

# A Study of Aircraft Taxi Performance for Enhancing Airport Surface Traffic Control

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**Abstract**—In view of the ever-increasing air traffic, much attention in air traffic management research has been given to improving arrival and departure efficiency. As air traffic begins and ends at the airport, the issues of taxi delays and ground incursions are becoming more evident. This paper considers the surface-traffic problem at major airports and envisions a collaborative traffic and aircraft control environment where a surface traffic automation system will help coordinate surface traffic movements. Specifically, this paper studies the performance potential of high-precision taxi toward the realization of such an environment. A state-of-the-art nonlinear control system based on feedback linearization is designed for a detailed B-737 aircraft taxi model. The simulation model with the nonlinear control system is evaluated extensively in a scenario representing the demanding situation of an arrival aircraft crossing an adjacent active runway immediately following its own landing. The evaluation establishes the potential of an automated system to achieve high-precision taxi control, including the ability to comply with taxi clearances with tight time margins. Such a high-precision taxi capability reduces the time margin required for clearing taxiing aircraft to cross active runways, thus increasing the opportunity for issuing such clearances, which in turn reduces the need for aircraft to hold short at the runways to wait for the opportunity for crossing. The results from the analyses provide insight into future aircraft operational capabilities toward the design of the envisioned surface traffic automation system. Moreover, the nonlinear control design serves as a preliminary study for future auto-taxi functional development.

**Index Terms**—Active-runway crossing, aircraft taxi control, air traffic management, nonlinear control, runway incursion, surface movement.

## I. INTRODUCTION

THE anticipated increase in air travel demands a more efficient air transportation system to handle the increased traffic. Government agencies including the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) are researching advanced technologies to provide the efficiency enhancements. The first of a series of NASA/FAA programs to address the problem is the development of the Center-TRACON Automation System (CTAS) [1]. This system provides automation aids to air traffic control (ATC) at the Air Route Traffic Control Center (ARTCC or

Center) and the Terminal Radar Approach Control (TRACON) [2] to improve the efficiency of feeding arrival flights to an airport. The Terminal Area Productivity (TAP) program considers the combined ATC and cockpit capabilities [3]–[8] to push the efficiency envelope by considering reductions in required separations in both air and surface traffic without compromising safety. The Surface Movement Advisor (SMA) [9], [10] consists of an intelligent system to provide automated data exchange and fusion for use by multiple parties responsible for airport surface traffic management. The most recent Advanced Air Transportation Technologies (AATT) program is a more comprehensive program in exploring advanced concepts to enhance most aspects of the air transportation system. These programs are merely examples of research activities for the development of automation technologies for air traffic management (ATM). There is a myriad of other programs from the U.S. government, the international community, the aerospace industry and academia to address similar and other pressing air transportation issues. It is not the intent of this paper to provide a comprehensive survey of such programs; so only certain programs relevant to this paper will be discussed as appropriate.

Current experience with CTAS has been extremely successful in fulfilling its objectives of enhancing traffic efficiency through time-based metering. As it improves the efficiency in arrival traffic, airport surface traffic will become a weak link in the air traffic equation if it is not accorded the attention commensurate with other air traffic automation tools.

The many ideas being considered for improving surface traffic efficiency usually fall within several main categories. One category of ideas involves increasing usable airport real estate in terms of runways, taxiways, and terminal ramp areas. Another involves increasing efficiency through operational changes, ranging from minor changes such as altering runway configuration, to more-radical changes such as reducing separation requirements, hence increasing density, of vehicles in traffic. A third category involves modernization of equipment and use of computer automation to enhance safety and efficiency.

In many cases increasing the number of runways and taxiways to handle the increased traffic is unavoidable. Examples of such growth include the expansion of the Dallas/Fort Worth International Airport (DFW) from the previous six-runway configuration to the proposed eight-runway metroplex, and the recent replacement of the Denver Stapleton Airport with the much larger Denver International Airport (DEN). DFW is in the middle of the expansion effort and currently has seven runways, with Fig. 1 labeling in parentheses the proposed changes in runway layout due to the addition of the eighth runway.

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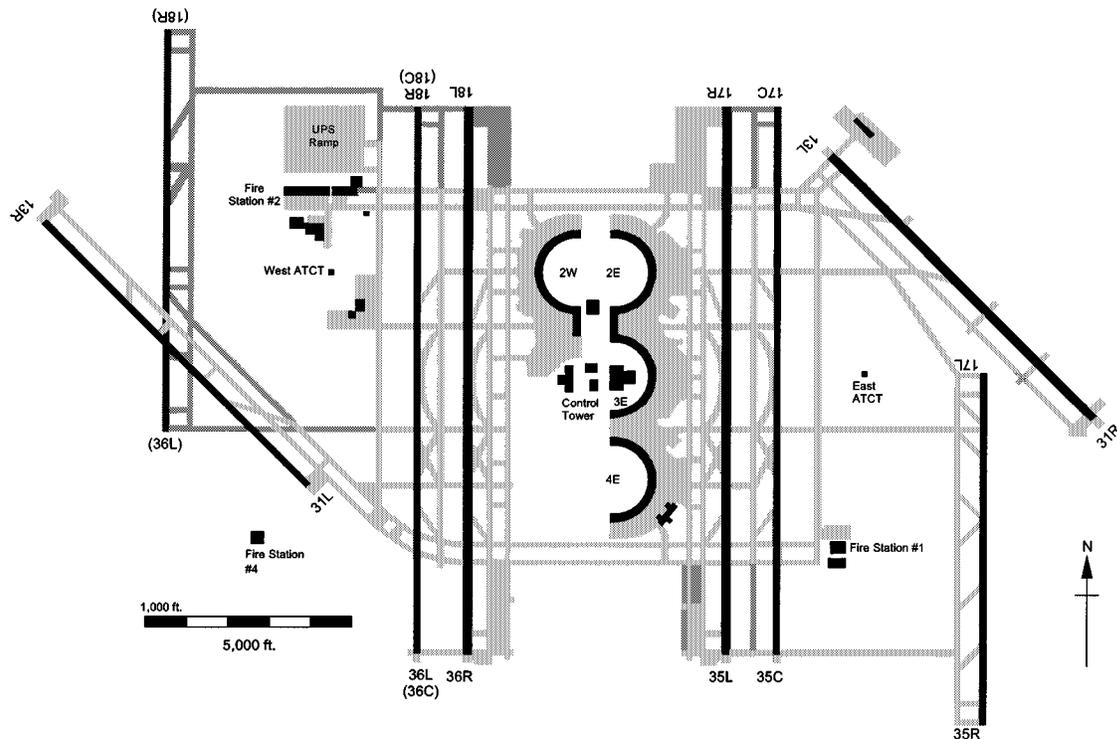


Fig. 1. Layout of Dallas/Ft. Worth International Airport (DFW).

Such expansion generally will also increase the complexity of the airport configuration. Under most airport configurations, adding runways results in some runways blocking the traffic between the terminal ramp area and other runways further out. As the tower controllers have more flights to control, they also have more taxiway intersections and runway crossings to worry about. If the increase in traffic leads to operational changes to reduce aircraft separation for increasing efficiency, the increased throughput of the outer runways will lead to a further increase in the need for runway crossings. Furthermore, a similar increase in throughput of the inner runways reduces the opportunity for runway crossings to take place. These operational changes to accommodate the increasing traffic compound the safety and efficiency issues.

The most notorious surface-traffic safety issue is the runway incursion problem, which is being addressed by major programs sanctioned by the FAA and the International Civil Aviation Organization (ICAO). The FAA Runway Incursion Reduction Program (RIRP) [11] studies technologies that can provide improved surveillance information to enhance situation awareness of ATC and the flight crew. Technologies being evaluated by RIRP include the Airport Target Identification System (ATIDS) [12], Airport Surface Detection Equipment (ASDE-3 and ASDE-X)[13], Inductive Loop Technology [14], Automatic Dependent Surveillance—Broadcast (ADS-B) [15], and the Surface Surveillance Data Server. It is conceivable that these technologies can address other ground-incursion problems if they are extended to cover all the vehicles on the airport surface. The ICAO Advanced Surface Movement Guidance & Control System (A-SMGCS)[16] is another concept which includes features and functions to enable safe and efficient airport surface operations. As these major

programs focus heavily on the safety issues of surface traffic, the current study explores the use of automation technologies for improving surface traffic efficiency, with the assumption that many of the communication, navigation and surveillance (CNS) technologies being studied by these major programs will be available. The technologies sought by this study should be considered supplementary to the aforementioned major programs and concepts.

For airports such as DFW with complex runway configurations to deliver high throughput with hub-and-spoke flight operations, runway-crossing delay is a major efficiency issue that has been well documented [17]. The increasing number of runways and the increasing traffic exacerbate the active-runway-crossing requirement. For instance, current south-flow operations at DFW, which account for the majority of the operations at this airport, use Runway 18L for departure and 18R for arrival. During rush periods, the arrival flights on 18R often have to queue up at the three taxiways WL, WM and B (see Fig. 2) after exiting from E3, E5, and E6, respectively, before they are cleared to cross 18L together as a group. Such holding prior to active-runway crossing means that sometimes three flights would line up for each of the three taxiways, a total of nine flights, before they are allowed to cross. This introduces substantial taxi delay to most of these flights. Any attempt to reduce separation to increase the throughput of the inside runways means that the time windows available for crossing of these runways are further reduced.

