Analysis of Train Suspension and Synthesis of Rail-Alignment Requirements," Report No. 69-0056, Aerotherm Corp., September 3, 1969, prepared by Tube Transit Corp., reviewed by Lloyd H. Donnell.

Authors' Closure

We have enjoyed working with TTC and Aerotherm during the past few years and thank Mr. Skov for his discussion of our paper. As indicated in the discussion, baseline system modifications have been made which have reduced the vertical track alignment requirements. The TTC and Aerotherm analyses of this modified system (references [8, 9, and 10]) are exceptionally good and we concur with the results of these studies; however, the results cannot be used to support some of the comments and conclusions presented in the discussion. Some reasons for this statement are as follows:

(1) The ability to adjust the GVT tube to the requirements predicted by the analyses cannot be demonstrated by the results of the analytical and experimental tube adjustment studies reported by Aerotherm (reference [8]). Local deflections can be expected in the full scale tube (reference [10]) but were not considered in the Aerotherm studies. The analysis assumed that the tube deflects by beam bending and a relatively stiff pipe was used for the experimental model.

(2) A direct analogy between lateral and vertical dynamics does not exist. In the analytical modeling for lateral dynamics the position of the center of gravity above the wheel-rail interface must be considered. This c.g. offset will induce a rocking motion to the vehicle.

(3) The Aerotherm analysis (reference [9]) on cross-coupled tube dynamics is limited to the critical velocity determination. No analyses have been performed on the dynamic interactions as trains pass each other in adjacent tubes; therefore, the statement that the Aerotherm analysis shows that no problems exist with coupled pairs of tubes cannot be substantiated.