Uncontrolled Movement, Collision, and Passenger Fatality on the Angels Flight Railway in Los Angeles, California February 1, 2001

Railroad Accident Report

NTSB/RAR-03/03

PB2003-916303
Notation 7575

National Transportation Safety Board
Washington, D.C.

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Adopted August 5, 2003

National Transportation Safety Board
490 L'Enfant Plaza, S.W.
Washington, D.C. 20594

National Transportation Safety Board. 2003. ***Uncontrolled Movement, Collision, and Passenger Fatality on the Angels Flight Railway in Los Angeles, California, February 1, 2001.*** **Railroad Accident Report NTSB/RAR-03/03. Washington, DC.**

Abstract: About 12:17 p.m. on February 1, 2001, the two cars of the Angels Flight funicular railway collided in downtown Los Angeles, California. The accident resulted in 7 injuries and 1 fatality among the 20 passengers aboard the two cars and injuries to a pedestrian. The Angels Flight Operating Company estimated monetary damage to the cars at $370,000 with an additional $1.2 million to replace the funicular haul system.

The safety issues discussed in this report are the adequacy of the safety oversight of the Angels Flight reconstruction project; the adequacy of the design of the reconstructed Angels Flight system; the adequacy and appropriateness of the braking systems designed for Angels Flight; and the adequacy of Angels Flight Operating Company's maintenance and operating procedures

As a result of its investigation, the National Transportation Safety Board issued safety recommendations to the California Public Utilities Commission, the City of Los Angeles Community Redevelopment Agency, and the American National Standards Institute.

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Contents

Executive Summary

About 12:17 p.m. on February 1, 2001, the two cars of the Angels Flight funicular railway (Angels Flight) collided in downtown Los Angeles, California. The accident resulted in 7 injuries and 1 fatality among the 20 passengers aboard the two cars and injuries to a pedestrian. The Angels Flight Operating Company estimated monetary damage to the cars at $370,000 with an additional $1.2 million to replace the funicular haul system.

The National Transportation Safety Board determines that the probable cause of this accident was the Yantrak Company's (Lift Engineering's) improper design and construction of the Angels Flight funicular drive and the failure of the City of Los Angeles Community Redevelopment Agency, its contractors (Pueblo Contracting Services, Yantrak, and Harris and Associates), and the California Public Utilities Commission to ensure that the railway system conformed to initial safety design specifications and known funicular safety standards.

The major safety issues identified in this investigation are:

- The adequacy of the safety oversight of the Angels Flight reconstruction project;
- The adequacy of the design of the reconstructed Angels Flight system;
- The adequacy and appropriateness of the braking systems designed for Angels Flight; and
- The adequacy of Angels Flight Operating Company's maintenance and operating procedures.

As a result of the investigation, the National Transportation Safety Board makes safety recommendations to the California Public Utilities Commission, the City of Los Angeles Community Redevelopment Agency, and the American National Standards Institute.

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Factual Information

Accident Synopsis

About 12:17 p.m. on February 1, 2001, the two cars of the Angels Flight funicular railway[1] (Angels Flight) collided in downtown Los Angeles, California. The accident resulted in 7 injuries and 1 fatality among the 20 passengers aboard the two cars and injuries to a pedestrian. The Angels Flight Operating Company[2] estimated monetary damage to the cars at $370,000 with an additional $1.2 million to replace the funicular haul system.

Angels Flight Funicular Railway

Angels Flight is a funicular railway in downtown Los Angeles that was originally built in 1901 to move passengers one city block between the commercial district at the bottom of Bunker Hill and the residential area at the top of the hill. Angels Flight operated until 1969, when it was dismantled, and the original cars and portions of the infrastructure were stored. Beginning in 1993, the Angels Flight funicular was reconstructed 1/2 block from its original location. It began operations in 1996 using the original two cars. (The two Angels Flight cars were named *Olivet* and *Sinai*. The cars were given these names in 1901, and the names were retained for the renovation.)

In a basic funicular, the two cars operate in tandem and are connected to each other by a single haul rope (a steel cable). When one car goes up the incline, the other comes down. The two cars counterbalance each other, with the descending car's weight working to neutralize the weight of the ascending car. Therefore, the power required for operation is nominal, basically only that which is necessary to overcome friction and the relatively equal countervailing forces. The reconstructed Angels Flight funicular used a different haul system (described in the "Angels Flight Design" section of this report), with each car connected to its own cable and the cars interconnected through the cable drums and driving gears.

The guideway was a single track at the top and bottom with offset passing sidings midway on the incline. (See figure 1.) The Angels Flight funicular was 298 feet long on an approximately 33-percent grade. Passengers boarded and disembarked from either the lower station or the upper station that was one block uphill. (See figure 2.) Car movement was controlled by an operator inside the upper station house. No Angels Flight personnel

[1] A *funicular railway*, or *funicular*, is a cable railway on a steep incline with counterbalanced cars simultaneously ascending and descending on parallel sets of rails.

[2] The Angels Flight Operating Company managed the revenue operations and physical maintenance of the Angels Flight railway under a contract with the Angels Flight Railway Foundation.

were on board either car during movement. The single operator in the upper station house was responsible for visually determining that the track and vehicles were clear for movement, closing the platform gates, pressing the start button,[3] monitoring the operation of the funicular cars, observing car stops at both stations, and collecting fares from passengers.

Figure 1. Angels Flight viewed from upper station.

Figure 2. Angels Flight car at the passing siding with upper station in the background.

[3] The start button initiated automatic operations. This was the mode of operation at the time of the accident. Manual control was available and occasionally used.

Accident Narrative

Just after noon on February 1, 2001, the Angels Flight operator was making change for a customer when he saw the ascending car stop about 30 feet from the top platform. As he focused his attention on the stopped car, he said, it slid downward a few feet, hesitated for an instant, and then began accelerating downward. The operator said that he had seen cars stop on the hill before but had never seen a car reverse direction. He said that as soon as the ascending car started moving downward, he pushed the emergency stop button. He said that the car did not slow or stop after he pushed the button and that the car continued gaining speed until it collided with the other car near the bottom of the hill. (See figure 3.) Persons waiting at the bottom platform who witnessed the collision said that the struck car stopped before the collision.

Figure 3. Position of cars after collision.

The runaway car derailed during the crash; the struck car did not. The derailment marks and the dispersal of debris after the collision indicated that both cars moved about 20 feet downward from the point of impact.

Emergency Response

The collision occurred about 12:17 p.m. in a busy section of downtown Los Angeles. Local emergency response agencies reported receiving multiple phone calls almost immediately. A Los Angeles police officer heard the collision and responded to the accident scene within 1 minute. The first fire department vehicle arrived within 4 minutes. Firefighters and paramedics used wooden extension ladders to reach, provide emergency treatment to, and evacuate the passengers. (See figure 4.) The injured passengers were strapped to backboards that were lowered to the ground by firefighters standing along the lengths of the ladders. (See figure 5.)

Figure 4. Ladders placed for the emergency evacuation. Walkway on the other side of the tracks can be seen below track level.

Figure 5. Passenger evacuation after collision.

Injuries

At the time of the accident, 8 people were aboard the runaway car and 12 were aboard the car that was struck. One passenger was ejected from the open end of the struck car. Other passengers were injured when they struck vertical grabrails, each other, and various objects inside the cars. One of these injured passengers, an 83-year-old man, died later at a hospital. The Los Angeles County coroner's office reported the cause of his death as multiple traumatic injuries. Debris from the collision fell onto the surrounding area and injured one pedestrian.

Table 1. Injuries.[a]

	Passengers	Pedestrians	Total
Fatal	1	0	1
Serious	5	0	5
Minor	2	1	3
None	12	0	12
Total	20	1	21

[a] 49 *Code of Federal Regulations* 830.2 defines *fatal injury* as "any injury which results in death within 30 days of the accident" and *serious injury* as "an injury which: (1) requires hospitalization for more than 48 hours, commencing within 7 days from the date the injury was received; (2) results in a fracture of any bone (except simple fractures of fingers, toes, or nose); (3) causes severe hemorrhages, nerve, or tendon damage; (4) involves any internal organ; or (5) involves second or third-degree burns, or any burn affecting more than 5 percent of the body surface." The *minor injury* category includes all other persons, not cited in the other injury categories, who were reported treated by area hospitals within 24 hours following the incident.

Damage

The lower inboard quarter of the runaway car struck the upper inboard quarter of the stationary car. Approximately 4 feet of each car was crumpled. (See figures 6 and 7.)

Figure 6. View of some of the exterior damage to cars.

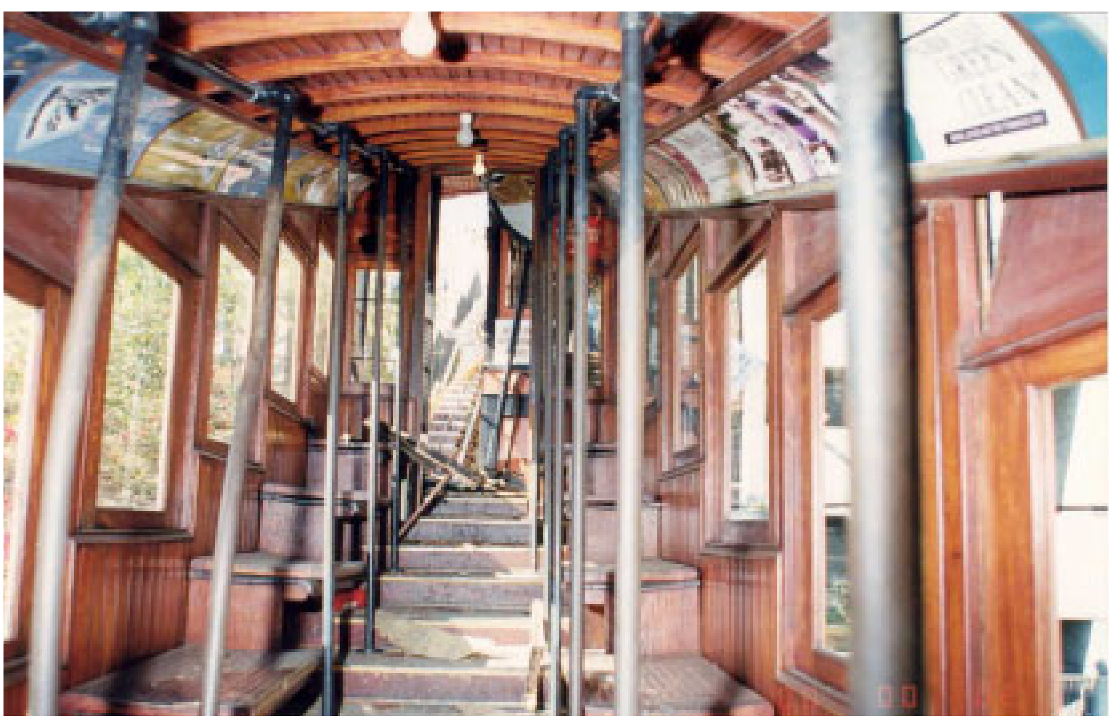

Figure 7. View of some of the interior damage to one of the cars.

The concrete crossties and rail fasteners under the derailed car were scored and dislocated. Some internal haul system components were broken and destroyed. Monetary damage estimates provided by the Angels Flight Operating Company were as follows:

Table 2. Damage.

	Damage Estimate
Equipment	$370,000
Wreckage removal	57,000
Infrastructure	73,000
Haul mechanism	1,200,000
Total	$1,700,000

Meteorological Information

At the time of the accident, the temperature was 72º F, winds were calm, and the skies were clear.

Postaccident Onsite Examination

The system's operating machinery was in the machinery room underneath the operator's station house. The Angels Flight haul system consisted of a separate cable, drum, axle, and planetary gear for each car, with a sun gear driven by a single 100-horsepower electric motor. (See figure 8.) The driven sun gear meshed with the planetary gear for the *Olivet* car (the struck car in this accident), which in turn meshed with the planetary gear for the *Sinai* car (the striking car). Axle shafts (about 3 inches in diameter) connected the planetary gears with their respective cable drums. This gear arrangement meant that the two planetary gears, and thus the two cable drums, were counter-rotational, resulting in counterbalancing loads as one car descended while the other ascended.

Emergency brakes (discussed in detail later in this report) that were designed to stop the rotation of the drum were found to be in the released position even though the emergency stop button had been pressed by the operator. Initial inspection also revealed that the 7/8-inch-diameter cable for the *Sinai* car was intact but that two rows of the wound cable had de-spooled from its drum.