An MIT study reported by Idris *et al.* [18] indicates that among the many factors affecting airport surface traffic flow when the runway is studied as a flow constraint, the factor classified as “other flight landing/departing” stands out as the most prominent one. Since the runway is shared for landing, takeoff,

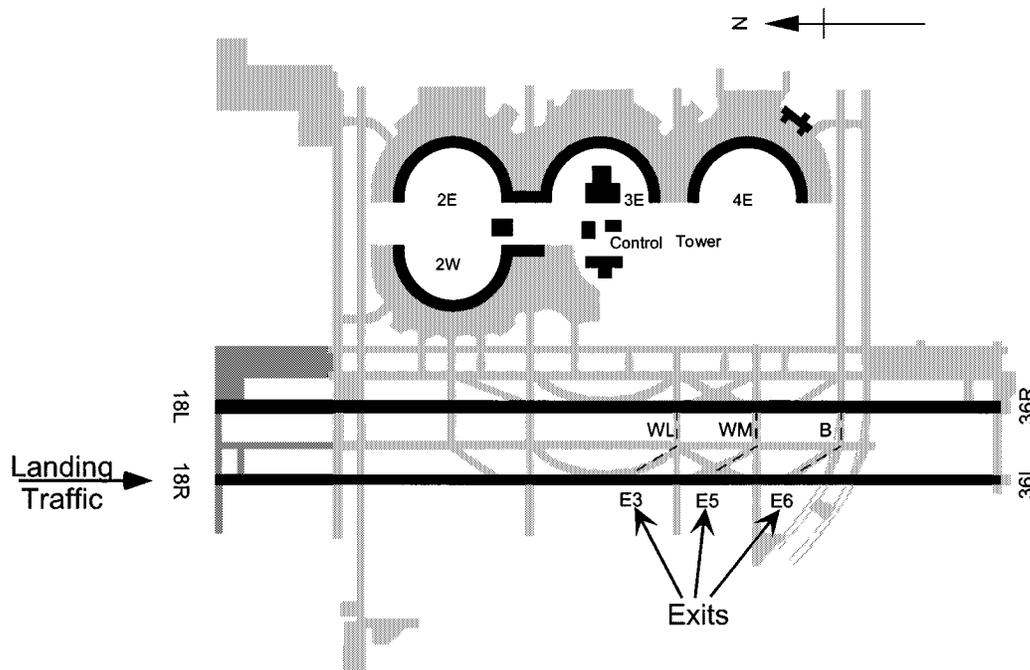


Fig. 2. Example of landing, turn off and runway crossing at DFW.

and crossing, these results are consistent with the notion that the taxiing traffic requiring active-runway crossings experiences substantial taxi-delays when the runways are heavily occupied by takeoff and landing traffic. This suggests that substantial taxi delay savings may be possible if active-runway crossings are allowed promptly without introducing significant delays to the takeoffs and landings. [19] indicates that, for departure traffic, there would be substantial savings by converting runway queueing time into gate delays. It is therefore reasonable to conclude that minimization of unnecessary taxi time would increase savings for both departure and arrival traffic, even if it means more gate holding delays. Gate holding schemes such as those studied in [19] can be used in conjunction with a surface traffic automation system that controls the taxiing traffic.

With active-runway-crossing delays identified as an important factor affecting airport operations, the DFW Airport Development Plan [17] includes two proposed ideas to ease the impact. The first idea involves construction of “perimeter taxiways” to allow arriving aircraft to taxi in by going around the north and south ends of the other runways. The second idea involves “rotational runway use” to place all arrivals on one side of the airport and all departures on the other to eliminate the crossing requirement. Neither of these two concepts is particularly attractive. Construction of the “perimeter taxiways” will be expensive and will require the aircraft to taxi longer distances around the runways, thus increasing taxi time and fuel consumption, further adding to noise and air pollution. Under the second concept, putting arrival runways on one side of the airport does not eliminate active-runway crossing of arrival flights over other arrival runways.

The study reported in this paper represents the first of what is expected to be a series of studies toward a concept to achieve collaborative traffic and aircraft control for improving efficiency while maintaining safety in airport surface operations. The en-

visioned collaborative system includes a surface traffic control automation system for coordinating traffic in a more orderly manner, including the possibility to allow flights to execute active-runway crossing under tightly controlled conditions. In the far term, the system may involve ground clearances including complete optimal taxi routes with specific time markers issued via data link. In addition, auto-taxi may be possible, and situation awareness of nearby vehicle traffic can be automatically fed from surveillance sources directly into the vehicle control system for incursion avoidance. In the near term, the far-term ideas need to be adapted to address limited data-link functionality, limited surveillance technologies, and manual pilot control. The full realization of this vision will depend on the aircraft’s ability to execute precision taxi, including active-runway crossing with tight time margins.

The purpose of the current study is to establish the feasibility of aircraft control to execute precision taxi. The reasons for the study are twofold: the results will serve as guidelines in the form of potential aircraft-taxi performance toward the design of the surface traffic control automation system; and they also provide insight into the development of auto-taxi capabilities to accomplish precision taxi. To this end, the paper studies the feasibility of a taxi control law for precision taxi using a detailed aircraft taxi model and a taxi guidance and control system designed for the model. The control system is designed using a nonlinear control approach based on feedback linearization [20]–[26], by virtue of its ability to handle nonlinear model dynamics without cumbersome gain scheduling of linear controllers.

In order to accomplish safe operation when the traffic demands more occurrences of active-runway crossing with smaller time windows, it is imperative that aircraft taxi operations be enhanced to deliver the necessary taxi performance. Minimization of runway-crossing time implies maximum taxi speed, which can benefit from a maximum permissible initial speed. As il-

illustrated by the simple analyzes in Section II, the most effective way to improve runway-crossing efficiency can be provided by the ability to taxi across the runway when permitted without having to stop at the hold line. Although this capability to taxi across an active runway without stopping has the property that crossing time is minimized, the saving in taxi time is not its main benefit. A more important result of this capability is that reducing the crossing time eases the impact on the landing/takeoff operations on the runway, leading to more opportunities for the taxiing traffic to cross the runway. Furthermore, not having to stop can reduce taxi delay due to hold-short operations, and can further benefit surface traffic efficiency by reducing taxi traffic backup. All of these factors lead to the additional benefit of improving fuel efficiency due to the reduction in braking and acceleration associated with stop and go, and the reduction in engine idle time.

To taxi continuously and cross runways safely without requiring a large safety margin in the time window will require a high precision in aircraft taxi control in arriving at the runway accurately at the time when the window opens. The guidance and control designs in Section III apply automation to achieve this objective. The analyses in Section IV demonstrate the potential performance of such an automated system through digital simulations and Monte-Carlo analysis. The vehicle performance data under different operating conditions are applicable to all taxi phases, including runway crossing as well as traffic sequencing and scheduling at merging taxiways. As mentioned above, such data will be useful in the design of a ground ATC automation system for coordinating surface traffic over the entire airport, and the full-scale development of cockpit automation for taxi operations. Further discussions of these concepts are provided in Section V.

## II. RUNWAY-CROSSING TIME ANALYSIS

The analyzes in this paper use an aircraft dynamic simulation model adapted from the NASA Transport System Research Vehicle (TSRV), which was a B-737 flight-research aircraft. The 12th-order state vector includes three inertial position components, three velocity components, three body Euler angles representing the body attitude, and three angular velocity components. Seven control inputs are included in this B-737 model: aileron, elevator, rudder, tiller, throttle, and left and right brakes.

The two key factors affecting runway-crossing efficiency are: (i) runway-crossing time (i.e., width of time window required), and (ii) accuracy of arrival time at the runway-crossing hold line for aircraft in motion. It should be emphasized that these two factors are only concerned with the individual aircraft's efficiency; the overall efficiency of the airport's operation related to active-runway crossing depends on other factors such as the scheduling of runway usage among landings, takeoffs, and runway crossings. This bigger problem is not addressed in this paper, but discussions of potential solutions are provided in Section V. The study presented in this paper should be viewed as a component of the overall solution.

This section examines the runway-crossing time factor. Prior to crossing, the aircraft is either stationary (holding short of the

runway), or in continuous motion (ready to cross the runway without stopping). The physical dimensions used in the analyzes are based on the DFW airport layout. With the DFW runways ranging between 150 and 200 ft in width, and the length of the B-737 in the order of 100 ft, the analysis assumes that the aircraft needs to travel 100 m (i.e., over 300 ft) for crossing the runway.

For the situation where the aircraft is stationary prior to crossing, two cases are compared. They assume that the window for crossing would open at the 10-s point of the simulation. In both cases the aircraft has 100% brakes applied until the 10-s point. In the first case, the throttle remains at idle (i.e., 0%) until the 10-s point, at which time it is allowed to increase to 100%. In the second case, the throttle is allowed to be set to deliver acceptable thrust prior to the 10-s point.

From previous experience involving the TSRV B-737 flight tests, the acceleration for takeoff and deceleration after landing were limited to 0.25 G. This value was used to assure passenger comfort during takeoffs and landings, and it is chosen as an upper limit for the taxi analyzes in this paper. It should be noted that this value is likely to be too high for passenger acceptance during taxi, except under extraordinary conditions. Nevertheless, with 0.25 G chosen as the acceleration limit for the analyzes, the throttle needs to be reduced when the load factor reaches 0.25 G. It is possible that, if an automatic control system is available with appropriate feedback to control the vehicle, it can continuously adjust the throttle to maintain the acceleration at 0.25 G as the vehicle picks up speed. In today's operation under manual pilot control, however, it is more likely for the throttle control to exhibit a piecewise-constant behavior over time. To simulate this control behavior while observing the 0.25-G acceleration limit, the throttle is cut back to 75% shortly after 15 s for the first case where no pre-throttling is used. For the second case where there is pre-throttling, the throttle level is set to 75% at 4 s, i.e., 6 s ahead of the runway-crossing window, so that the acceleration load factor can jump instantaneously to 0.25 G when the window opens.

The results are depicted in Fig. 3, with the runway-crossing time and speed data tabulated in Table I. Although in both cases the final throttle level is 75%, the load factor for the pre-throttle case initially exceeds 0.25 G briefly, because the thrust of the engine is typically higher at lower in-take speed.

The data in Table I show that pre-throttling reduces the runway-crossing time from 12.7 s to 8.7 s, a 31.5% reduction. Table I also includes the runway-crossing time for an aircraft in motion taxiing at 30 kn without stopping prior to crossing. Even though 30 kn is substantially below the final speed reached by the earlier cases, the runway-crossing time is only 6.5 s. This shows the additional benefit when the aircraft is allowed to taxi without stopping before crossing the runway.

Although this reduction in runway-crossing time is relatively insignificant when compared to the overall taxi time, it shows that if the aircraft is allowed to taxi across the runway without stopping, it will require a smaller time window for crossing, thus reducing the impact on the landing/takeoff operations. The smaller time windows also imply that there may be more opportunities for scheduling active-runway crossings, further reducing the need for the crossing traffic to hold short, thus reducing taxi delays. To accomplish continuous taxi for active-

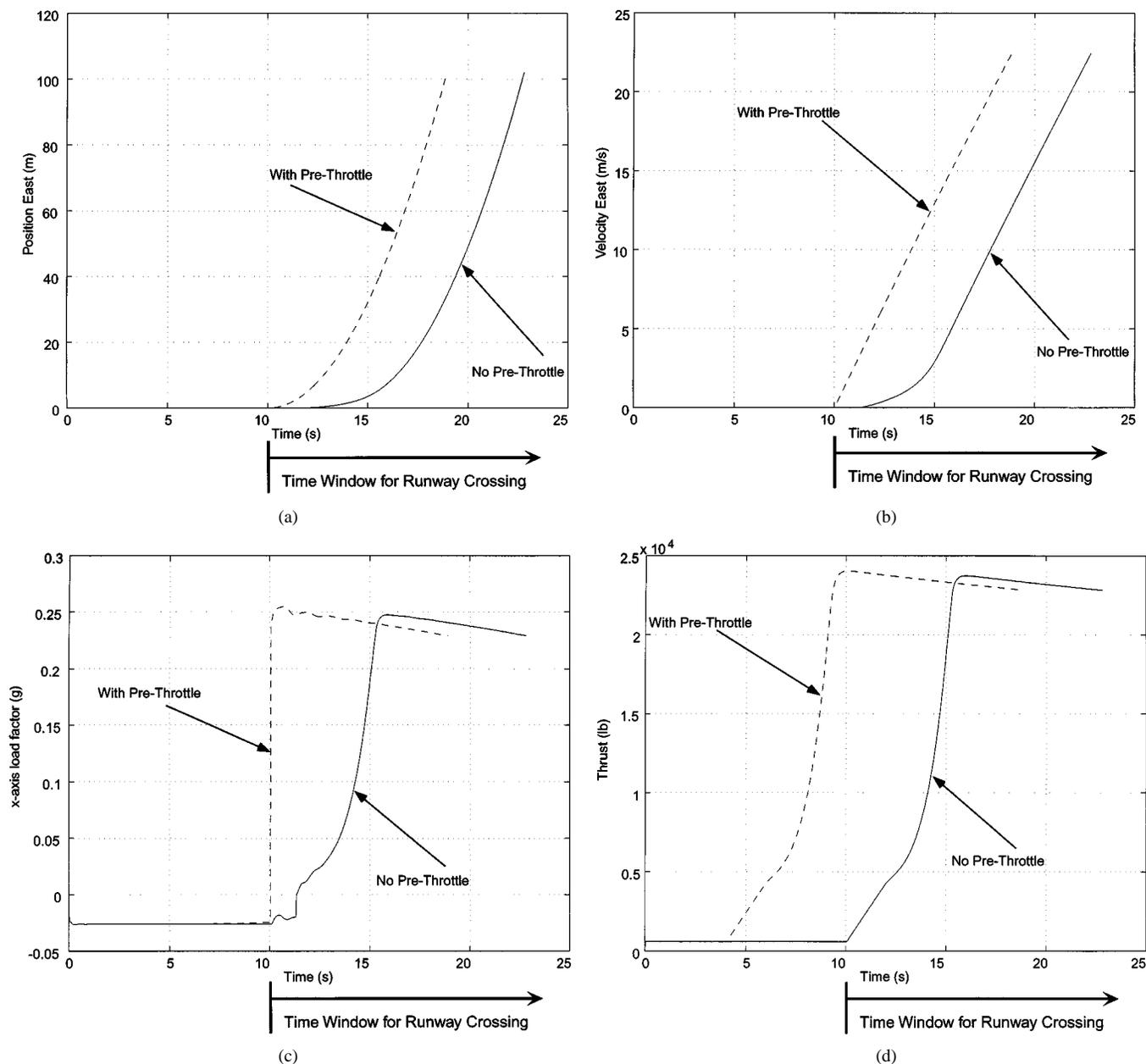


Fig. 3. Comparison of throttle timing for runway crossing from rest with acceleration load-factor limit of 0.25 G. (a) Distance traveled. (b) Forward velocity. (c) Acceleration load factor. (d) Thrust.

TABLE I  
RUNWAY CROSSING RESULTS WITH ACCELERATION LOAD-FACTOR LIMIT OF 0.25 G

	Runway Crossing Time (s)	Final Speed (m/s)	Average Speed (m/s)
No Pre-Throttle	12.7	22.2	7.9
With Pre-Throttle	8.7	22.4	11.2
Constant Speed 30kn	6.5	15.4	15.4

runway crossing will require a precision-taxi capability, which is the subject of the following section.

### III. GUIDANCE AND CONTROL DEVELOPMENT

This section explores the use of automation in the form of guidance and control to enable high-precision taxi for arriving at a runway for crossing at the instant when a cleared window

opens. It may be noted that if the runway-crossing time window has to be padded with a substantial margin to account for imprecision of aircraft taxi, then much of the direct savings in crossing time as demonstrated above would be lost. However, the precision-taxi capability in confidently meeting scheduled time of runway crossing without stopping and holding will still enjoy valuable benefits of reduced traffic backup, thus reducing taxi delay, improving fuel efficiency and reducing pollution.

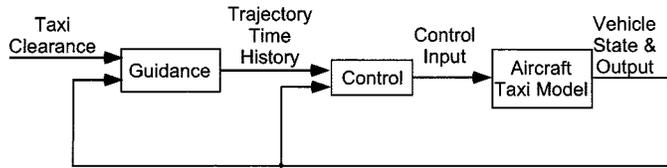


Fig. 4. Overall guidance and control structure.

### A. Overall Guidance and Control Concept

The objective of the automation system is to control the aircraft's taxi operation to comply with the clearance issued by the ground control tower. Common taxi clearances include taxiing from a landing runway to the ramp area, and taxiing from a ramp holding position to a departure runway. As envisioned in the collaborative surface traffic automation system, the most demanding aircraft taxi maneuver will likely involve a taxi clearance issued to a landing aircraft to execute an active-runway crossing immediately after landing. The clearance may include an assigned exit and a time window for crossing an active runway adjacent to the landing runway. These conditions define the scenario for the subsequent analyses.

The aircraft-taxi automation system concept consists of a guidance subsystem and a control subsystem as depicted in Fig. 4. The guidance function in the outer loop of Fig. 4 is to generate the vehicle trajectory time history for achieving the taxi clearance. The trajectory may include position and velocity as functions of time. The control function in the inner loop of Fig. 4 is to produce the control-input commands necessary to make the vehicle state track the reference trajectory provided by the guidance function. The control and guidance functions are discussed in Section III-B and Section III-C, respectively.

### B. Nonlinear Controller Based on Feedback Linearization

1) *Control Loop Structure*: This study applies a form of feedback linearization [20]–[26] to design the control function in the inner loop of Fig. 4. Fig. 5 illustrates the design concept. The design treats the aircraft as a point-mass model, with its state  $x$  consisting of the position vector  $r$  and velocity  $v$ . The acceleration  $a$  is assumed to be some nonlinear function  $f$  of the control input  $u$  and state  $x$ , where  $u$  contains the seven control commands described in Section II.

The control function has two components: a feedback-linearization controller and a linear controller. The feedback-linearization controller  $\tilde{f}$  is designed so that, given  $x$ , the composite function  $f(x, \tilde{f}(x, a_c))$  is linear in the commanded acceleration  $a_c$ . In fact, it is desirable to have

$$f(x, \tilde{f}(x, a_c)) = a_c$$

This means that when  $x$  is given,  $\tilde{f}$  behaves like the inverse of  $f$ ,  $f(x, \tilde{f}(x, \cdot))$  behaves like an identity feed-through,  $a$  would track  $a_c$  precisely, and the system in Fig. 5 with the feedback-linearization controller would behave like a simple double integrator. Under this condition, any conventional linear design technique [27] can be used to synthesize a linear controller to

complete the closed-loop system of Fig. 5 to provide desirable performance for trajectory tracking.

The effort to determine the function  $f$  for representing the B-737 is described in Section III-B-II, followed by the descriptions of the feedback-linearization controller  $\tilde{f}$  and the linear controller in Sections III-B-II and III-B-IV, respectively.

2) *B-737 Design Model for Taxi Control*: The controls for taxi operation are throttle and brakes for speed control, and tiller (superceding rudder pedals) and differential brakes for turns. The scenario assumes that the taxi speed is sufficiently low that the aerodynamic effects can be ignored. The performance data required for controller synthesis for forward motion include the effect of throttle on propulsion thrust and the effect of brakes on friction for deceleration. The propulsion performance is known to depend on air speed at the intake. To generate the data, the B-737 simulation is hard-coded to fix the taxi speed at different specific values, and the steady-state effects on thrust due to different values of throttle are recorded. Fig. 6 depicts the effect of throttle settings on the achieved thrust at various taxi speeds.