Reconstruction of Angels Flight

The City of Los Angeles Community Redevelopment Agency (Community Redevelopment Agency) purchased Angels Flight in 1962 because Angels Flight was within the Bunker Hill district urban renewal project area. At that time, Angels Flight was

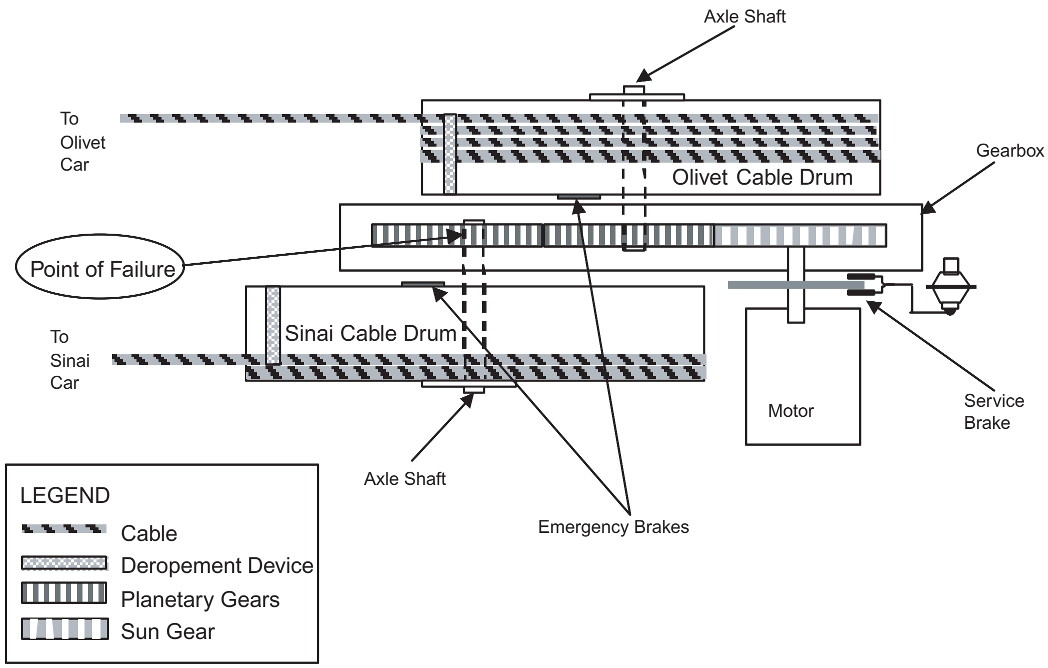

Figure 8. Schematic of Angels Flight haul system.

a designated historic and cultural monument. In response to community interest in and concern about the eventual fate of Angels Flight, the Community Redevelopment Agency pledged to restore the funicular railway as part of the Bunker Hill urban renewal project.

In 1991, the Community Redevelopment Agency hired Parsons Brinckerhoff Quade & Douglas Engineering (Parsons) as an advisor on the reconstruction of Angels Flight. In 1992, the Community Redevelopment Agency hired Harris and Associates (Harris) as the construction manager for the renovation of Angels Flight. In 1993, Harris hired Parsons to design specifications for the project.

On June 17, 1993, the Community Redevelopment Agency approved the Angels Flight Restoration and Reconstruction Plan. The Community Redevelopment Agency selected Pueblo Contracting Services, Inc., (Pueblo) to be the general contractor for the Angels Flight reconstruction. On November 17, 1994, the Community Redevelopment Agency awarded two construction contracts to Pueblo to rebuild Angels Flight according to the Parsons specifications, and construction began soon afterward. In 1995, Pueblo hired Lift Engineering (Yantrak[4]) to implement Parsons's conceptual design by designing and building the funicular drive, control, and braking systems and the haul and drum assembly. (See figure 9.) About 15 months later, a ceremonial opening of Angels Flight took place on February 23 through 25, 1996.

[4] Yantrak, a company that built automated trains such as those used at airports, was established in the early 1990s by the owner of Lift Engineering, which until that time had built only ski lifts. During the Angels Flight project, Lift Engineering often sent letters and faxes bearing the Yantrak company name, and parties to the reconstruction commonly referred to Lift Engineering as Yantrak.

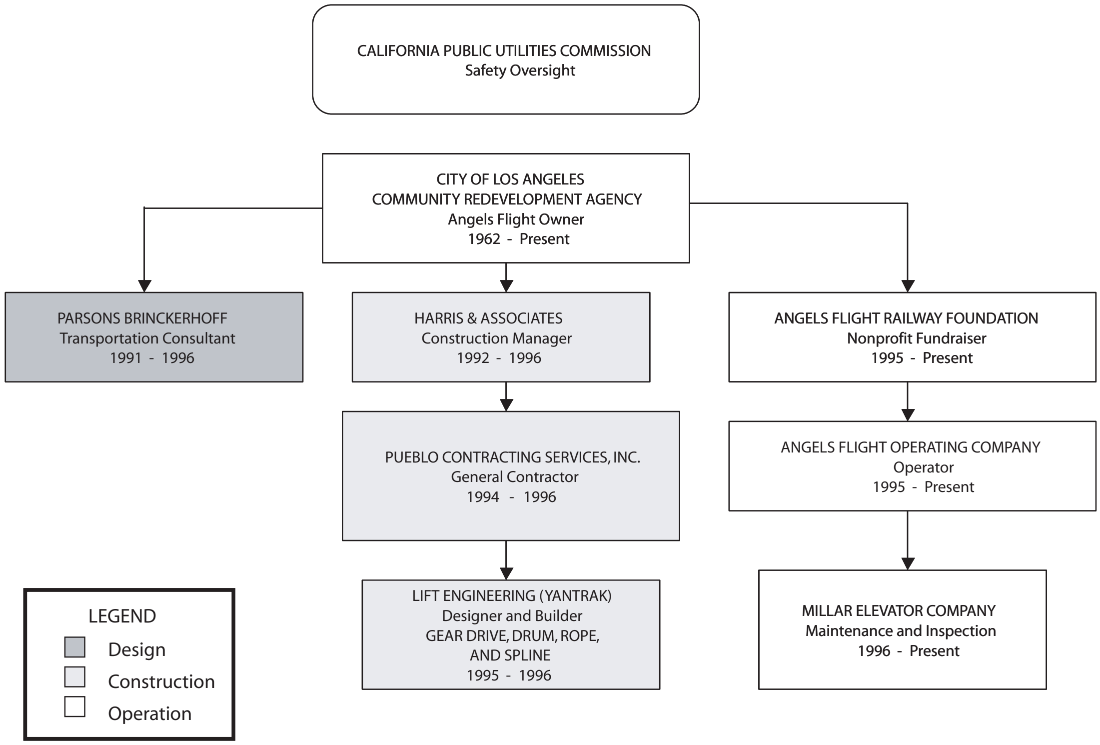

Figure 9. Organizations involved in Angels Flight design, construction, and operation.

During the project, the Community Redevelopment Agency had responsibility for contract negotiations, safety oversight, deletions from and modifications of the original safety designs, and safety certification. As owner of the funicular, the Community Redevelopment Agency made final decisions concerning the original engineering design of Angels Flight and subsequent modifications. The project lasted from 1991 through April 1997, when the completed funicular was leased to the nonprofit Angels Flight Railway Foundation, which entered into a 99-year lease with the Community Redevelopment Agency to operate and maintain Angels Flight. The Community Redevelopment Agency maintained ownership but was not involved with the operation or maintenance of Angels Flight. The Angels Flight nonprofit foundation contracted with the for-profit Angels Flight Operating Company to manage the operation and maintenance of the railway.

The Angels Flight Operating Company hired the Millar Elevator Service Company (Millar) in 1996 to perform maintenance and inspections. The Millar elevator mechanic assigned to Angels Flight eventually became the maintenance contractor, and he subsequently became vice president of the Angels Flight Operating Company while simultaneously remaining an employee of Millar.

Angels Flight Design

Parsons's specifications for the funicular system included a trackway design with standard steel rails attached to concrete ties, all supported on an elevated framework from 10 to 20 feet above the ground. (See figure 10.)

Figure 10. Elevation of Angels Flight track (at left).

Drive System

When originally built in 1901, Angels Flight was a basic funicular, with two cars, connected by a single cable, whose weights counterbalanced each other. The haul system was powered through an arrangement of wheels and gears that the cable passed around at the top of the hill.

For the reconstruction of Angels Flight, Parsons did a conceptual design of the haul system. (Subsequently, Yantrak modified the haul system design. A schematic diagram of the Yantrak haul system is shown in figure 8.) Instead of a single cable connecting the two cars, the new haul system consisted of an autonomous cable, drum, axle, and planetary gear for each car, with a common driven, or sun, gear. Thus, each car was attached to its own cable; each cable was wound around and attached to the outside of an independent 6-foot-diameter drum; each drum was connected to its own axle; the axles were connected inboard to separate planetary gears; and the planetary gears were meshed together. One of the planetary gears meshed with a driven sun gear that was powered by a 100-horsepower motor. This design made Angels Flight a double winding drum system that was operated as a double reversible funicular.[5] Maximum operating speed was about 352 feet per minute (4 miles per hour).

[5] A double reversible funicular has two cars that reciprocate between stations or terminals on two paths of travel.

The 1901 Angels Flight had a second "safety cable" that was used to prevent a runaway if one of the cars became detached from the primary cable, if the primary cable failed, or if anything else happened to cause uncontrolled movement. The reconstructed version of Angels Flight did not have a safety cable.

Braking Systems

Angels Flight was equipped with two disc-brake-style braking systems: a service brake and emergency brakes. The service brake stopped rotation of the motor shaft powering both cable drums through the gear train. Because the service brake acted on the motor shaft only, it would have no effect on a car that became disconnected from the motor because of failure of a cable or gear train component.

Each of the two cable drums was equipped with emergency brake calipers that operated by closing against the drum flanges when the emergency brake was activated. The calipers on both drums closed when the emergency brake was activated; thus, the emergency brake stopped the rotation of both drums simultaneously. The emergency brakes operated to stop the cars if a failure in the gear train caused them to be disconnected from the drive motor; however, the emergency brakes could not stop a car whose drive cable had broken or become detached from the drum.

The service and emergency brake systems were both spring-applied brake systems. Hydraulic pressure for the two systems was provided by two identical hydraulic pumps. In the "applied" state for both brake systems, spring pressure held the brake calipers closed. Hydraulic pressure was then used to counteract the spring pressure and release the brakes. The brakes would remain in the released state as long as the hydraulic systems were sufficiently pressurized. To activate the service brake, a solenoid valve had to open, thereby relieving hydraulic pressure in the system. Similarly, to activate the emergency brakes, an identical solenoid valve had to open to relieve the hydraulic pressure. With hydraulic pressure reduced or removed, spring pressure would close the brake calipers against the motor shaft disc or the cable drum flanges, depending on which brake system was activated. The operator's console had an emergency stop button and a button that operated the service brake.

Design Changes

Parsons's specifications called for both cars to be fitted with emergency track brakes, end gates on the cars to contain passengers, and an emergency walkway for the entire length of the tramway to facilitate the evacuation of passengers in the event of an emergency. As discussed below, none of these features were included in the final design and construction.

Track Brakes

The original design submitted by Parsons and approved by the Community Redevelopment Agency called for both cars to be fitted with emergency track brakes. Track brakes are attached to the underside of the car body with the brake pads configured to apply against the top of the rail, against the sides of the rail, or around the entire railhead. In the event a car exceeds a safe speed because of a loose or broken cable or other catastrophic failure of either the drive or haul system, track brakes provide an independent means of stopping the car by applying a retarding force directly between the car and the track structure.

Parsons interoffice communications indicate that final track brake application and configuration was being discussed routinely throughout 1993. Records show that Parsons continued to research recent funicular construction even after the original design was submitted and approved. Nothing in the records from 1993 indicates that the elimination of track brakes was being considered.

An August 22, 1995, letter from Yantrak (which was building the drive, control, and braking systems) to Parsons summarized the technical points of a meeting held that morning. Under the section "Track Brake," the letter stated the following:

> This track brake is frequently eliminated on modern high-speed (more than 10 m/sec) tramways. Track brake used in the case of overspeed is not very practical. …With such a short track, there is little room to brake, and the probability of running out of track before the tramway stops is high. Rail brake as suggested by the specification is not possible. (Clearances, dynamics, lack of braking surface, lateral displacement of the undercarriage, etc.)….

In response, Parsons (which had developed the design specifications) sent Yantrak the engineering calculations for braking Angels Flight, information from two manufacturers of modern track brakes, and comments concerning the use of a disc brake on a 33-percent grade. On August 30, 1995, Parsons wrote Harris (the construction manager) about its concerns regarding Yantrak's response:

> [Yantrak] states 'This track brake is frequently eliminated on modern high-speed (more than 10 m/sec) tramways.' This statement appears to be incorrect and irrelevant to inclined railway applications. The average speed specified for the Angel's Flight is around 6 ft/s or (1.8 m/s). All modern inclined railway systems [Parsons is] aware of are equipped with an emergency track brake for safety reasons.

In the letter, Parsons went on to ask for "a list of modern inclined railway systems <u>not</u> equipped with an emergency track brake to support [Yantrak's] claim [that track brakes are not practical]." In support of Parsons's inclusion of track brakes in its design, the letter stated the following:

> The statement made that 'the probability of running out of track before the tramway stops is high' because of 'such a short track' appears incorrect. A simple calculation shows that the minimum specified track brake rate (1.75 mph/s) at the specified speed (about 4 mph), the stopping distance is approximately 8 to 10 feet. This calculation considers the response time of the brake system.

> The statement that 'rail brake as suggested by the specification is not possible' is incorrect. The suggested concept is actually in use in the USA, Switzerland, Germany, and France, and has been proven to be efficient and reliable. [Yantrak] should support [its] claim with specific evidence.

Between August 22, 1995, and September 6, 1995, Harris, Parsons, and Yantrak exchanged correspondence concerning track brakes. The need for a "fail-safe" application, current industry applications of various forms of track brakes, track brake guard rails, a second haul cable, and additional braking calculations were discussed. A September 7, 1995, interoffice Parsons communication stated:

> …it is my understanding that a decision has been made by [Harris] <u>not to have</u> a track brake to stop the Angel's Flight vehicles should a rupture of the haul cable occur.
>
> It is my professional opinion that the above violation of the technical specification is unacceptable because of the risks of potential injuries/fatalities it may cause to the passengers…. My advice is that [Parsons] should stand firm on the issue or disclaim any responsibility. Alternate solutions will require a complete re-study of the conceptual design. (Example: 2 haul cables.)

Parsons sent a letter to Harris on September 8, 1995, objecting to the elimination of track brakes from the Angels Flight vehicles. That letter stated, in part:

> [Harris has] advised that [Yantrak] … has proposed to delete the track brake required.… The reason stated for this deletion was incompatibility between the conceptual arrangement of the track brake…and the guard rail…. As previously stated, we find no incompatibility between the conceptual arrangement of the track brake and the guard rail. It is our opinion that the deletion of the track brake is an unacceptable departure from the technical specifications. In the event of a rupture of the haul cable the absence of the track brake poses the risk of potential injury or fatality to passengers. Therefore, it is recommended that [Yantrak's] proposal be rejected.

Harris, with the Community Redevelopment Agency giving final approval, decided not to equip the Angels Flight vehicles with track brakes. An October 10, 1995, Parsons document details a review of Yantrak technical drawings. Under the "Trucks" section, the review states in part: "Only a single cable is shown. Since it is understood that the vehicle will not have track brakes, there should be two cables for safety conditions."

Records indicate that on October 11, 1995, a Parsons engineer sent an interoffice communication with annotated photographs of current funicular operations that had either track brakes or two haul cables; these were Peak Tramway in Hong Kong, with two haul cables and no track brakes, and Rigiblick in Switzerland, with one haul cable and track brakes.

A meeting was held in Atlanta, Georgia, on November 11, 1995, between Parsons and Harris. Minutes of that meeting state the following:

> The general safety philosophy of the drive system is discussed at length. [Parsons's] representatives state that over-design of the drive system is not a satisfactory answer to their concerns about the safety of the system. A failure analysis has not been performed by [Yantrak] to identify the possible catastrophic hazards, and should be required. However, it can be said that there is always a possibility of rupture of the haul cable, or slip of a pinion or bull gear, and both may cause a catastrophic hazard. Present industry practices show that a track brake will satisfy the safety requirements, as well as the redundancy approach of having a second haul 'safety' cable. However, due to the project schedule, the track brake approach seems the only possible solution to comply with the safety requirements without impact on the project schedule. A quick review of the undercarriage structure shows that there should be no problems to weld two track brake mounting assemblies to the metallic beams supporting the wooden carbody.

The Harris construction manager wrote to Pueblo on November 28, 1995, to express concern about modifying Parsons's original Angels Flight design:

> One of [Parsons's] concerns about your design was the lack of precedent for a system without a safety cable or track brake. [Yantrak] has always indicated that the systems in Pittsburgh operate without either component. [Yantrak] is incorrect. I have photographs of the two Pittsburgh systems and both have safety cables. It would be of benefit if you could produce a documentable example of a system in operation that is similar to the one you are currently designing.

On January 22, 1996, about 1 month before Angels Flight began passenger service, Parsons wrote the following to Harris:

> The submitted documents [see below] show evidence that the proposed design is not in compliance with the required scope of work as related to the safety of the system. As written, they pass on to the Owner, or his representative, the responsibilities/liabilities of a non compliant and non failsafe design.

Supporting documentation for the letter detailed the following specific safety weaknesses:

- Lack of a back-up safety feature for a haul cable rupture;
- Inadequate definition of supervisory responsibilities;
- Lack of detailed operating procedures;
- Inappropriate operating prohibitions;
- Lack of an emergency evacuation plan;
- Lack of details, definitions, and values for maintenance procedures and inspections of the undercarriage, haul cable, drive frame, gear case, gearbox mounting flange, rope drum, D-9 hubs, and gearbox;
- Out-of-date log sheets and inspection forms; and
- Inadequate recommendations to address the deficiencies of the proposed design identified in the hazards analyses.

There is no indication that, in response to this letter, substantial revisions or inspection procedure changes were made to Angels Flight before it opened for passenger service. In a February 13, 1996, letter to Pueblo, Yantrak declared that a careful analysis of the conceptual design showed areas that were technically incorrect or inefficient. On the issue of track brakes, the letter stated that "Suggested use of the caliper rail brake was an oversight, since such a brake cannot be employed on the split rail of the train bypass." The letter also stated that:

> A higher level of safety was achieved by conservatively sizing the rope and rope supporting elements and in the redundancy of rope attachment, than by monitoring the loss of the rope tension and vehicle overspeed and applying a secondary safety device acting in the case of rope failure.

End Gates

End gates were proposed for the Angels Flight vehicles by Parsons in its 1993 design. The proposal was based on a formal hazard analysis. The Community Redevelopment Agency approved installation of end gates and included the requirement in the contract that was later awarded to Pueblo.

Throughout the Angels Flight reconstruction project, the Los Angeles Conservancy, a historic conservancy group, provided information to the Community Redevelopment Agency concerning the historical accuracy of the restoration.[6] The historic conservancy group objected to the Angels Flight vehicles' being equipped with end gates. According to the group, the cars operated with open entrances and exits without incident from 1901 until 1969. The cars were restored without end gates.

In a February 14, 1996, letter to Pueblo, Harris included in its safety concerns about Angels Flight the following about the end gates on the cars:

> … The formal design (not concept) required gates on the cars. These have not been installed on four of the openings. What issues are involved with the removal of these gates?

The cars were operated without end gates at the ceremonial opening February 23 to 25, 1996, and in passenger service thereafter.

A March 25, 1996, letter from Harris to Pueblo about contract requirements that needed to be either completed or discussed stated: "Provide gates to cars and automatic stop provisions as required or provide professional opinion supporting evidence that the system can be operated safely without the specified gates and interlocks."

A Community Redevelopment Agency memorandum to Pueblo dated April 5, 1996, requested a change order in the existing contract regarding the end gate. The memorandum stated the following:

[6] The primary liaison between the Conservancy and the Community Redevelopment Agency was an individual who later became president of both the Angels Flight Railway Foundation and the Angels Flight Operating Company.

> The contract specifications … required gates to be added to the two historic funicular cars as part of the rehabilitation of the cars. As work progressed … for the reconstruction of Angels Flight, it became apparent that there was a conflict between the two contracts. … Review of the plans for the reconstruction by the system designer [Parsons] and the system operator [the operating company] along with the regulatory agencies [Public Utilities Commission] led to the question of whether or not the gates are really necessary.

In a May 20, 1996, letter to Pueblo, Harris wrote:

> [Community Redevelopment Agency] desires that [Pueblo] take the necessary steps to immediately install the gates to the cars. Gates at the lower ends are of utmost importance at this time. Please advise [Harris] of the proposed schedule for shop drawings, construction and installation.

In a July 29, 1996, letter to the Community Redevelopment Agency concerning this issue, the Angels Flight president (the president of both the nonprofit foundation and the for-profit operating company) wrote:

> [Rule Company (the company that provided liability insurance for Angels Flight), in its] 'Insurance Review of Operations' confirms the opinions expressed when the underwriters first studied [Angels Flight] and underwrote [the] liability insurance with the cars operating open-ended – as the cars operated for 68 years.

The letter from the Angels Flight Operating Company also stated that the Rule Company's letter confirmed that after conducting a review of the first 5 months of operations**, "the insurers are not aware of any problems, including any relating to 'the traditional open end of the cars.'"** (Emphasis in original.)

On July 30, 1996, Harris sent a written proposal detailing "Safety Gate Shop Drawings" and "Sample of Metal Mesh" to Tetra Design, Inc.,[7] for review and approval. In an August 6, 1996, letter to Pueblo, Harris mentioned the end gates and reminded Pueblo that it had not yet complied with the contract requirement that Angels Flight would not operate if a gate were open and would stop if a gate were opened while the tramway was operating.

During October 1996, the Community Redevelopment Agency staff exchanged a series of memorandums concerning end gates for Angels Flight. In that correspondence, the Community Redevelopment Agency deputy administrator first opposed the addition of end gates because he believed the risk of a passenger falling from a car with an open end was lower than the risk of a passenger being pinched or hurt by a gate, and "the additional occasional risk from a passenger relying upon a closed end gate that fails is far greater than the risk of having no gates." However, the Community Redevelopment Agency engineer assigned to the Angels Flight project protested the decision not to have end gates on the Angels Flight cars. Some of that engineer's objections were as follows:

[7] Tetra Design, Inc., was a prospective subcontractor for designing the end gates.

- He and others had observed conditions on Angels Flight cars where accidents could have occurred.
- The original design team of engineers and transportation experts saw the need for gates to prevent a person from falling out of the Angels Flight cars, which led to gates being specified that were to be interconnected to the control system to stop the drive system if a gate was opened.

The project engineer summarized his view as "When weighing the risks of persons getting a pinched finger vs. a possible fatality, … we should protect against the possible fatality."

The deputy administrator then changed his mind on end gates. The Harris construction manager's written notes indicate that the project engineer:

- Told the Harris construction manager that he had been directed by his supervisor to install the gates,
- Had prepared a letter to Harris directing that the gates be installed, and
- Sent word to the Community Redevelopment Agency director asking whether the decision to install the gates would be appealed to the Community Redevelopment Agency board.

Before the end gates could be installed, the Angels Flight president wrote an objection to the Community Redevelopment Agency deputy administrator, stating:

> … Is it most prudent to add new gates, as some have suggested, or is it more prudent to leave the cars as they always have been—open at the ends? This is an issue that the Angels Flight Operating Company and our insurance advisers have studied carefully. Our conclusion is that it would be less prudent to add new gates.
>
> … In every case, the hazards of adding gates equal or outweigh the hazard of leaving the cars as they have been for the first 68 years of operation and for the past 8 months of renewed operation. This is why my advisers and I have concluded that **what is most prudent is to not alter the cars by adding the proposed end gates**. [Emphasis in original.]

In response, the Community Redevelopment Agency administrator wrote to the Angels Flight president announcing the issuance of a contract change order to delete installation of the end gates. The letter noted that it was at the insistence of the Angels Flight foundation and operating company that the agency had contemplated issuing the change order. The administrator also stated that there were safety advantages and disadvantages involved with installing end gates and that the decision not to install the end gates must continue to be studied. Finally, the letter stated that the change order to delete the end gates from the Angels Flight cars would be issued provided that five safety conditions were incorporated in the agreements to be executed between the Community Redevelopment Agency and the Angels Flight Railway Foundation for the conveyance and operation of Angels Flight. As written, those conditions were as follows:

> First, upon the execution of the conveyance documents, the [foundation] and the [operating company], or any subsequent operator, will be wholly responsible for the maintenance and operation of Angels Flight, including the safety and security of the Angels Flight patrons, as already set forth in the conveyance documents.
>
> Second, the [foundation] and the [operating company] will be legally liable for any event or occurrence related to the design, installation and operations of the railway following the conveyance of Angels Flight to the [foundation] and must defend, indemnify and hold harmless the Agency, its Board and staff and the City of Los Angeles.
>
> Third, appropriate signage must be installed or verbal warnings enhanced to advise riders of the potential for harm that exists because of the open ends of the cars. …
>
> Fourth, a monitoring procedure, including electronic monitoring, such as was discussed in the August meeting and agreed to in your October 29 letter, should be considered by the [foundation] and must be formally incorporated into the Angels Flight operations. …
>
> Fifth, and finally, the end opening of the cars must continue to be studied by the [foundation] and [the operating company] for the dual purposes of potential future installation of the end gates and equally important, the introduction of other safety and security measures which may be beneficial.