To obtain the performance data for the effect of brakes on friction, the B-737 simulation is hard-coded to fix the taxi speed at different specific values, and the steady-state effects on friction due to different values of parallel braking are recorded. Similar to the plots in Fig. 6, Fig. 7 depicts the effect of parallel braking on friction at various taxi speeds. In Fig. 7, however, the plots for the different taxi speeds overlap, implying that the braking effect as formulated in the B-737 model is independent of vehicle speed.

The throttle and parallel braking controls for the forward acceleration/deceleration have opposing effects and hence should be commanded in a mutually exclusive manner. If necessary, any desired negative values of braking would translate into positive values of throttle, and vice versa. This throttle-brake conversion is important when differential braking is applied to accomplish turns that cannot be achieved with the tiller alone, resulting in some level of braking that has to be compensated for with throttle.

Shallow turns are accomplished through rudder pedals, while the tiller extends the control beyond the rudder's limit. If tighter turns are needed, differential braking can be applied. Analysis results show that if lateral load factor is limited to 0.15 G, then the tiller should have enough control authority. Nevertheless, differential braking is included in the controller design for the sake of completeness for handling extraordinary maneuver requirements.

To compile the performance data of lateral acceleration due to these control inputs, a special B-737 simulation is implemented with a feedback system designed to adjust the engine thrust to maintain speed while turning, so that steady-state lateral acceleration can be determined as a function of these controls. Fig. 8 depicts the resulting steady-state effects of the tiller and differential braking on lateral acceleration. The first 100% of the control on the left-hand side of the plot is due to rudder and tiller. Since differential braking should be used only after the tiller has reached its limit, the second 100% of the control on the right-hand side of the plot represents differential braking *in addition to* maximum tiller usage. Again the resulting data are generated for different values of taxi speed.

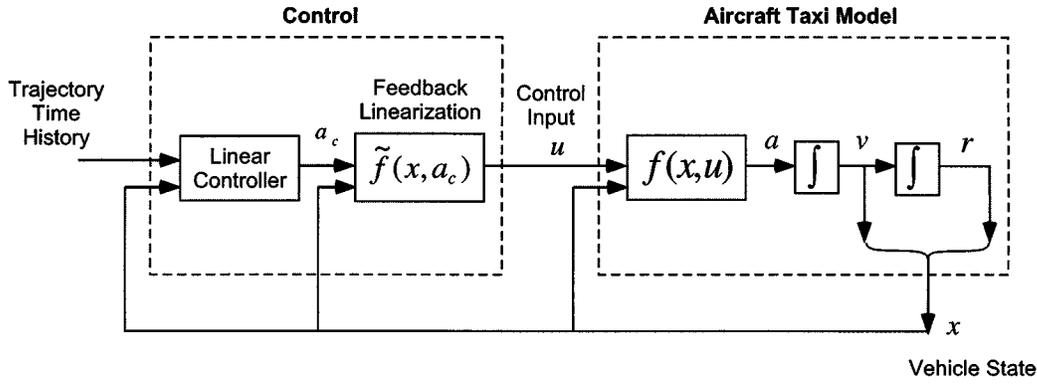


Fig. 5. Simplified illustration of controller design with feedback linearization.

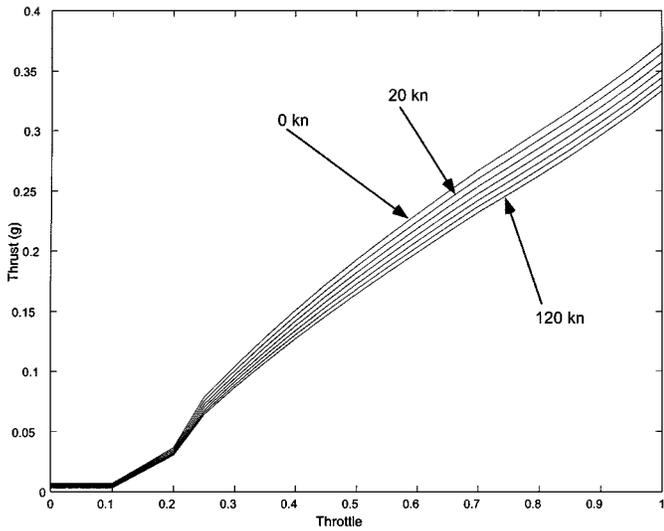


Fig. 6. Effect on thrust due to throttle at various speeds.

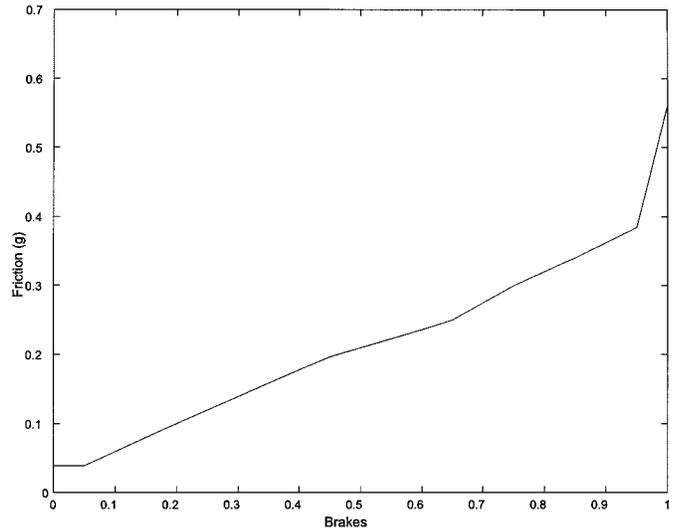


Fig. 7. Effect on friction due to parallel braking.

3) *Feedback Linearization Algorithm*: The performance data collected as described in Section III-B2 are used in the design of the feedback linearization controller, which maps the commanded acceleration to the desired control input. Let the commanded acceleration  $a_c$  as provided by the linear controller (see Fig. 5) be represented by the longitudinal and lateral components as

$$a_c = \begin{bmatrix} a_{xc} \\ a_{yc} \end{bmatrix}.$$

For the point-mass model, the yaw angle between the vehicle's longitudinal axis and the velocity vector is ignored.

The desired longitudinal acceleration  $a_{xc}$  is expected to be provided as the sum of engine thrust and brake friction, for which the data in Figs. 6 and 7 can be used to determine the settings of the throttle ( $\delta_T$ ) and parallel brakes ( $B_{||}$ ). The  $\delta_T$  and  $B_{||}$  settings are obtained by interpolating the data in Figs. 6 and 7 based on the current vehicle speed, with the additional constraint that  $\delta_T$  and  $B_{||}$  are mutually exclusive, i.e., they cannot be both nonzero.

Similarly, the desired lateral acceleration  $a_{yc}$  is expected to be provided by the tiller ( $\delta_t$ ) if possible, with additional differential braking ( $B_{\Delta}$ ) if necessary. Again, the  $\delta_t$  and  $B_{\Delta}$  are obtained

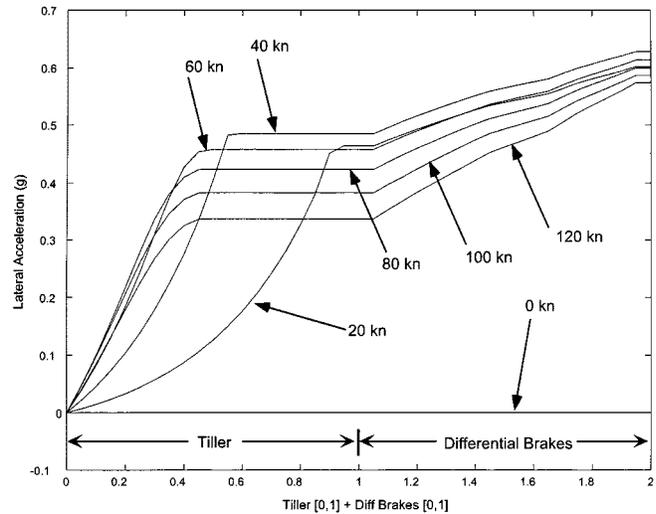


Fig. 8. Effect on lateral acceleration due to tiller and differential braking.

by interpolating the data in Fig. 8 based on the current vehicle speed. The value for  $\delta_t$  has to reach 100% before  $B_{\Delta}$  can become nonzero. The only possible complication may arise when  $B_{\Delta}$  is nonzero, because superimposing  $B_{\Delta}$  on  $B_{||}$  may lead to one of the two brakes being out of range.

Under the condition that differential braking is not required, the left brake ( $B_L$ ) and right brake ( $B_R$ ) are set to the parallel brake setting  $B_{||}$ , i.e.

$$B_L = B_R = B_{||}$$

and total braking can be written as

$$B_L + B_R = 2B_{||}.$$

If differential braking  $B_{\Delta}$  is required, the desired brake settings are centered about  $B_{||}$ , hence

$$B_L = B_{||} - \frac{1}{2}B_{\Delta}$$

and

$$B_R = B_{||} + \frac{1}{2}B_{\Delta}.$$

If both  $B_L$  and  $B_R$  are within the range of 0% and 100%, then the settings are used for the brake control. Otherwise, one of two possibilities takes place: (i) the lower brake setting is negative or (ii) the higher brake setting has exceeded 100%.

The way to adjust the brake settings under situation (i) is illustrated by Fig. 9. Without loss of generality, assume  $B_L$  has the lower brake setting. If  $B_L$  is below 0 by an amount  $\delta B$ , then both  $B_L$  and  $B_R$  are increased by  $\delta B$  to maintain the differential braking. Effectively, the total braking has increased by  $2\delta B$ , i.e., from  $2B_{||}$  to  $2(B_{||} + \delta B)$ . This leads to additional friction that has to be compensated for with additional thrust. The throttle is adjusted to provide the incremental thrust required.