In a November 13, 1996, letter, the Community Redevelopment Agency administrator instructed Harris to prepare a change order that deleted the requirement for end gates on the Angels Flight vehicles. The letter stated that the gate requirement was deleted after a comprehensive and diligent review at the request of the current operator of Angels Flight and the nonprofit foundation. The next day, November 14, Harris issued a request for quotation to Pueblo that stated: "Delete the four gates, hardware, design and interconnect to the operating system as shown at the top and bottom of the funicular cars.…"

Emergency Walkway

Parsons's original design called for a walkway along the entire length of the guideway for the evacuation of passengers from stranded vehicles. Preservationists raised concerns about the historical accuracy of the walkway as early as 1993, pointing out that Angels Flight did not have such a walkway between 1901 and 1969. Parsons wrote a memorandum to Harris on December 6, 1993, on the subject of safety versus historical accuracy issues:

> …the Project Owner [Community Redevelopment Agency] must exercise final approval on various Project features, characteristics, etc. i.e., it cannot delegate certain policy matters to its consultants. Under California Government Code Section 835, a public entity is liable for injury caused by a dangerous condition of its property if the dangerous condition was created by a negligent or wrongful act or omission…and failed to take appropriate measures to protect against the

> dangerous condition. … a successful effort by others to override the Public Utilities Commission and/or the Fire Department on the need for the emergency staircase … would place the Community Redevelopment Agency in jeopardy.

The Community Redevelopment Agency's deputy director of engineering detailed his position concerning the necessity of an emergency walkway next to the Angels Flight trackway in a memorandum to the Community Redevelopment Agency director of engineering dated March 2, 1995. In that memorandum, he stated that the Community Redevelopment Agency's acting administrator and senior staff concurred with the need for an emergency walkway and raised concerns that Angels Flight might not be insurable without it.

In a March 24, 1995, letter to the Angels Flight Operating Company, an insurance loss control consultant stated his opinion that the track-adjacent walkway "could present an attractive nuisance and facilitate vandalism and malicious mischief." In a March 28, 1995, letter to the Community Redevelopment Agency's deputy director of engineering, a supervising engineer from the Public Utilities Commission Rail Transit Safety Section noted that the Public Utilities Commission staff agreed that the safety advantages of the proposed emergency walkway immediately adjacent to the Angels Flight trackway were outweighed by the attractive nuisance safety hazards created.

On April 18, 1995, the Community Redevelopment Agency's director of engineering issued a memorandum to eliminate the emergency stairway. That memorandum stated the following:

> This Change Order authorizes the contractor to proceed with designs for requested changes which would alter the method of providing emergency egress from the funicular. The Los Angeles City Fire Department (LAFD) and the State Public Utilities Commission have given their approval to delete the trackway emergency stairway they had required, if certain other equipment and facilities are added to Angels Flight.
>
> BACKGROUND
>
> During the planning for the reconstruction of Angels Flight, the regulating agencies, the LAFD and the Public Utilities Commission, required that some method of emergency egress be provided for the funicular even though historically there was none. After many discussions, LAFD and the Public Utilities Commission recommended that a trackway emergency stairway be included in the plans.
>
> Because a trackway emergency walkway was not in keeping with the historic context of Angels Flight, the Los Angeles Conservancy expressed concerns about its inclusion during review of the reconstruction plans. ... a member of the Conservancy and potential operator of Angels Flight, further investigated the need for the trackway emergency stairway and any alternatives thereto. Through various meetings with LAFD and the Public Utilities Commission, [he] has convinced them to agree to an alternative to the trackway emergency stairway which would consist of:

- A combination ground-level and elevated stairway separated from the trackway
- Auxiliary emergency power supply
- Reversible funicular controls
- Security system and fence

The items noted above were added during the renovation of Angels Flight by the Community Redevelopment Agency. A walkway next to the trackway to facilitate the emergency evacuation of passengers was never constructed.

Haul Cable

In the aftermath of the decision not to include track brakes or a safety cable on the reconstructed system, Yantrak specified a haul cable that was thicker (7/8, or .875, inch in diameter) and had a higher safety factor than the cable specified in the original Parsons design. Yantrak did not redesign the drums on which the cable wrapped and unwrapped, which were constructed to the original specifications.

Cable Drum Design

The two Angels Flight cable drums were grooved to accept the cables as they were wound onto the drums to help prevent deropement. The cable drums had outer flanges to help contain the cable. Investigators measured the height of the flanges on both drums. On the *Olivet* drum, the flanges measured .594 inch on the outer side and .75 inch on the gearbox side. For *Sinai*, the measurements were .625 inch for the outer side and .75 inch for the gearbox side. Postaccident examination of the drum for *Sinai*'s cable revealed that during or immediately after the accident, the cable had become partially unspooled from its drum.

Deropement Switch Device

Both of the Angels Flight cable drums were equipped with switches intended to activate the system brakes to stop the funicular in the case of deropement. (See figure 11.) The switches contained pressure-sensitive edges and were mounted directly above the surface of each haul cable when it was stored on its respective drum. Because the deropement switches did not extend all the way across the drum's surface, the outboard haul cable coils could derope without triggering the deropement switch, as occurred with the *Sinai* drum in this accident.

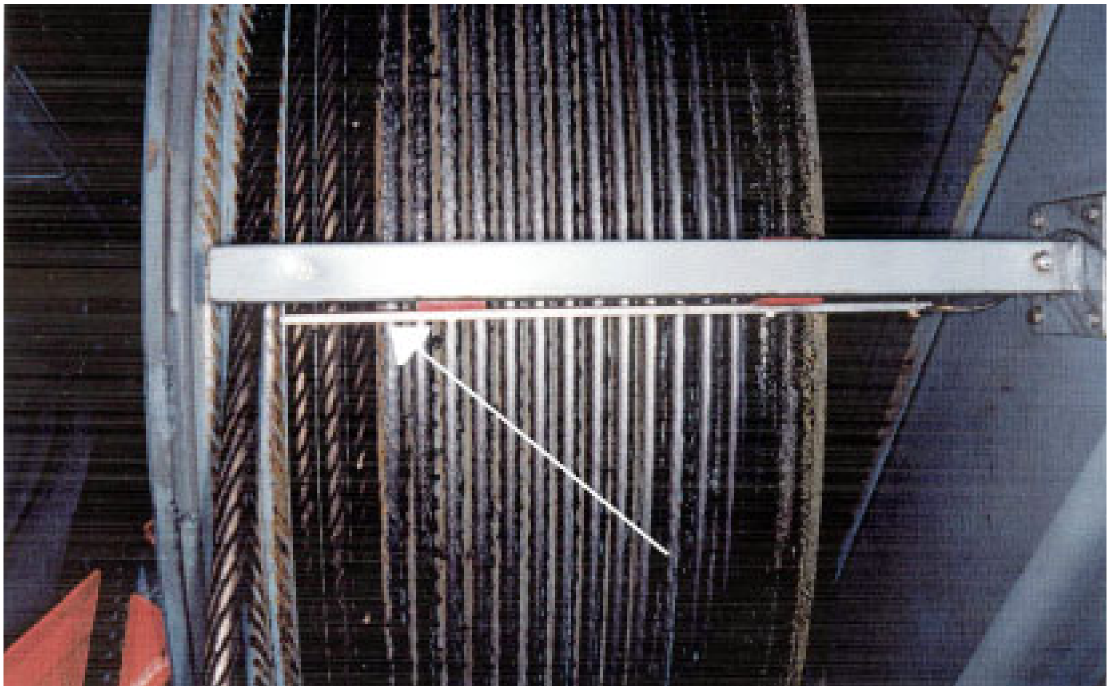

Figure 11. Deropement device.

Angels Flight had been in passenger service for several months before the deropement switches were added. On August 12, 1996, Harris sent a letter to Pueblo listing "de-roping annunciation and system halting" as requirements that had not been completed. The deropement switches described above were subsequently added.

Operations

Gearbox Overheating

According to the Angels Flight president, high oil temperatures in the gearbox became a concern soon after Angels Flight opened in February 1996. Angels Flight representatives made repeated telephone calls to Yantrak in a continuing attempt to evaluate and correct the problem. Yantrak's initial response referenced a memorandum from Fairfield Manufacturing,[8] which stated:

> … oil temperatures up to 225 degrees F will not cause gear or seal problems in your Angels Flight drive. …The level of oil in the box will change your operating temperature. I would lower it to the centerline and see how much that helps. As you continue to lower the level, the temperature will fall to a point where you are no longer getting enough lubrication and then it will start to rise. Since your unit is critical, I would not take this test to the point where you get the temperature rise

[8] Fairfield Manufacturing supplied most of the gears (but not the hubs, which were supplied by Yantrak) for the Angels Flight gearbox.

> but do feel you could safely go two inches below centerline and would see significant improvement in oil temperature.

During periods of overheating, incidents occurred in which the Angels Flight system automatically shut itself down while in passenger service.[9] A California State assistant attorney general told the Safety Board that he had stopped riding Angels Flight long before the accident because he had been stranded on the hill several times when the system shut down while the cars were midway between stations. The assistant attorney general said that Angels Flight operators told him that the shutdowns occurred when the system "got hot" and that the only thing they could do was to wait for it to cool down. He further said that on occasions when the system had stopped, he had observed other passengers exit the cars and walk on the track structure to the bottom of the hill. The Angels Flight vice president stated that he had seen a passenger evacuate a car and walk down the track to the bottom of the hill when the cars were stopped. In a February 27, 1995, letter addressed to the insurer for Angels Flight, the Angels Flight president referenced an insurance loss control consultant's recommendations that "passenger egress from the cars or from the landings onto or near the tracks should be prevented at all times, 'emergency' or otherwise."

The Angels Flight president issued instructions that the cars would be stopped at their terminal berths any time the oil temperature approached 225º F, but this procedure did not completely eliminate the shutdowns. The operating company continued Angels Flight passenger service and did not modify the operating schedule to help prevent delays caused by excessive oil temperatures.

According to the Angels Flight vice president, in 1996, the gearbox oil would heat to the point that it vaporized and the vapor filled the machine room. As the oil cooled, it would condense and leave a slick surface on the floor, walls, ceiling, and equipment. During the on-scene investigation, the Angels Flight vice president said he had feared during this period that an electrical spark or other source of ignition could trigger an explosion. He stated that Yantrak was reluctant to install an oil cooler. Initially, an expansion tank that collected the hot oil and returned it to the gearbox sump was added to the lubrication system. The vice president said this measure helped with the overflow situation but did not eliminate the overheating problem. He stated that the high oil temperatures had carbonized the seals around the bearings in the gearbox in 1996, and the seals began to leak.

After a debate throughout 1996 that involved Yantrak, Angels Flight, the Community Redevelopment Agency, Pueblo, and Harris, an oil cooler was added to the system in 1997. Additionally, a synthetic oil replaced the conventional oil used previously, and the bearings and seals on the drive side were replaced. The Angels Flight vice president stated that the oil temperatures dropped into "…the 150º [F] to 175º [F] range…" after these changes were made to the system. Eventually, all of the seals and bearings that had been affected by excessive oil temperatures in 1996 were replaced in 1997.

[9] An oil temperature sensor and monitoring system automatically shut down the funicular drive when the oil temperature exceeded 225º F.

Maintenance

According to the *Angels Flight Railway Operations and Maintenance Manual,* published by Yantrak and accepted by the operating company in 1996, the oil in the gearbox was to be sampled and analyzed every 18,000 cycles or 6 months.[10] There was no guidance regarding the reasons for performing the oil analyses, the contaminants or properties that should be measured, or how to evaluate the results of such testing. The manual noted that the gears were to be inspected visually on an annual basis, but there was no guidance on measuring gear wear or the appropriate tolerances between major components within the gearbox.