When situation (ii) takes place, the higher brake setting would exceed 100% by  $\delta B$  as in Fig. 10. In this case the brake or both brakes have to be lowered to bring this setting back within range. If this results in a reduction in total braking, then ideally the throttle should be decreased to compensate for the reduction in braking friction. However, the situation (ii) with one brake setting exceeding 100% implies that  $B_{||}$  is already at least 50%, where the nonzero value implies that throttle  $\delta_T$  is already zero and cannot be further reduced. Three possible ways to deal with this condition are illustrated in Fig. 10, but none of them can preserve the originally desired longitudinal and lateral accelerations.

The first approach as explained in Fig. 10(c) is to keep the total braking the same, so that it does not need any compensation in thrust. This means that the lower brake setting has to be increased so that the higher brake setting can be decreased back to 100%. The result is that the effective differential braking is reduced from  $B_{\Delta}$  to  $B_{\Delta} - 2\delta B$ .

The second approach as illustrated in Fig. 10(d) is to maintain the differential braking by lowering both  $B_L$  and  $B_R$  by  $\delta B$ . The side effect from this approach is that total braking is reduced by  $2\delta B$ , from  $2B_{||}$  to  $2(B_{||} - \delta B)$ .

The third approach as illustrated in Fig. 10(e) is a compromise between the previous two approaches. In this case only the higher brake setting is reduced back to 100% without adjusting the lower brake setting. Effectively the total braking is reduced to  $2B_{||} - \delta B$ , and the differential braking is reduced to  $B_{\Delta} - \delta B$ .

4) *Linear Controller*: With the feedback linearization designed to mitigate the nonlinearities of the B-737 taxi model,

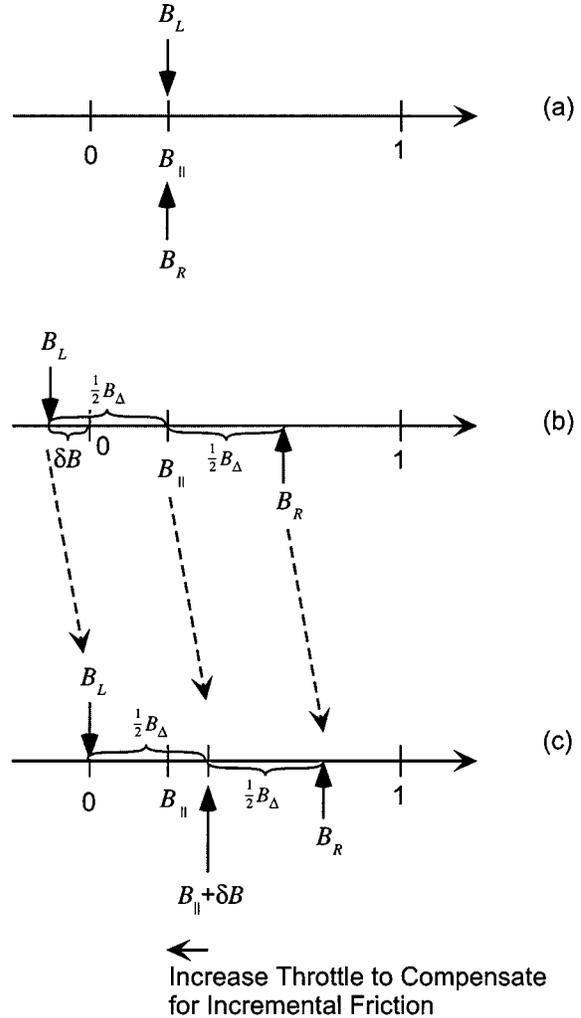


Fig. 9. Increase total braking and throttle to compensate for negative brake setting due to differential braking. (a) Parallel brake settings. (b) Differential braking calls for negative brake setting. (c) Increase brake settings, and increase throttle to compensate for increased friction.

a linear controller for shaping the feedback system to deliver the desired performance can be designed to complete the control function. This study uses conventional proportional-plus-derivative (PD) control for designing the linear controller. The controller gains are selected to prescribe a desirable natural frequency and damping ratio for the closed-loop system [28].

### C. Guidance Trajectory for Taxi

The taxi paths at an airport generally involve linear segments. The guidance function is designed to generate trajectory time histories given piecewise-linear routes. Transition between linear segments is accomplished through turning along a circular arc, modeled according to constant speed and constant centripetal acceleration. The speed profiles along most taxiways are usually relatively benign. Takeoffs usually involve throttle settings published by the aircraft manufacturer to provide the necessary thrust and hence do not pose difficult requirements on aircraft control. The most demanding speed control takes place after landing. The control will be further complicated if

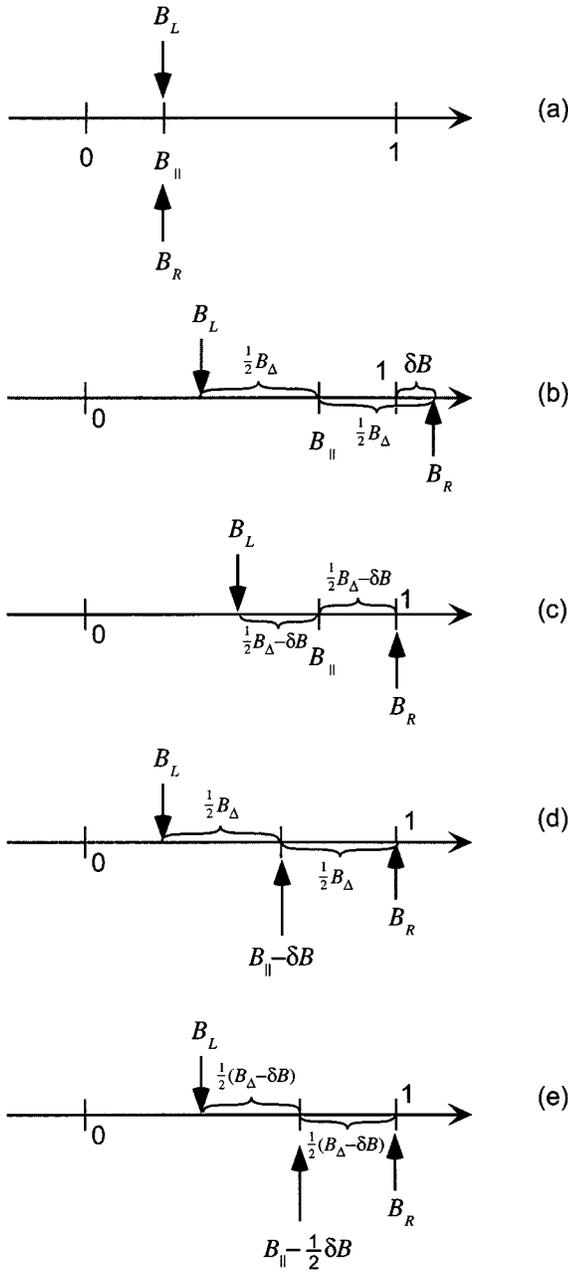


Fig. 10. Alternatives for out-of-range differential braking adjustments. (a) Parallel brake settings. (b) Differential brake calls for brake setting over 100%. (c) Approach I: Reduce differential braking without changing total braking. (d) Approach II: Reduce total braking by keeping differential braking. (e) Approach III: Compromise by keeping lower brake setting.

the flight is required to perform high-speed roll out and turn off after landing, followed immediately by an active-runway crossing within a time window cleared by ground control.

Fig. 2 shows a scenario at DFW where airplanes landing on Runway 18R would turn off at exits E3, E5, or E6 to cross Runway 18L. The path between the point of landing and the runway-crossing hold line is made up of three linear segments as illustrated in Fig. 11. The trajectory profile includes a deceleration leg immediately following nose-gear touch down. The exit involves a shallow turn-off from the landing runway to the exit segment, transitioning to a second turn ending on a

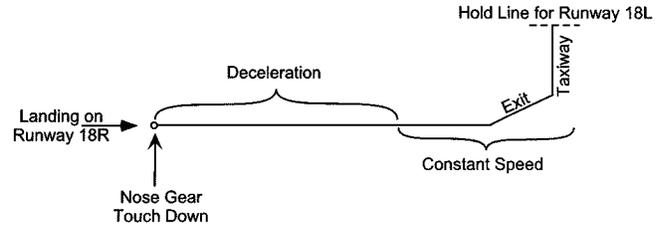


Fig. 11. Generic taxi path for landing, exit and runway crossing.

taxiway normal to the two runways. This scenario is chosen for the analyses discussed in the next section.

To generate the trajectory time history given a cleared taxi time to traverse the hold line of the adjacent runway without stopping, the guidance will perform a constant deceleration on the landing runway, slowing down to a final taxi speed before the exit turnoff. This taxi speed is maintained through the turnoff and taxi across the adjacent runway. When this taxi speed is specified, the trajectory profile can be determined backward from the hold line through the two turns onto the landing runway. The deceleration can then be uniquely determined based on the landing speed and the final taxi speed to complete the total trajectory profile to achieve the cleared taxi time.

#### IV. GUIDANCE AND CONTROL EVALUATION

The evaluations are based on the condition that the B-737 is 3000 ft past the threshold of Runway 18R when the nose gear touches down, at a speed of 120 kn. To avoid any undesirable behavior due to the delay between the nose-gear actuation and the response at the center of gravity (CG), the implementation uses the nose-gear position instead of the CG as the reference for trajectory tracking.

##### A. Initial Evaluation

The initial test is based on a 30-kn turn off at Exit 5. The lateral acceleration used for computing the turn arcs is 0.15 G. Fig. 12 contains the simulation results. The runway-crossing time error is  $-0.004$  s, with a cross-track error of 1.07 m. The position error in the direction of the runway in Fig. 12(c) shows that the along-track error was largest during the initial deceleration phase. Since the error is along the direction of the runway and the aircraft executed two turns to end up being normal to the runway, only the initial portion of the error corresponds to along-track error. The errors shown in Fig. 12(c) and Fig. 12(d) indicate that the aircraft is lagging slightly behind the reference trajectory. The other parts of Fig. 12 show the relevant controls and responses.

##### B. Guidance Taxi Time Range

Before further evaluation of the guidance and control design, the range of possible taxi times for arriving at the adjacent runway is determined, based on variation of the deceleration from a maximum of 0.25 G to a minimum required for achieving the final taxi speed prior to the exit turn off. Fig. 12(h) shows that the lateral acceleration can experience an overshoot

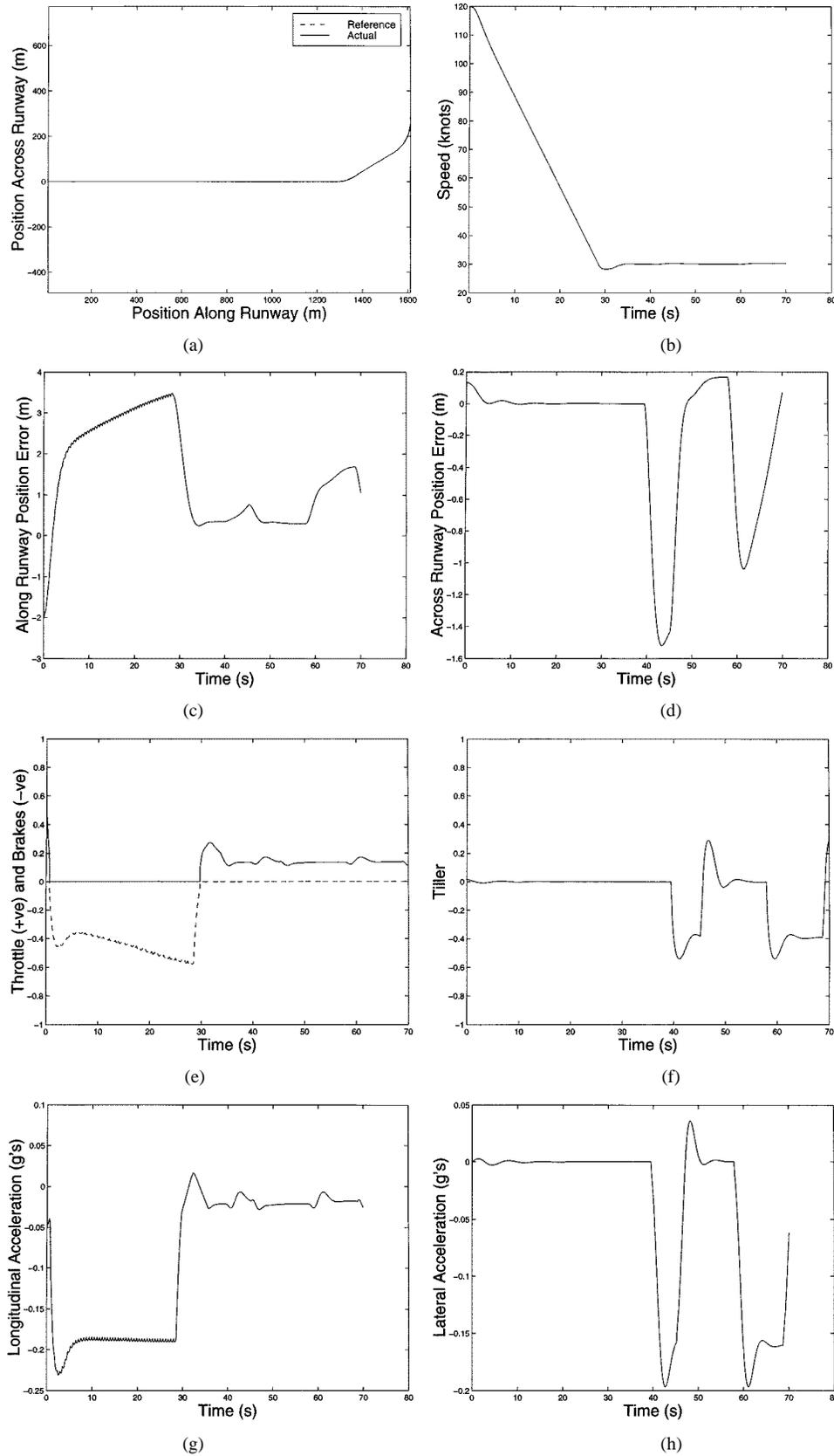


Fig. 12. Simulation results for 30-kn exit to E5. (a) Actual and reference trajectories. (b) Speed. (c) Position error in direction of runway. (d) Position error normal to runway direction. (e) Throttle and brakes. (f) Tiller. (g) Longitudinal acceleration. (h) Lateral acceleration.

exceeding 0.15 G, even though the centripetal acceleration used for computing the turning arcs is set to 0.15 G. Consequently,

the centripetal acceleration used for defining the turning arcs is reduced to 0.1 G for taxi speeds up to 25 kn. For the 30-kn

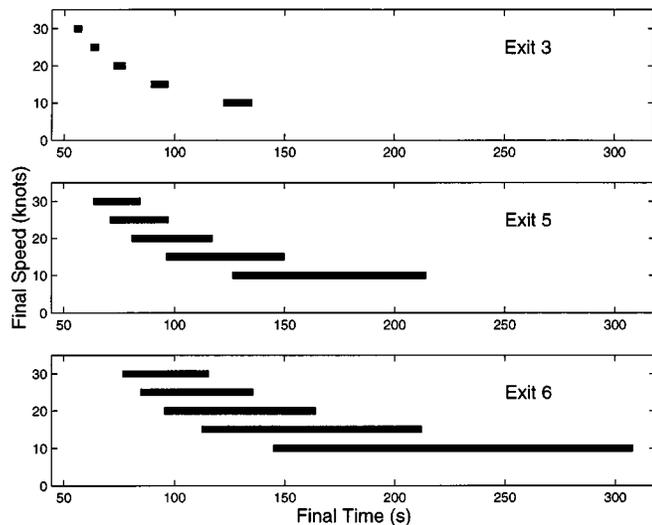


Fig. 13. Range of taxi times from landing to runway crossing through exits 3, 5 and 6.

case, if the centripetal acceleration is set at 0.1 G, the turn radius would be too large for the B-737 model to complete the second turn before crossing the hold line at Runway 18L. For this reason, the centripetal acceleration is set at 0.15 G for the 30-kn case. The range of taxi times for Exits 3, 5, and 6 is depicted in Fig. 13. Only conditions within this data set are used in the subsequent analyses.

### C. Performance Over Different Exits with Different Distances

The effects of performing runway-crossing taxi through different exits based on the same taxi speed are studied next. In this case, a taxi speed of 20 kn is selected. Since the three exits would require the B-737 model to taxi for different distances, the taxi time would increase accordingly. Table II tabulates the results of the simulations. It is immediately obvious that the runway-crossing time error and cross-track error are negligible in all cases.

### D. Effect of Taxi Speed

The effect of different taxi speeds is evaluated for an Exit 5 turn-off. Three taxi speeds are used: 10 kn, 20 kn, and 30 kn. The different taxi speeds call for different taxi times. The results are tabulated in Table III. Again, the runway-crossing time errors and cross-track errors are all negligible.

The reason behind the larger final cross-track error for the 30-kn case is that the B-737 model at this higher speed is just transitioning out of the second turn at the moment of runway crossing. The transient response at this moment contributes to the cross-track error. This error can be reduced if there is more room to straighten out after the turn. The error is nonetheless smaller than expected navigation error.

### E. Effect of Initial Delay in Automation Engagement

Initial delay can be caused by misjudgment in landing time or landing position, or it can be caused by communication delay. For this part of the study, the guidance trajectory is assumed to have been pre-computed to anticipate landing at 3000 ft beyond

the runway threshold. To simulate the delay, the aircraft would taxi without braking for a pre-specified delay time before the automatic guidance and control engage. The scenario is based on the 20-kn taxi through Exit 5, with 90-s taxi time. The delays considered are 1, 5, and 10 s. These delays may seem small in view of current operational characteristics. What values are considered appropriate will depend on the level of automation for controlling the landing approach. In the context of the envisioned collaborative air traffic control environment, these values may be reasonable. Furthermore, if the delay is much larger, the results below will show that the responses may become unacceptable. Continuously updating the landing time will allow a better estimate to be computed shortly prior to landing, bringing the delay time back into reasonable range with the updated trajectory.

Once the guidance and control engage, the automatic system would try to make up for the time lost by exercising heavy braking. As it catches up with the predetermined trajectory, the final runway-crossing time error of  $-0.03$  s and cross-track error of 0.2 m are achieved in all cases. The throttle-and-brakes profiles are compared in Fig. 14.

As the delay increases, maximum braking is required to slow the vehicle down to the predetermined trajectory. In the 10-s delay case, the heavy braking induces an overshoot, which in turn triggers the throttle to engage for a few seconds.

The heavy initial braking also causes the deceleration to exceed the 0.25 G limit for the 5 s and 10 s cases. Fig. 15 shows the longitudinal acceleration for the 5-s case. One way to overcome this reaction is to continuously re-compute the reference trajectory prior to touch down, so as to eliminate any trajectory mismatch. Another way is to limit the braking to a level that satisfies the deceleration limit. As long as the delay is not so large as to render deceleration to taxi speed impossible, the control law will ultimately be able to mitigate the initial errors.