Records of fluids analyses for 1997–1999 were reviewed. Fluids analysis tests were performed on Angels Flight five times in 1997, three times in 1998, and three times in 1999. The tests in 1999 showed that the level of iron in the oil was increasing. A fluids analysis on June 2, 1999, noted that "FE (iron) is starting to increase." The company that conducted the oil sampling recommended resampling after 250 hours. After the June 1999 oil analysis, bearings were replaced, and the drive system gears were visually inspected. The gear hub splines (described in the next section of the report) were not inspected. No further fluids analysis tests were performed after June 1999, however, contrary to the semiannual requirement in the operations and maintenance manual. A postaccident fluids analysis test on February 28, 2001, showed elevated iron levels in the gearbox oil compared to previous oil analysis results.

Tests and Research

A series of tests and inspections was conducted at the accident site and at the laboratory of Exponent Failure Analysis Associates (Exponent). The complete funicular system and individual components were examined. The Public Utilities Commission, the Community Redevelopment Agency, Angels Flight Railway Foundation, Pueblo, Caterpillar,[11] and Fairfield Engineering[12] participated in the postaccident inspections and testing. Testing and inspection protocols were developed by Safety Board staff and Exponent, reviewed by the participants, modified as appropriate, and conducted and documented by Exponent. The outcome of initial testing resulted in additional examination in some areas.

Shafts, Splines, and Bearings

In the Angels Flight drive system, the planetary gears were connected to the cable drums through axle shafts. Longitudinal grooves (splines) about 4 inches long had been machined into each end of each axle shaft. These splined sections fit into and meshed with

[10] Section VII, Gearbox, under Maintenance – Procedures and Intervals.

[11] The drums for both of the cars were mounted on Caterpillar D-9 final drive hubs.

[12] The D-9 hubs were connected to a gearbox, with many of the parts supplied by Fairfield Manufacturing.

splined receiving hubs for the planetary gears and the cable drums. The splines were designed to lock these components in place.

The Angels Flight gearbox was disassembled. The gears, shafts, and splines from both the *Sinai* side and the *Olivet* side were removed and examined and the results documented. Parties to the investigation were present.

Axle Shafts and Splines. The Caterpillar-manufactured axle shafts for both the *Sinai* and the *Olivet* sides were found to be in good condition. For the *Sinai* car, metal shavings were found on the surface of the axle shaft, and the splines of the end of the axle shaft that engaged the planetary gear were slightly worn but otherwise intact. (See figure 12.) The outside diameter of the *Sinai* shaft, measured at the splines that mated with the receiving hub splines, was 2.912 inches. The outside diameter for the *Olivet* shaft at the corresponding splines was 2.917 inches.

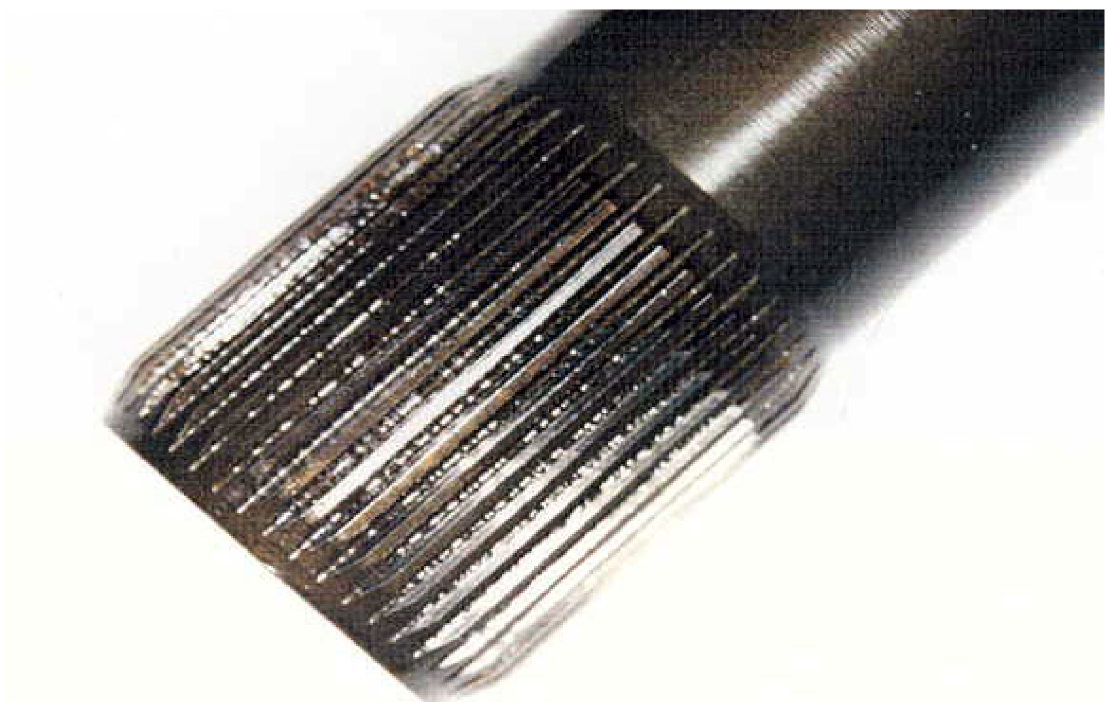

Figure 12. Splined end of *Sinai* axle shaft that engaged the planetary gear receiving hub.

Both axle shafts were subjected to Rockwell C hardness tests.[13] The average Rockwell C hardness for the *Olivet* shaft was 57 and for the *Sinai* shaft, 60. These hardness levels are near the higher end of the range measured for steel and indicate that the axle shafts were subjected to a hardening heat treatment to maximize their load-bearing capacity.

[13] Rockwell hardness tests range from A to V, with the test chosen depending on the hardness of the material tested. The Rockwell C test is used for steel, hard cast iron, and titanium. The Rockwell B test is used for softer metals, such as copper and aluminum alloys, soft steel, and malleable iron.

***Sinai* Receiving Hub and Splines.** The Yantrak-supplied receiving hub for the *Sinai* planetary gear was pressed out of the gear and then sectioned by electron discharge machining. The splines that mated with those of the axle shaft were found to be stripped, thereby preventing the interlocking of the planetary gear with the cable drum. (See figure 13.) Thus, the *Sinai* car's cable drum had effectively become disconnected from the drive mechanism, and it became freewheeling. The metal shavings removed from the surface of the *Sinai* shaft were consistent with the metal of the sheared female splines of the planetary gear receiving hub with which the *Sinai* axle shaft splines mated. The sectioned piece from this receiving hub was polished using standard metallurgical techniques and then examined under an optical microscope. The microstructure was found to consist of ferrite and pearlite typical of an unhardened steel. The sample of the receiving hub was then subjected to hardness testing at a variety of locations through its cross section, both near and away from the spline teeth. The hardness of the steel was between 78.0 and 80.5 on the Rockwell B scale for softer metals and was consistent throughout the piece. The receiving hub's average Rockwell B hardness of 79 is typical of a nonheat-treated, soft steel. Thus, the *Sinai* receiving hub was softer than the axle shaft.

Figure 13. Section of planetary gear receiving hub showing stripped splines.

Ball Bearings. The ball bearings supporting the receiving hubs on both the *Sinai* side and the *Olivet* side of the gearbox were inspected. The bearings on both the *Sinai* and *Olivet* sides were coated with a hard black material where they were exposed to the oil reservoir. The bearing races, or grooves for the ball bearings, showed some bluing.

Ground metallic residue that was removed during disassembly of the bearings was found to contain both metal shavings originating from the sheared splines and small, spherical pieces of metal that had spalled from the balls. The drum side (outer) ball bearing from the *Sinai* side of the gearbox was sectioned for study. The outer race was found to be relatively smooth with some pitting. The balls were badly chipped and pitted, as was the surface of the inner race. The condition of the ball bearings was consistent with exposure to high temperatures and inadequate lubrication. The bearings also may have been subjected to high contact stress.

Brake System

As mentioned previously, the service and emergency braking systems have calipers that are normally clamped shut by a number of springs, and hydraulic pressure is needed to open the brake calipers. Investigators and party members measured the capacity of the emergency brakes on each of the two drums by attaching the cable from the drum through a 20,000-pound load cell to a winch attached to structural members in the machine room. The winch was then used to increase the load on the cable gradually until the drum moved. The maximum force indicated by the load cell was then recorded. *Sinai*'s emergency brake withstood a cable load of 7,150 pounds before moving. *Olivet*'s emergency brake capacity was 4,700 pounds. In a second test, the *Olivet* emergency brake capacity was measured to be 5,300 pounds, for an average of 5,000 pounds.

Service brake capacity was also tested. The service brake, like the emergency brake, is normally clamped in the absence of hydraulic pressure. The test was conducted by attaching a 10-foot torque bar to the coupling flange on the service brake and using a hydraulic jack to apply a load to the end of the torque bar. In this test, the disk began to slip when 2,250 foot-pounds of torque were applied to the service brake. This was within the expected range for the service brake.

When the emergency brakes were operationally tested, the hydraulic pump functioned as expected to build pressure in the system and cause the brakes to release. This was the normal state during operation of Angels Flight. Further testing, however, revealed that the brakes, once released, could not be reapplied. Investigators determined that the solenoid valve, which was intended to open to relieve pressure (by returning oil to the oil reservoir), had a burned-out coil and therefore did not operate. Because the valve had failed in the closed position, pressure would build in the system to release the brakes, but the always-closed valve would prevent the pressure reduction needed to engage the brakes when needed.

Solenoid valves are designed to be "normally open" or "normally closed" when de-energized. In other words, application of electrical current to the solenoid will close a normally open valve and open a normally closed one. The design of the electrical control system for the Angels Flight emergency and service brake systems called for the hydraulic pumps and solenoid valves to be energized whenever the brakes were to be released for operation of the railway. To function properly, this design required a normally open solenoid valve, which would close when energized, thus allowing sufficient hydraulic pressure to build within the system to compress the springs and release the brake calipers.

Cutting power to the hydraulic pump and to a normally open solenoid valve would have caused the solenoid valve to open, thus reducing hydraulic pressure and applying the brakes. A normally open valve would also have been fail-safe, that is, it would have kept the brakes applied (because of insufficient hydraulic pressure) in all four failure modes—failure of the electrical system, failure of the solenoid itself, failure of the hydraulic pump, or significant leakage within the hydraulic system. Moreover, in this design, if a normally closed solenoid valve (which opens when energized, thereby preventing hydraulic pressure buildup) were used, neither the service nor the emergency brakes would have released.

The latest available schematic diagram of the brake hydraulic system was stamped and dated February 16, 1996, by a civil engineer employed by Yantrak. The diagram for the service brake showed a normally closed solenoid valve. The diagram for the emergency brake system did not indicate whether the solenoid valve was of the normally closed or normally open type, but the parts list supplied by Yantrak specified a normally closed valve. Although the two solenoid valve types perform opposite functions, they look identical except for the part numbers imprinted on them. Inspection of the solenoid valves used in the Angels Flight brake systems determined that the defective valve for the emergency brake system was of the normally closed type, whereas the valve for the service brake system was of the normally open type.

Electronic Control System. As noted above, Yantrak's electric control drawings show a system that either supplies electrical power to both the hydraulic pump and the solenoid valve at the same time or to neither the pump nor the valve. When power is supplied to both the pump and a normally closed solenoid valve, the pump attempts to pressurize the brake system (to open the brake calipers) while at the same time the open solenoid valve is draining off the pressure (to close the calipers). When no power is provided to either the pump or the valve, the valve is closed, and it retains whatever pressure was in the system at the time of the closing, resulting in unpredictable brake behavior. In this design, normally open solenoid valves would have been required to apply and release the brakes in a conventional, fail-safe manner.

Electronic-Hydraulic Control Interaction. The control electronics and hydraulics for the emergency brake were reassembled. Pressure sensors were installed, and system voltages were read at key locations using a computer data acquisition system. The hydraulic hoses were attached to the emergency brake calipers to simulate, as closely as possible, the conditions during actual use. Angels Flight personnel provided their recollections of maintenance events to assist in the process. The following was determined from the bench experiments and discussion:

- Using the as-built Angels Flight control electronics and the normally closed solenoid valve called for in Yantrak's design and parts list, the emergency brake hydraulic system developed minimal hydraulic pressure because of the open relief valve. Because the specifications called for the hydraulics to supply a minimum pressure of 1,500 psi to open the brakes, it was concluded that in the as-designed condition, neither the emergency brakes nor the service brake should ever have released.