### F. Human Performance Factors

If the control commands generated by the automatic guidance and control functions are used as advisories to the pilot in a form analogous to a flight director, the pilot's reaction has to be taken into consideration, as it affects the conformance to the advisories [29]. It should be pointed out that reference to the flight director here does not necessarily imply the use of today's head-down displays. To maintain situation awareness during taxi, any guidance display will most likely be provided on a head-up display (HUD), such as that studied as a component of the Taxiway Navigation and Situation Awareness (T-NASA) system [5]–[7]. In fact, this technology is already being commercialized as the Surface Guidance System [30] by a producer of head-up systems.

The effect of the pilot's reaction to the advisory interface is initially studied by approximating the pilot's reaction delay with a first-order lag, whereas the phase-advance factor of the pilot is already adequately modeled by the PD controller described above. For the 20-kn scenario off Exit 5 with 90 s taxi time, four time constants are considered: 0.1, 0.2, 0.5, and 1 s. The effects of the pilot reaction lag on the final results are tabulated in Table IV. Throttle-and-brakes profiles for the 0.5- and 1-s cases are shown in Fig. 16, whereas that with a zero time constant is

TABLE II  
COMPARISON OF TAXI PERFORMANCE THROUGH THREE DIFFERENT EXITS: TAXI SPEED OF 20 KN

Exit	Cleared Taxi Time (s)	Actual Taxi Time (s)	Runway-Crossing Time Error (s)	Runway-Crossing Cross-Track Error (m)
3	75	74.97	-0.03	0.26
5	90	89.97	-0.03	0.20
6	105	104.97	-0.03	0.23

TABLE III  
COMPARISON OF TAXI PERFORMANCE WITH THREE DIFFERENT TAXI SPEED THROUGH EXIT 5

Taxi Speed (kn)	Cleared Taxi Time (s)	Actual Taxi Time (s)	Runway-Crossing Time Error (s)	Runway-Crossing Cross-Track Error (m)
10	150	149.92	-0.08	-0.002
20	90	89.97	-0.03	0.20
30	70	69.996	-0.004	1.07

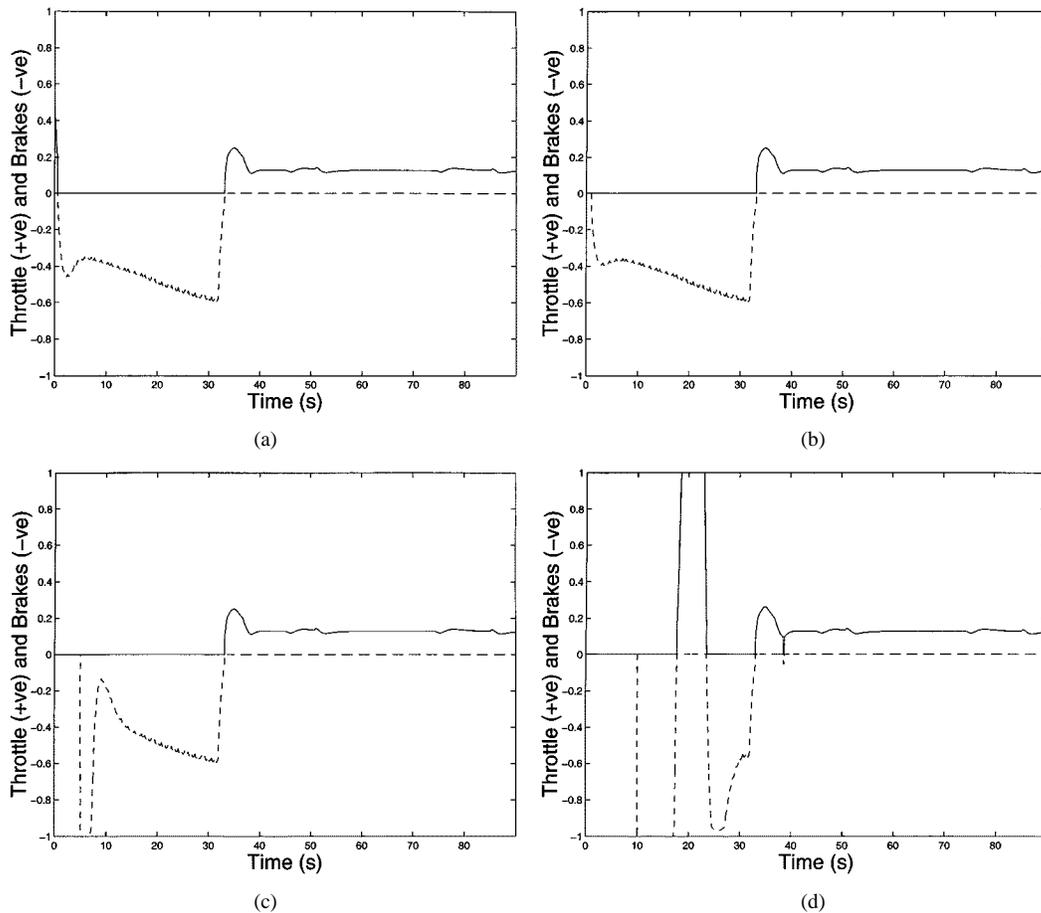


Fig. 14. Comparison of throttle and brakes due to initial delay: exit 5, taxi speed 20 kn, runway-crossing clearance time of 90 s. (a) No delay. (b) 1-s delay. (c) 5-s delay. (d) 10-s delay.

given in Fig. 14(a). Observe that a time constant of 1 s corresponds to a rise time of 4 s to 5 s, which represents rather sluggish reaction by the pilot.

An interesting observation from Fig. 16 is that with a first-order lag of 1-s time constant, the throttle and brake controls become oscillatory. However, the results tabulated in Table IV still indicate that the runway-crossing time and cross-track errors have not increased.

To add realism to the problem, an input disturbance is added to the input of the first-order lag to model inaccurate advisory conformance by the pilot. The disturbance is modeled with

zero-mean Gaussian white noise. Standard deviations of 0.01 and 0.05 are used for the analysis. Since the analysis is based on digital simulation, it effectively approximates the Markov process model of the disturbance by a Markov sequence [31 p. 342]. To account for this approximation, the standard deviation has to be *scaled up* in the digital simulation by a factor of  $1/\sqrt{\Delta T}$ , where  $\Delta T$  with a value of 1/30 sec is the integration step size of the simulation. It should be pointed out that the disturbance is introduced as a convenient way to analyze pilot reaction error. Its purpose is to capture the effect of inaccurate compliance with the desired control, but it does not accurately

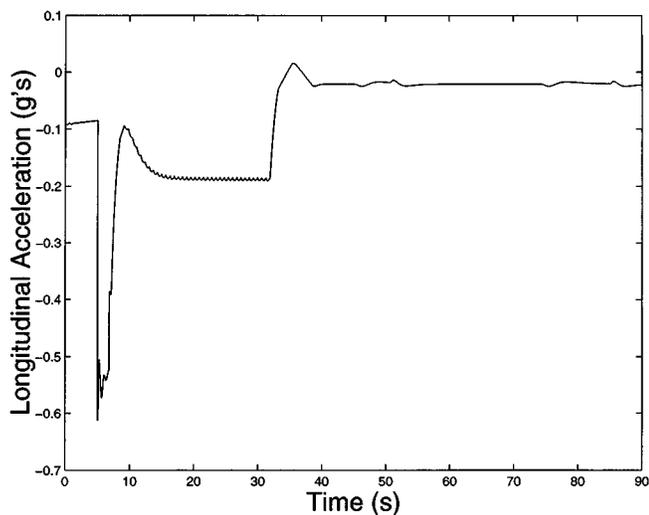


Fig. 15. Longitudinal acceleration due to initial delay of 5 s.

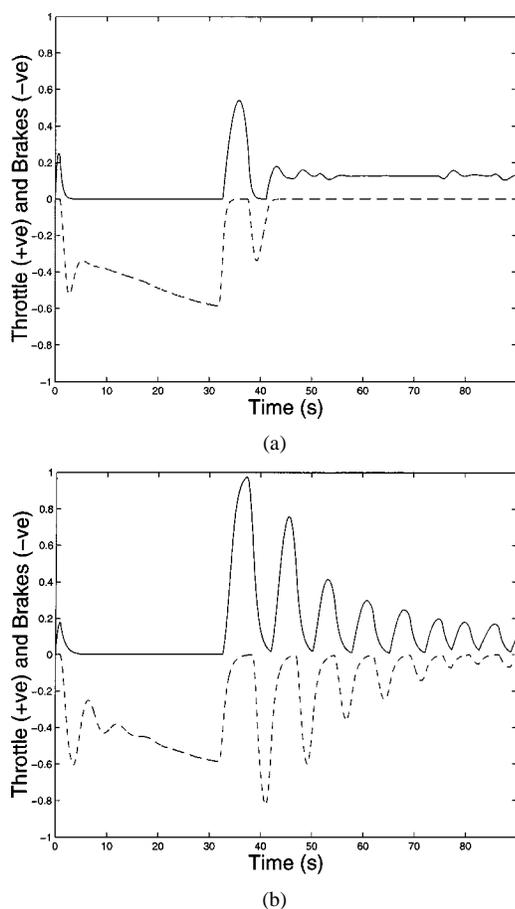


Fig. 16. Throttle-and-brakes profiles with pilot reaction lag. (a) 0.5-s time constant. (b) 1-s time constant.

model the physical phenomena affecting the process. The quantities chosen are to illustrate the stochastic effect of noncompliance, and larger disturbances would naturally lead to even larger inaccuracies. Larger disturbance values are not selected

since the simulation results show that the selected quantities are already drowning out the signals.