- The fact that the Angels Flight system operated for 5 years showed that the brakes did, in fact, function to some extent. It was theorized that Yantrak may have discovered during initial testing that the brakes would not function and must have replaced the normally closed solenoid valves with normally open ones. After this replacement, both the emergency brakes and the service brake would have functioned. Another possibility is that the system was initially constructed using normally open valves even though the drawings and parts list indicated normally closed valves.
- Angels Flight service logs show that one of the solenoid valves later burned out and was replaced. After the solenoid valve failed, Angels Flight ordered normally closed replacement valves. It is not clear from the logs or statements made by Angels Flight maintenance personnel whether the solenoid valve that burned out was an original equipment unit or a replacement unit that was ordered in accordance with Yantrak's parts list.

As previously noted, however, a normally closed solenoid valve would have prevented the emergency brake from releasing. No information was available to investigators that would explain how the funicular could have been operated with a normally closed valve installed in the emergency brake system. However, once the normally closed solenoid valve failed, the railway could be operated, albeit without available emergency brakes.

Daily Brake Testing. The Angels Flight vice president stated that he personally performed the daily and monthly maintenance inspections, following the operations and maintenance manual, which included inspecting brake operation. Daily inspections were performed in the morning before passenger service began. The vice president said he would manually reposition the cars from their overnight storage positions[14] so that one car (typically *Olivet*) was at the upper station and the other car was at the lower station. When the cars had been repositioned, he would place the system in automatic operation from the operator's station house and wait for the cars to begin accelerating. Before the cars attained full speed, he would engage the emergency brake button. The vice president further testified "As I was doing my inspection in the machine room, daily, I would climb up this ladder and the machine was set on a cantilever and you could actually, you know, physically see that the pads were dropped and that's one of the procedures." However, the emergency brake pads always looked like they were dropped, because of their distance from the ladder and the small clearances separating the brake pads from the drum flanges. As noted previously, the postaccident inspection found that the emergency brake system had a burned-out coil and therefore did not operate.

Capacity of Components

Exponent reviewed and analyzed calculations generated by Yantrak for the size and durability of gears, ropes, splines, brakes, bearings, and structural components. The calculations were stamped by a Yantrak civil engineer and dated October 9, 1995. In the

[14] The cars were stored beside each other on the passing portion of the track structure.

course of its review, Exponent discovered several errors in those calculations that are believed to have affected the selection of brake size and the lifetime of the gears and splines:

- In a hand calculation sheet marked "Drive Frame Analysis, Angels Flight Funicular, Community Redevelopment Agency – Los Angeles, CA," under the subheading "Eqpt Weights & Rope Forces," rope tensions are calculated assuming a "crush load" of 20,000 pounds in the car and a slope of 19 degrees. In a later page of calculations titled "Haul Rope Analysis," Yantrak uses a 0.1 g acceleration rate to the calculated maximum rope tension noted above to arrive at a total maximum rope tension of 9,080 pounds. In the Angels Flight acceptance tests on February 15, 1996, the cars were brought to a stop from full speed in 1.0 second under a variety of loading conditions, including crush loads on both vehicles. Since the maximum speed of the cars was 352 feet/minute, or about 5.9 feet/second, this test corresponds to a measured average acceleration of 0.18 g, almost double the acceleration assumed by Yantrak. Thus, Yantrak's calculation underestimates the maximum rope tension (10,680 pounds) by 1,600 pounds. Furthermore, this figure accounts for the average acceleration only, and not for transient dynamic effects, which occur whenever the brakes are applied. These dynamic effects can be substantial and further increase component stresses. The underestimation of the load affects the calculated life of all gears, shafts, and splines.
- According to page 7 of Yantrak's typed calculation and the catalog from the emergency brake caliper manufacturer, the disc brakes have a maximum available braking force of 12,814 pounds. Assuming Yantrak's figure for maximum rope tension, 9,080 pounds, and accounting for the difference in effective moment arm for the brakes (29.5 inches from the drum's center of rotation) and the rope (35 inches from the drum's center of rotation), Yantrak calculates a maximum required brake force of 10,772 pounds. Using the larger acceleration described above, the maximum required brake force is 12,671 pounds, which is at the upper limit of published maximum brake capacity for these brake calipers.
- On page 6 of the typed calculations, under the headings "Input [Axle] Shaft to D-9 Hub" and "Gear Shaft [Hub] Splined onto D-9 [Axle] Shaft," appear to be calculations of the stresses in these components. However, the calculations do not address the splines themselves, but only the two parts that are splined together (the D-9 axle shaft and the receiving hub on the planetary gear). But because the splines' teeth reduce the load-bearing surface area and introduce stress concentrations, the splines are significantly weaker than the shafts. Furthermore, the stresses in the shafts are calculated assuming 15,000 inch-pounds of torque. Assuming Yantrak's own figure of 9,080 pounds of rope tension on a 35-inch-radius drum and accounting for the 20:1 gear reduction on the D-9 hub results in a torque of 15,900 inch-pounds. The corrected rope tension of 10,680 pounds results in a hub torque of 18,700 inch-pounds. These figures exceed the torque used by Yantrak in its calculations. Transient dynamic effects would lead to further increases in the effective torque experienced by the gears, shafts, and splines.

Funicular Railway Standards

At the time Angels Flight was redesigned and renovated, California had no standards or regulations for the design, construction, and operation of funiculars. Also at that time, the American National Standards Institute (ANSI)[15] had no explicit standard covering funiculars, although sections of Standard B77.1, *Aerial Tramways, Aerial Lifts, Surface Lifts, and Tows Safety Requirements*, contained guidance that could apply to portions of the Angels Flight system. Since approximately 1984, Colorado has had regulations that cover design, construction, and maintenance of funiculars in the Colorado Passenger Tramway Safety Board's *Passenger Tramway Rules and Regulations*. The Colorado regulations include ANSI Standard B77.1, revisions to ANSI rules by the Colorado Board, and additional technical rules. The California Public Utilities Commission did not reference any particular set of standards that were to be followed in the reconstruction of Angels Flight.

By February 2001, ANSI began internal circulation of a draft Standard B77.2, *Funicular Safety Requirements,* specifically for funiculars. The B77 Accredited Standards Committee has approved a draft, but it has not been adopted as final by ANSI. The first tentative funicular standards were developed in the early 1980s. The tentative standards were available to the parties during the Angels Flight reconstruction project. Because Standard B77.1 did not cover funicular systems, the tentative standards were suggested for use as a guideline for any authority having jurisdiction in connection with the design, manufacture, construction, and operation of a funicular system.

After the accident, a review was made of the ANSI and Colorado standards that were available to, if not specifically referenced by, the Public Utilities Commission and that addressed issues of funicular safety. The guidance existing at the time Angels Flight was redesigned and rebuilt (ANSI tentative standards and the Colorado regulations) agreed that a tramway should have two completely independent brake systems that do not operate at the same time and that each car should be equipped with a braking system capable of stopping and holding the car in the event of a rope failure.

The tentative ANSI standards called for each car to have doors that filled the entire entrance opening. Additionally, they stated that each door should have a lock located so that it could only be locked and unlocked automatically or by an authorized person. The tentative standards also stated that funiculars should be equipped with means for evacuation of passengers from stranded vehicles along the entire length of the guideway. The tentative ANSI standards and the Colorado standards stated that cable drums should be designed and built to retain the cable in the event of the failure of a drum, shaft, or mounting. Grooves in the drum were to be designed and built to retain the haul cable in the event of a deropement. A minimum flange extension of 1 1/2 times the cable diameter (measured from the bottom of the cable groove) was considered adequate.[16]

[15] ANSI is a private organization that administers and coordinates the U.S. voluntary standardization and conformity assessment system.

[16] The Angels Flight cable was .875 inch in diameter. Therefore, the minimum flange extension would be 1.31 inches. The flanges on the Angels Flight cable drums measured between .594 and .75 inch.

Regulatory Oversight

In a December 10, 1991, letter to the Community Redevelopment Agency project manager, Parsons called for the creation of a task force to address jurisdictional and safety issues related to the renovation of Angels Flight. Representatives from the California Public Utilities Commission, the City of Los Angeles Department of Building and Safety, the Los Angeles Fire Department, and the Community Redevelopment Agency staffed the task force.

The California Public Utilities Commission accepted the responsibility to view Angels Flight as a public utility and to monitor the safety of the design, construction, and operation of Angels Flight. In so doing, it applied selected portions of the provisions from its Rail Transit Safety Section's procedures manual for State safety oversight of rail fixed guideway systems. In part, California Public Utilities Code 99152 reads as follows:

> Any public transit guideway planned, acquired, or constructed, on or after January 1, 1979, is subject to regulations of the Public Utilities Commission relating to safety appliances and procedures. … The commission shall develop an oversight program employing safety planning criteria, guidelines, safety standards, and safety procedures to be met by operators in the design, construction, and operation of those guideways. Existing industry standards shall be used where applicable.…

On September 16, 1994, the Rail Transit Safety Section of the Public Utilities Commission Safety Division issued *Safety Oversight Plan for Design and Construction of Angels Flight Funicular Railway.* That plan stated, in part:

> Successful implementation of the [Public Utilities Commission] staff's safety oversight plan will … effectively serve as an endorsement of the Community Redevelopment Agency's decision to begin revenue service on the Angels Flight Funicular Railway Project.

The Public Utilities Commission staff suggested that the Community Redevelopment Agency and its consultants perform safety hazards analyses on the Angels Flight project and then indicate the actions required to mitigate hazards to passengers and employees through design solutions and operating procedures. The Public Utilities Commission staff commented on the adequacy and completeness of the hazard analysis and on the efficacy of the design solutions and operating procedures and witnessed the testing of equipment where the effectiveness and completeness of those procedures were demonstrated.

Between 1993 and 1996, Parsons and Harris submitted copies of the preliminary hazard analysis report, the preliminary operations and evacuation plan, and the emergency evacuation plan to the Public Utilities Commission. The preliminary hazards analysis report identified hazards that needed to be addressed during the reconstruction process. Among the identified hazards were the lack of end gates on both cars, the lack of track brakes, and the absence of an emergency stairway. Public Utilities Commission staff reviewed the documents and concurred with the report's findings.

The Federal Transit Administration required States to designate an oversight agency to implement requirements of 49 *Code of Federal Regulations* 659, "State Safety Oversight of Fixed Guideway Systems." The Governor of California designated the Public Utilities Commission as the State oversight agency. Public Utilities Commission representatives said that although Angels Flight met the definition of a railway for Public Utilities Code 99152, it did not meet the full Federal Transit Administration definition of a rail fixed guideway system. Nevertheless, Public Utilities Commission staff members said they believed it necessary to monitor the operations of Angels Flight, and they applied some of the provisions of the Public Utilities Commission's *Rail Transit Safety Section Procedures Manual for State Safety Oversight of Rail Fixed Guideway Systems*.

The day before the scheduled ceremonial opening of Angels Flight on February 23, 1996, the Harris construction manager sent a letter to the Community Redevelopment Agency that stated:

> I have reviewed the submissions by Pueblo and Yantrak relating to the safety and capacity of Yantrak's design. Based on that review I will recommend to the [Community Redevelopment Agency] that the system designed by Yantrak be accepted by change order as equivalent in safety and operation to the … design proposed in the contract drawings.

The Public Utilities Commission supervising engineer sent a letter to the Community Redevelopment Agency acknowledging the Public Utilities Commission's acceptance of the Community Redevelopment Agency's letter certifying that "Angels Flight is safe for limited use during the three-day dedication weekend." The letter stated that Public Utilities Commission safety oversight would "continue after the dedication weekend until all of the outstanding issues" were completed, that is, acceptance of the operations and maintenance manual, completion and acceptance of the hazards analysis, and training of the Angels Flight operating personnel. On February 23, 1996, Angels Flight began service to the public for the ceremonial opening.

In March 1997, Public Utilities Commission staff performed an inspection of Angels Flight that was limited to witnessing a magnetic haul cable inspection. Public Utilities Commission staff members stated that they performed informal checks of Angels Flight throughout the succeeding years.