The results for the 20-kn case off Exit 5 and 90-s taxi time are tabulated in Table V and compared to the case with no disturbance, i.e., standard deviation = 0. The throttle-and-brakes profiles for the cases with 0.01 and 0.05 standard deviations are given in Fig. 17. Although the control signals appear noisy, the final errors in Table V are similar to the previous results, as much of the noise spectrum is outside the bandwidth of the vehicle dynamics and thus the noise has little effect on the tracking error.

To more appropriately assess the effect of the random disturbance, a Monte Carlo analysis is performed. The ensemble results with 30 runs for the case with 0.05 standard deviation are given in Table VI, which indicates the errors are consistent with the deterministic values observed before. Ensemble position error statistics along the direction of the runway is plotted in Fig. 18, showing the mean position error bounded by the associated standard deviation. The performance of the guidance and control in meeting a cleared taxi time is extremely high, even in the presence of disturbance. It is evident from the results in Table VI that the runway-crossing error is much smaller than the navigation error currently achievable with GPS, where even P-code GPS accuracy is in the order of meters. More specifically, these results compare favorably with the performance requirements of A-SMGCS [16], where the requirement of horizontal accuracy with 95% probability is 2.2 m for guidance performance and 10 m for surveillance performance.

The results of Table VI can also be studied from the runway-incursion point of view. We can say that runway incursion occurs whenever the aircraft crosses the hold line too early or too late, where too early means that the aircraft crosses the hold line before it is supposed to, and too late implies that it will lead to a delay in finishing the crossing by that amount of time. It follows immediately from probability theory that it is meaningless to specify an exact time instant when the aircraft has to cross the hold line, because the probability of achieving any specified time with zero time margin is zero; in other words, the probability of runway incursion will be 100%. It makes more sense to talk about the probability of runway incursion as a function of the time margin within which the aircraft is allowed to cross the hold line. Assuming the statistics in Table VI correspond to the mean and standard deviation of a normal distribution, then with a  $\pm 0.1$ -s time margin, the probability of runway incursion happening due to the control inaccuracy is 0.002%. For all practical purposes, any time margin required to handle navigation inaccuracies will be much larger than that required to compensate for the control inaccuracies observed here. Specifically, the surveillance requirement of A-SMGCS on horizontal error is 10 m. This error, during a 30 kn taxi, would translate into a  $\pm 0.65$ -s time margin to assure 95% probability of not causing runway incursion, and this required time margin would increase as the taxi speed decreases. With the A-SMGCS guidance requirements of 2.2 m on horizontal error, a 30-kn taxi would translate into a  $\pm 0.14$ -s requirement in time margin to assure 95% safety from runway incursion. It is obvious that the control system performance of Table VI is well within the requirements of A-SMGCS, and hence will not adversely affect the compliance with the A-SMGCS requirements.

TABLE IV  
EFFECT OF FIRST-ORDER LAG IN APPROXIMATING PILOT REACTION

Time Constant (s)	Cleared Taxi Time (s)	Actual Taxi Time (s)	Runway-Crossing Time Error (s)	Runway-Crossing Cross-Track Error (m)
0	90	89.97	-0.03	0.20
0.1	90	89.97	-0.03	0.20
0.2	90	89.97	-0.03	0.19
0.5	90	89.97	-0.03	0.17
1	90	89.96	-0.04	0.13

TABLE V  
EFFECT OF 0.5 S FIRST-ORDER LAG WITH DISTURBANCE FOR MODELING PILOT REACTION

Standard Deviation	Cleared Taxi Time (s)	Actual Taxi Time (s)	Runway-Crossing Time Error (s)	Runway-Crossing Cross-Track Error (m)
0	90	89.97	-0.03	0.20
0.01	90	89.97	-0.03	0.18
0.05	90	89.98	-0.02	0.21

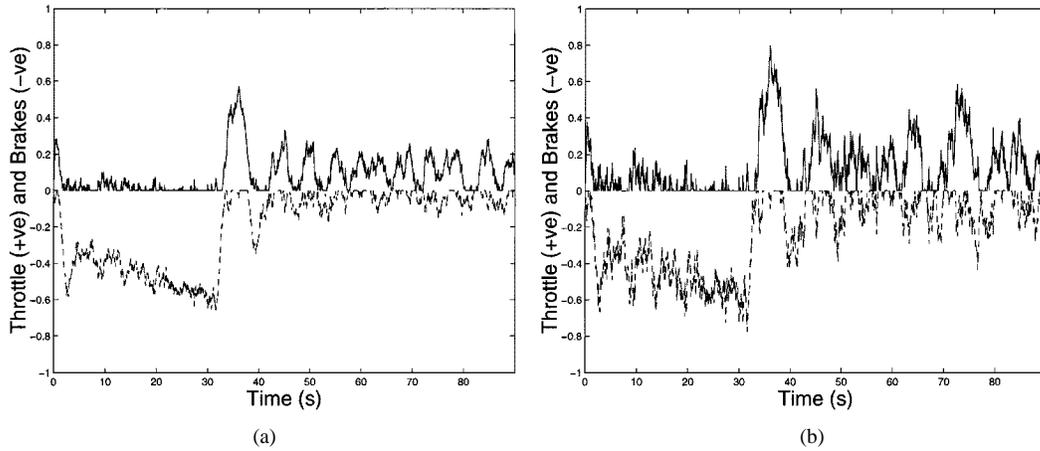


Fig. 17. Throttle-and-brakes profiles with pilot reaction lag of 0.5 s time constant and disturbance with standard deviations of 0.01 and 0.05. (a) 0.01-s standard deviation. (b) 0.05-s standard deviation.

## V. CONCLUDING REMARKS

This paper considers the increasing surface-traffic problem at major airports, and envisions a collaborative traffic and aircraft control system to provide more efficient traffic flow through improved traffic coordination and movement precision. As an initial study toward this collaborative system, this paper has established the potential performance of high-precision taxi, especially in the demanding situation of active-runway crossing. In particular, the paper has proven that state-of-the-art automatic control technologies can enable high-precision taxi.

Due to the high-speed environment, high-precision taxi is most difficult on or across an active runway, where such ability is potentially most beneficial. By focusing on the active-runway-crossing problem, this study has established ways to minimize the runway-crossing time. More importantly, the study has verified the potential performance of a nonlinear guidance and control system that can achieve high-precision taxi control for surface movement, including taxiing continuously immediately after landing to cross an adjacent runway with the tightest of time margin. This capability is instrumental

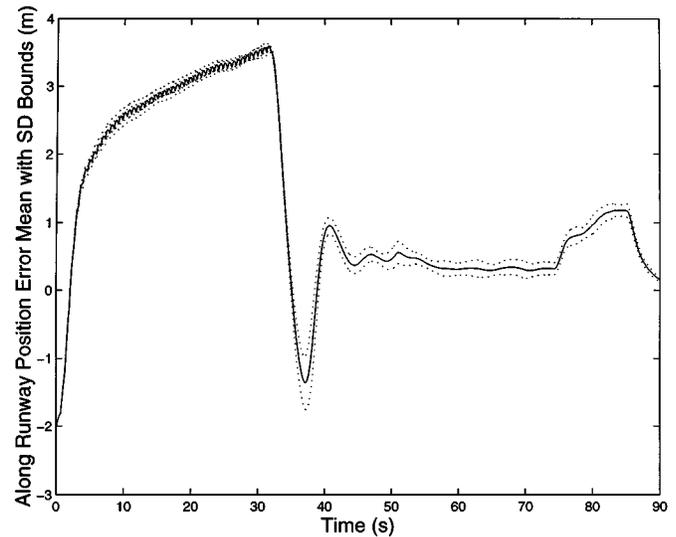


Fig. 18. Monte-Carlo result of position error in direction of runway: mean  $\pm$  standard deviation.

in increasing the opportunity for active-runway crossing amidst landing/takeoff operations, and reducing taxi delay due to

TABLE VI  
STATISTICS FROM MONTE-CARLO ANALYSIS

	Runway-Crossing Time Error (s)	Runway-Crossing Cross-Track Error (m)
Mean	-0.0312	0.1591
Standard Deviation	0.0167	0.0369

hold-short operations that will be otherwise necessary. Evaluation of the guidance and control concept was based on a detailed B-737 taxi model which included landing-gear suspension and tire modeling. The evaluation results have confirmed that the errors due to the guidance and control system are well within the limits of navigation errors being considered for aircraft surface operations.

The results are useful for two applications: development of a surface traffic automation system, and development of an auto-taxi capability compatible with such system. A follow-on study is already underway to develop surface traffic automation technologies: the Ground-Operation Situation Awareness and Flow Efficiency (GO-SAFE) program. GO-SAFE will provide a suite of automation tools for helping the ground controllers in identifying surface traffic problem spots, and in determining efficient taxi clearances, taking into account the scheduling of runway usage to address landing, takeoff and crossing requirements. GO-SAFE is being designed to encourage compatibility with other air-traffic-management automation systems, such as CTAS for arrival flights, and departure planners being investigated by different organizations.

Development of an auto-taxi guidance and control system can be considered as an extension to the flight management system. Such a capability will help achieve the full benefits of the collaborative surface traffic automation system. In the near term before a fully automatic taxi control system can be realized, automated taxi advisories can be conveyed to the pilot to assist the pilot's manual control of the aircraft. A HUD concept such as the one studied under the T-NASA system will allow the pilot to respond to the taxi advisories without losing out-the-window situation awareness. On the other hand, while the fully automatic nonlinear control system studied in this paper uses continuous feedback to control the aircraft, manual pilot control tends to exhibit a piecewise-constant behavior. This behavior and the reaction of the pilot to the display design should affect the tracking performance of the automated system with the pilot in the loop. The degradation in performance of the manual system compared to a fully automatic feedback system deserves additional investigation.

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