On January 9, 2002, the Public Utilities Commission filed an order to initiate rulemaking concerning safety certification. The Public Utilities Commission's existing requirements (General Order[17] 164-B) focused on the safety of transportation systems after they are placed in passenger service. On February 27, 2003, the Public Utilities Commission adopted General Order 164-C, *Rules and Regulations Governing State Safety Oversight of Rail Fixed Guideway Systems,* which supersedes General Order 164-B. The new rule strengthens the safety review process before passenger service is initiated by

[17] General Orders set rules for all utilities or classes of utilities, as opposed to decisions rendered in a particular case for a particular utility.

establishing Public Utilities Commission review and approval requirements for safety certification program plans, project-specific safety certification plans before construction, and project-specific safety certification verification reports before passenger service. As defined in the rule, a public transit guideway would include all rail transit agencies, rail fixed guideways, and all other light rail, rapid rail, monorail, inclined plane, funicular, trolley, or automated guideways offering transit service to the public, whether or not Federal guidelines or definitions apply.

Current Status

The Angels Flight railway has not been in operation since the accident on February 1, 2001.

Analysis

The Accident

Postaccident inspection of the Angels Flight drive mechanism revealed that the *Sinai* car stopped ascending and began its uncontrolled descent when the drive axle for the car's cable drum became disengaged from its driving planetary gear. When the Angels Flight operator saw the car begin to descend the grade, he pushed the stop button on the operator's console, which should have simultaneously activated the service and emergency brakes. But the service brakes, which operated on the drive train, had no effect on the freewheeling cable drum that was no longer connected to the drive train mechanism. The emergency brake would have stopped, or at least slowed, the rotation of the cable drum had it applied, but it was found to be inoperative. The cars themselves were not equipped with track brakes that could have operated independently to significantly slow the car or bring it to a stop before the collision. End gates on the cars may have prevented the passenger from being ejected from the end of the *Olivet* car when it was struck by the *Sinai* car. Finally, rescue efforts were hampered by the absence of emergency walkways that would have facilitated evacuation of injured passengers.

The Safety Board's investigation of this accident focused on the following safety issues:

- The adequacy of the safety oversight of the Angels Flight reconstruction project;
- The adequacy of the design of the reconstructed Angels Flight system;
- The adequacy and appropriateness of the braking systems designed for Angels Flight; and
- The adequacy of Angels Flight Operating Company's maintenance and operating procedures.

Gear Hub Failure

The splines on the *Sinai* planetary gear receiving hub were found to be stripped, which prevented the gear from engaging the axle shaft. This allowed the axle shaft to rotate within the planetary gear hub and rendered the cable drum (connected to the other end of the axle shaft) freewheeling. Testing revealed that the steel used for the receiving gear hub was much softer than the steel used for the axle shaft. The difference between the hardness of the receiving gear hub and that of the axle shaft likely contributed to the failure of the gear by accelerating the damage to the softer gear hub splines. The presence of metal shavings on the *Sinai* car axle shaft indicated that damage to the planetary gear hub splines had been occurring for some time before the accident.

The failure of the *Sinai* planetary gear receiving hub may also have been accelerated by the daily brake tests conducted on the system. The Angels Flight Operating Company vice president tested operation of the brakes by placing the cars in operation and then activating the system service and emergency brakes to bring the cars to a stop. Under normal conditions, the service brakes would have stopped rotation of the motor shaft while the emergency brakes simultaneously stopped rotation of the two cable drums. But postaccident investigation revealed that, for some period of time before the accident, only the service brakes were operable. During the daily brake tests, the service brake activated to stop the driven sun gear, but without emergency brakes, substantial dynamic forces acted on the cable drums and various components of the drive system.

Finally, the investigation determined that the dynamic and transient forces acting on the various components of the drive gear system, including the axle and receiving gear hub splines, were greater than those calculated by Yantrak. Because these calculated loads were used to develop the specifications for the drive system components, the service life of those components, including the gear hubs and splines, would likely have been less than predicted even under normal conditions. Under the abnormal stress conditions posed by the daily brake tests conducted with non-functioning emergency brakes, the rate of damage likely increased, as did the likelihood of the kind of catastrophic failure that occurred in this accident. The Safety Board concludes that the planetary gear hub for the *Sinai* car failed because of one or a combination of the following: (1) the metal used in the manufacture of the gear hub was considerably softer than the metal used for the axle shaft with which it mated, causing deformation damage and eventual failure; (2) the drive train components, including the planetary gear hubs, were not designed for the stresses to which the components were subjected during operation; and (3) the daily brake tests, which were conducted for some period of time without working emergency brakes, placed additional stress on the drive train components and accelerated gear hub damage.

Postaccident research and inspection also revealed that the Angels Flight drive system was equipped with deropement switches and cable drum flanges that were inappropriately sized. The .875-inch-diameter cable needed 1.31-inch flange extensions on the drums to meet the minimum height that was considered adequate. However, all of the flange extensions were less than 1 inch high. Further, initially the gearbox lubrication system was problematic, allowing the lubrication oil to overheat and cause system shutdowns. This deficiency went unresolved for more than a year until an oil cooler was installed.

The Safety Board therefore believes that before recommencing passenger service on the Angels Flight funicular railway, the Community Redevelopment Agency should conduct a comprehensive review of the design and specifications for the Angels Flight drive system, then make the design or component changes necessary to ensure that the drive system meets accepted industry standards and engineering practices.

Brake System Failure

Once the cable drum for the *Sinai* car became disconnected from the drive gear system, the car's haul cable was able to unwind freely as gravity pulled the car down the incline. The emergency braking system was designed to prevent such an occurrence by clamping against the cable drum flanges to stop the drum's rotation. Had the emergency brakes functioned when activated by the operator, the descent of the car would have been stopped even though the cable drum was no longer connected to the rest of the drive system. The Safety Board therefore concludes that had the Angels Flight emergency braking system been functional on the day of the accident, the brakes would likely have stopped the descent of the runaway car and prevented the collision.

The investigation determined that if the Angels Flight service and emergency braking systems had been installed in accordance with the design drawings and parts list, neither of the brakes would have released, and Angels Flight could not have been operated. In this design, normally open solenoid valves would have been required to apply and release the brakes in a conventional, fail-safe manner. At some point, either during initial brake system installation and testing or shortly thereafter, at least the service brake system had to have been equipped with a normally open valve. Postaccident inspection found that the service brake was still equipped with a normally open valve, and it operated properly. But the emergency brake system was equipped with a normally closed valve. Because the valve had failed in the normally closed position, the emergency brake could be released, but it could not be reapplied when needed.

Angels Flight records indicated that a solenoid valve had burned out and been replaced with a normally closed valve as indicated on the drawings and parts list. But as noted, this would not have allowed the system to be operated. Although it cannot be known for sure, it is possible that the new valve was inoperative when it was installed or was defective and failed very quickly after its initial activation. Either scenario would explain how the system was able to be operated and would account for the valve configuration found during the postaccident inspection.

Although the test procedure for the Angels Flight emergency brakes was conducted daily, the button that activated those brakes simultaneously activated the service brake. Therefore, this method of testing could not confirm that both braking systems were operational. The Safety Board therefore concludes that the brake system as designed was inoperable, as implemented was not fail-safe, and was further inadequate because the emergency brakes could not be activated independent of the service brake and tested separately, which would have revealed that the system's emergency brakes were inoperative.

The Safety Board believes that before recommencing passenger service on the Angels Flight funicular railway, the Community Redevelopment Agency should require that the current Angels Flight emergency braking system (acting on the cable drums) be redesigned to allow it to be tested independent of other braking systems.

Angels Flight Operations and Maintenance

The primary responsibility for day-to-day operations and maintenance of Angels Flight belonged jointly to the Angels Flight Railway Foundation and the Angels Flight Operating Company. Shortly after Angels Flight began passenger service, a problem was noted with overheating of the gearbox oil. The problem was severe enough that on numerous occasions, the system shut down automatically, leaving passengers stranded between stations. At these times, witnesses reported seeing passengers making unauthorized and unsafe evacuations from the cars over the unprotected elevated track structure. As a loss control consultant had noted, such evacuations were so dangerous to passengers that they should have been prevented even during emergencies.

But despite the hazard posed to passengers, the operating company did not establish operational practices that would have prevented the system shutdowns or egress onto the tracks. For example, the number of scheduled trips per hour could have been reduced to allow the gearbox to cool between trips while a permanent solution was researched and implemented. Instead, the system was kept operating for more than a year until the overheating problem was ultimately resolved by the installation of an oil cooler.

In addition to representing an inconvenience and possible hazard to passengers because of the system shutdowns, the overheating and vaporizing oil was also likely not providing optimal lubrication to the Angels Flight drive system. Within the first few months of operation of Angels Flight, the bearing seals had carbonized due to overheating and had begun to leak. The gearbox bearings and seals had to be replaced in 1997.

After the overheating problem had been addressed in 1997 and synthetic oil was used, the Angels Flight Operating Company never changed the oil. It did initially adhere to a regular fluids analysis schedule, sampling the lubricating oil about once every 4 months from 1997 to 1999. After three successive fluid analyses during 1999 showed an increased presence of iron in the oil, the company that conducted the fluid analyses in June 1999 recommended resampling the oil after an additional 250 hours. However, although bearings were replaced and the drive system gears were inspected after the June 1999 analysis, the operating company conducted no additional fluid analyses. As a result, the lubricating oil went untested for 20 months while Angels Flight continued daily operation until the accident occurred.

The Safety Board is concerned at the lack of detailed guidance regarding the oil analysis program or maintenance procedures for the funicular drive gearbox. A postaccident fluids analysis test on February 28, 2001, confirmed the presence of elevated iron levels in the gearbox oil. In addition, ground metallic residue, containing both metal shavings from the sheared splines and small metal pieces from the ball bearings, was removed during disassembly of the gearbox after the accident, indicating that damage was occurring before the planetary gear hub splines failed. Therefore, if Angels Flight Operating Company personnel had continued the oil analyses, as required in the operations and maintenance manual, and if the cause of the elevated iron content had been investigated further, through a gearbox teardown, for example, they may have discovered the damage in the *Sinai* car's planetary gear hub splines.

The Safety Board concludes that by allowing Angels Flight to remain in normal passenger service for more than a year with an unresolved problem with overheating of the gearbox, which at times caused cars to stop unexpectedly between stations, the Angels Flight Railway Foundation and the Angels Flight Operating Company adversely affected drive system component integrity and compromised passenger safety.

The Safety Board believes that before recommencing passenger service on the Angels Flight funicular railway, the Community Redevelopment Agency should require that the organization(s) responsible for operating and maintaining the Angels Flight funicular develop and follow detailed operating, inspection, and maintenance procedures to ensure the operational integrity of the system and safety of passengers.

Oversight of Angels Flight Design and Construction

A complex web of organizations was involved in the Angels Flight redevelopment project. Ultimately, this complexity may have contributed to the failure of various oversight agencies to ensure that the Angels Flight system was reconstructed and operated with adequate passenger safeguards.

City of Los Angeles Community Redevelopment Agency Oversight

As the owner of Angels Flight, the Community Redevelopment Agency was responsible for contract negotiations, safety oversight, design changes, and safety certification. Additionally, beginning in 1991 with its selection of Parsons as a consultant, the Community Redevelopment Agency was responsible for the selection of many of the companies involved in the design and construction of Angels Flight. It hired Harris as the construction manager and selected Pueblo as the general contractor. And even though the Community Redevelopment Agency did not hire Yantrak directly, it was responsible for the selection of the company in its role as overseer of the performance of its contractors and subcontractors and for monitoring how its money was being spent.

The Community Redevelopment Agency contracted with Harris as construction manager for the project, and Harris subsequently contracted with Parsons for the design specifications for the reconstructed Angels Flight. Parsons's specifications called for both cars to be fitted with emergency track brakes and end gates to contain passengers. They also called for an emergency walkway to be constructed for the entire length of the tramway to facilitate the evacuation of passengers in the event of an emergency. None of these features was included in the final system build.

Track Brakes. The original Parsons design specifications for the reconstructed Angels Flight included track brakes designed to deploy automatically and stop a runaway car in case of an overspeed condition or the failure of the haul cable or other major components that might allow a car to freely translate. Yantrak, the design-build contractor for Angels Flight, took issue with the track brakes in the design specifications. In a September 8, 1995, letter, Parsons informed Harris that it considered the elimination of the track brakes to be unacceptable in that, without either the brakes or a suitable alternate backup safety system, a break in the haul cable could result in injury or fatality to passengers. Based on this risk, Parsons continued to recommend that Harris reject the Yantrak proposal to omit track brakes. Nonetheless, Harris, with the approval of the Community Redevelopment Agency, decided not to equip the Angels Flight vehicles with the track brakes that would likely have prevented the February 1, 2001, collision.

In a series of letters and memorandums, Yantrak argued that track brakes would be ineffective in this application and that, in any case, the design of the cars and trackway would not permit their installation. In its February 13, 1996, letter to Pueblo, Yantrak had said that track brakes could not be used on the split rail of the train bypass. The Safety Board notes, however, that the conceptual design specified track brakes only on the outer rail, thereby avoiding the shared (split) rail used by both cars. Increasing the diameter of the haul cable (rope) and other measures proposed by Yantrak did increase the safety factors associated with loss of the cable or car attachment. However, deleting the track brakes (a secondary safety device) ignored other potential failure modes that were unrelated to the haul cables. Redundancy has always been a key factor in the design of transportation systems. For example, even though the original Angels Flight was not equipped with track brakes, it did have a safety cable designed to prevent a runaway car. Further, the guidance on funiculars existing at the time Angels Flight was redesigned and rebuilt (ANSI tentative standards and the Colorado regulations) called for each individual car to be equipped with a braking system. A survey of funiculars worldwide also found that each system utilized cars equipped with braking systems or backup safety cables.

The Safety Board therefore concludes that had the Angels Flight cars been equipped with track brakes or a safety cable in accordance with known funicular safety standards and redundant design principles, either of those safety features likely would have stopped the runaway car and prevented the collision even without working emergency brakes.

End Gates. The initial design specifications for the reconstructed Angels Flight also called for the installation of end gates to prevent passengers from falling from the cars. The Community Redevelopment Agency approved the installation of end gates and required them in the contract to Pueblo. Later, objections were raised by a conservancy group, which argued that end gates not only would have been inconsistent with the original Angels Flight design but also were unnecessary as shown by the fact that the system had been operated without them and without incident between 1901 and 1969.

The Community Redevelopment Agency, while reviewing the issue of whether end gates were necessary to the safety of the system, allowed Angels Flight to begin passenger service without them. In November 1996, some 9 months after Angels Flight began passenger service, the Community Redevelopment Agency consented to requests from Angels Flight officials and issued a change order directing that end gates not be installed. Although the Community Redevelopment Agency stated that the issue would need continued study, there is no record of such, and the gates were never installed.

Emergency Walkway. The original Angels Flight did not have a walkway adjacent to the trackway that would extend the entire length of the trackway. Such a walkway was included as part of the original reconstruction design specifications, but as with the end gates, a conflict soon developed with the historic preservationist viewpoint. In addition, Public Utilities Commission staff and an insurance loss control consultant supported the view that the walkway would be an attractive nuisance more hazardous than the absence of the walkway. However, the Safety Board notes that an attractive nuisance can be averted in many cases with relatively simple measures, such as installing a fence with locking gates to restrict access.

Community Redevelopment Agency officials did require that alternatives to the walkway be included in the final design, including a combination ground-level and elevated stairway separated from the trackway, an auxiliary emergency power supply, reversible funicular controls, and a security system and fence. But none of these alternatives directly addressed the purposes of the emergency walkway, and because of the nature of the accident, these alternatives did nothing to facilitate access to and egress from the funicular vehicles. The Safety Board concludes that the absence of an emergency walkway hampered access by emergency responders to passengers in this accident, made difficult the evacuation of the injured, and increased the risk to both passengers and emergency responders.

The agency with overall safety oversight of the reconstruction and subsequent operation of the Angels Flight system was the Public Utilities Commission. Like the Community Redevelopment Agency, although the Public Utilities Commission often came down initially in support of the safety features, in most cases, the Public Utilities Commission ultimately either permitted the removal of safety features from the final Angels Flight design or allowed the system to be operated in passenger service while certain safety issues remained unresolved.

Apart from cost issues, it appears that during the Angels Flight reconstruction project decisions about safety features were based in large part on a feature's adherence to historical accuracy. In the years since the original Angels Flight was built in 1901, there have been great advances in engineering and transportation safety, and, therefore, transportation systems are not designed as they were 100 years ago. Even assuming that accurate accident records exist, the fact that accidents have not occurred with a historic design does not ensure that the design is safe. Given current state-of-the-art technologies, public transportation designs should not be dictated by a desire for historical accuracy at the expense of safety features.

The Safety Board believes that before recommencing passenger service on the Angels Flight funicular railway, the Community Redevelopment Agency should direct that the Angels Flight funicular be redesigned in accordance with all applicable funicular safety standards and include provisions for (1) emergency stopping under all foreseeable failure modes, including track brakes or some other independent backup system on the cars to prevent a runaway car if a failure occurs in the cable or its associated braking systems; (2) containment of passengers in the event of a collision; and (3) emergency egress and ingress for passengers and emergency responders.

California Public Utilities Commission Oversight

The Public Utilities Commission had responsibility for the safety of the design, construction, and eventual operation of Angels Flight. The Public Utilities Commission required that the Community Redevelopment Agency and its consultants perform safety hazards analyses on the Angels Flight project and indicate what actions were planned that would mitigate the danger to passengers and employees through design solutions or operating procedures. But the Public Utilities Commission did not require that track brakes, end gates, or an evacuation walkway be installed to address the safety hazards identified by the analyses. These inconsistent decisions suggest that the Public Utilities Commission policies and procedures were insufficient for ensuring the safety of Angels Flight.

The Public Utilities Commission granted limited authority for Angels Flight to operate for a 3-day dedication ceremony beginning February 23, 1996. The authorization letter acknowledged that there were "outstanding issues" related to safety at the time. Yet, Angels Flight opened for passenger service on February 26, 1996, without those safety issues being resolved. The Public Utilities Commission did not have an effective process in place to ensure that Angels Flight met all safety requirements before passenger operations were allowed to begin. The Safety Board therefore concludes that the Community Redevelopment Agency and the Public Utilities Commission failed to fulfill their safety oversight responsibilities for the Angels Flight reconstruction by allowing Angels Flight to begin passenger operations with unresolved safety issues.

The Safety Board is encouraged by the Public Utilities Commission's new General Order 164-C involving safety certification. The circumstances surrounding this accident accentuate the need to make ongoing safety assessments from the outset of a project. Under rules existing at the time of the accident, an agency or organization could potentially operate for 3 years before the first safety inspection.

California has no standards or regulations for the design, construction, and operation of funiculars. Although funicular standards of another State were available, the Public Utilities Commission did not require that the Angels Flight Railway be reconstructed and operated in accordance with them. Without established regulations, the Public Utilities Commission had no clear standards to use to evaluate the safety of the Angels Flight funicular project. The Safety Board believes the Public Utilities Commission should adopt comprehensive funicular design, construction, and operation regulations that include provisions for (1) emergency stopping under all foreseeable failure modes, (2) containment of passengers in the event of a collision, and (3) emergency egress and ingress for passengers and emergency responders.

To ensure that deficiencies discovered during the investigation of the Angels Flight funicular railway accident are specifically addressed, the Safety Board believes that before certifying Angels Flight to restart passenger service, the Public Utilities Commission should independently verify that the drive system meets accepted industry standards and engineering practices and that the funicular includes provisions for (1) emergency stopping under all foreseeable failure modes, including track brakes or some other independent backup system on the cars to prevent a runaway car if a failure occurs in the cable or its associated braking systems; (2) containment of passengers in the event of a collision; and (3) emergency egress and ingress for passengers and emergency responders.

The Safety Board is encouraged that ANSI is making progress on developing funicular safety standards. Although a draft standard has been approved by the B77 committee, it has not been adopted as final by ANSI. Such a standard would inform and guide organizations such as the Public Utilities Commission in their safety oversight of operations like the Angels Flight railway. Therefore, the Safety Board believes ANSI should establish an accelerated schedule for adoption of the draft ANSI Standard B77.2 for funicular safety requirements.

Conclusions

Findings

1. The planetary gear hub for the *Sinai* car failed because of one or a combination of the following: (1) the metal used in the manufacture of the gear hub was considerably softer than the metal used for the axle shaft with which it mated, causing deformation damage and eventual failure; (2) the drive train components, including the planetary gear hubs, were not designed for the stresses to which the components were subjected during operation; and (3) the daily brake tests, which were conducted for some period of time without working emergency brakes, placed additional stress on the drive train components and accelerated gear hub damage.

2. Had the Angels Flight emergency braking system been functional on the day of the accident, the brakes would likely have stopped the descent of the runaway car and prevented the collision.

3. The brake system as designed was inoperable, as implemented was not fail-safe, and was further inadequate because the emergency brakes could not be activated independent of the service brake and tested separately, which would have revealed that the system's emergency brakes were inoperative.

4. Had the Angels Flight cars been equipped with track brakes or a safety cable in accordance with known funicular safety standards and redundant design principles, either of those safety features likely would have stopped the runaway car and prevented the collision even without working emergency brakes.

5. The absence of an emergency walkway hampered access by emergency responders to passengers in this accident, made difficult the evacuation of the injured, and increased the risk to both passengers and emergency responders.

6. The City of Los Angeles Community Redevelopment Agency and the California Public Utilities Commission failed to fulfill their safety oversight responsibilities for the Angels Flight reconstruction by allowing Angels Flight to begin passenger operations with unresolved safety issues.

7. By allowing Angels Flight to remain in normal passenger service for more than a year with an unresolved problem with overheating of the gearbox, which at times caused cars to stop unexpectedly between stations, the Angels Flight Railway Foundation and the Angels Flight Operating Company adversely affected drive system component integrity and compromised passenger safety.

Probable Cause

The National Transportation Safety Board determines that the probable cause of this accident was the Yantrak Company's (Lift Engineering's) improper design and construction of the Angels Flight funicular drive and the failure of the City of Los Angeles Community Redevelopment Agency, its contractors (Pueblo Contracting Services, Yantrak, and Harris and Associates), and the California Public Utilities Commission to ensure that the railway system conformed to initial safety design specifications and known funicular safety standards.

Recommendations

As a result of its investigation, the National Transportation Safety Board makes the following safety recommendations:

To the California Public Utilities Commission:

Adopt comprehensive funicular design, construction, and operation regulations that include provisions for (1) emergency stopping under all foreseeable failure modes, (2) containment of passengers in the event of a collision, and (3) emergency egress and ingress for passengers and emergency responders. (R-03-14)

Before certifying Angels Flight to restart passenger service, independently verify that the drive system meets accepted industry standards and engineering practices and that the funicular includes provisions for (1) emergency stopping under all foreseeable failure modes, including track brakes or some other independent backup system on the cars to prevent a runaway car if a failure occurs in the cable or its associated braking systems; (2) containment of passengers in the event of a collision; and (3) emergency egress and ingress for passengers and emergency responders. (R-03-15)

To the City of Los Angeles Community Redevelopment Agency:

Before recommencing passenger service on the Angels Flight funicular railway:

Conduct a comprehensive review of the design and specifications for the Angels Flight drive system, then make the design or component changes necessary to ensure that the drive system meets accepted industry standards and engineering practices. (R-03-16)

Require that the current Angels Flight emergency braking system (acting on the cable drums) be redesigned to allow it to be tested independent of other braking systems. (R-03-17)

Require that the organization(s) responsible for operating and maintaining the Angels Flight funicular develop and follow detailed operating, inspection, and maintenance procedures to ensure the operational integrity of the system and safety of passengers. (R-03-18).

Direct that the Angels Flight funicular be redesigned in accordance with all applicable funicular safety standards and include provisions for (1) emergency stopping under all foreseeable failure modes, including track brakes or some other independent backup system on the cars to prevent a runaway car if a failure occurs in the cable or its associated braking systems; (2) containment of passengers in the event of a collision; and (3) emergency egress and ingress for passengers and emergency responders. (R-03-19)

To the American National Standards Institute:

Establish an accelerated schedule for adoption of the draft American National Standards Institute Standard B77.2 for funicular safety requirements. (R-03-20)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

Ellen G. Engleman
Chairman

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Richard F. Healing
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Adopted: August 5, 2003

Appendix A

Investigation

Both headquarters and Los Angeles staff of the National Transportation Safety Board became aware of the Angels Flight railway collision in Los Angeles, California, within a few minutes of its occurrence at 12:17 p.m. on February 1, 2001, from local and national coverage by the news media. Two railroad accident investigators were sent to the scene from the Gardena, California, office. They arrived on scene about 45 minutes after the accident occurred. No Board Member went with the team.

Parties to the investigation included the California Public Utilities Commission, the City of Los Angeles Community Redevelopment Agency, and the Angels Flight Operating Company. The company that designed and built the drive, control, braking, and haul systems, Lift Engineering/Yantrak, is no longer in business, and the principal's whereabouts are unknown.

As part of its investigation, on June 12, 2001, the Safety Board took testimony from the president and vice president of Angels Flight and from the administrator of the City of Los Angeles Community Redevelopment Agency. All parties to the investigation attended the proceeding.

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