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LIGHTNING PROGRESS: AN HPV DEVELOPMENT CASE HISTORY

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The IHPVA, in existence since 1976, has held many competitive events for human-powered vehicles during its nearly 20 years. Events during the first 5 years concentrated mostly on top speed, probably because

1. everyone wanted to know how fast it was possible to go; and
2. the lack of experience with these new types of vehicles made designing and building them much simpler if it was not necessary to provide for easy rider entry, visibility, cooling, and maneuverability.

As the years passed and top speeds increased past 25 to 27 m/s (55 to 60 mph), more emphasis was placed on the practical aspect of HPVs, starting in the early 1980s. This was done by including closed-course road races and "LeMans starts." The first race for HPVs on open roads was held in 1985, from Seattle to Portland. The decade culminated with the HPV Race Across America in 1989.

Practical-vehicle contests were also held, although the execution and judging process of some contests were not to the liking of all contestants. The problem was, and is, that *practical* means different things to different people. In the arena of human-powered road vehicles, one person may put the ability to carry 500 kg (1,100 lb) high on the scoring list, whereas another feels that weather protection is more important.

So how is it possible to resolve these conflicting requirements when designing a practical HPV? In a free-market society, you don't: you let the consuming public do it for you! The major use of bicycles in the U.S. today is for recreation. This includes racing, century rides, and weekend trips. The second most prevalent use is for commuting. Thus, the designer of an HPV intended to replace conventional bicycles should keep these facts in mind, along with what the intended market is willing to pay.

I have been involved with HPVs since 1977. This chapter examines the performance advances of four of my vehicles over the 1980s. Although the machines featured did not win every race or set all the records, they did win a few and were always near the top in competitions. On that basis, they are representative of HPV trends and progress in general.

These vehicles are also compared with a top Union Cicliste International (UCI) bicycle. The UCI, the organization that sets rules for professional and Olympic bicycle racing, does not allow recumbents and fairings because of their speed advantage. As a result, the majority of bikes sold today are "UCI" bikes, because manufacturers build bikes that are similar to those that have, for instance, "won twenty Tours de France." This chapter discusses how HPVs have made great improvements in practicality so that for some uses they are now superior to UCI bikes.

Vehicle Descriptions

The Lightning series of vehicles reflected contemporary design philosophy. The first vehicle of the series, the White Lightning, was designed when it was thought that maximum speed would be reached in a vehicle with several riders in a prone or supine position. Vehicles of that period had up to five riders. After the best of the multiple-rider vehicles, the two-person Vector, had been beaten decisively by a single-rider recumbent bicycle, designers turned equally decisively in this direction. Later Lightning-series vehicles reflected this changed design philosophy.

White Lightning

WEIGHT: 80 lb (36 kg)

LENGTH: 20 ft (6 m)

WIDTH: 28 in. (710 mm)

HEIGHT: 30 in. (760 mm)

BUILT: 1977

RACED: 1977 through 1983

LAYOUT: Two riders in a supine recumbent position facing forward. Three wheels: two rear-drive wheels, front wheel steers. Standard six-speed rear cluster and circular cranks. The rear rider also had a set of hand cranks.

CONSTRUCTION: Bonded and welded oversize-aluminum-tube frame. Fiberglass-honeycomb fairing. Acrylic windshield.

White Lightning was first conceived in 1977 as a club project by students at Northrop University. Since this was during the early days of the IHPVA, the only design criterion was to run at the highest possible speed. The final result was a two-person, three-wheel vehicle 6 m (20 ft) long, only 760 mm (30 in.) high, and weighing 36 kg (80 lb). As it would be run only on a race track, the ground clearance was 13 mm (0.5 in.), the turning radius was 15 m (50 ft), and the visibility was poor.

White Lightning was the first vehicle to break 24.6 m/s (55 mph), thus winning the Abbott Prize; it eventually went over 27.3 m/s (61 mph). In spite of not being raced for more than 11 years, it still holds the 5-mile, 1/4-mile, and 600-m records. We also discovered it was very comfortable when compared to a standard bike, which led to the incentive of trying to build something similar, but able to be ridden on the streets.

Lightning X-2

WEIGHT: 40 lb (18 kg)

LENGTH: 92 in. (2.34 m)

WIDTH: 22 in. (560 mm)

HEIGHT: 52 in. (1.32 m)

BUILT: 1983

RACED: 1983 through 1986

LAYOUT: Single-rider, medium-wheelbase, semirecumbent bicycle. Standard circular cranks and drive train, 12 speed (see Figure 9.1).

CONSTRUCTION: Brazed 4130-steel frame. Aramid-honeycomb fairing. Acrylic windshield.

Numerous designs were investigated and a couple of prototypes were built during design of the X-2. The seating position was raised considerably, compared to the White Lightning, to have good visibility in traffic. This seat height and the desire for a light, compact, and maneuverable machine led to a two-wheel, medium-wheelbase design. The frame was built of 4130 steel, for ease of modifications, with a nylon-mesh seat. The fairing construction is similar to White Lightning, with aramid being substituted for fiberglass.

One innovation that caused considerable interest was the ability of the rider to get into the bike and ride off without assistance. Until the X-2, all riders of fully streamlined machines needed help from the pit crew to get in, to put the canopy in place, and to hold the machine upright until the rider had gotten started. Two design features were used to achieve this capability. First was the pair of

FIGURE 9.1 Lightning X-2.

landing-gear-style doors that opened when the rider put his or her feet down: Thus, the rider could stop or start without assistance. Once underway, the doors were closed by hand. The second feature enabled the rider to enter by stepping in from the side. This was achieved by hinging the entire nose section of the fairing so it tilted forward. The object was to develop an HPV that was not only fast but also could be ridden on the street without assistance.

The X-2 enjoyed considerable racing success. It was the world's fastest bicycle in 1983 and 1984; in 1986 it recorded a low-altitude speed of over 28.6 m/s (64 mph). It also won the Seattle-to-Portland challenge in 1985, with an average speed of 11.4 m/s (25.5 mph). This was the first HPV event staged in the U.S. on open, public roadways.

The X-2 was not a commercial success, however, due to the high cost of the honeycomb fairing and the door-operating hardware. The vehicle also was too bulky and too hard to park in city use, as well as being hot on climbs.

In 1986 the Lightning X-2 suffered major damage in a high-speed (28.6 m/s; 64 mph) crash while attempting to set a new top-speed record. In 1991 it was repaired and modified for the John Paul Mitchell Systems Challenge from San Francisco to Los Angeles. Ridden by Pete Penseyres, it won that competition in a time of 18 hours 4 min, setting a new record.

Lightning X-4

WEIGHT: 50 lb (23 kg)

LENGTH: 92 in. (2.34 m)

WIDTH: 22 in. (560 mm)

HEIGHT: 48 in. (1.22 m)

BUILT: 1985

RACED: 1985 through 1989

LAYOUT: Same as the Lightning X-2 (X-4 is shown in Figure 9.2).

CONSTRUCTION: Brazed 4130-steel frame. Skin-and-stringer fiberglass fairing, with a nylon-fabric middle section. Acrylic windshield.

The X-4 was similar to the X-2, but with a fairing built of conventional fiberglass and with the rider's head sticking out the top. The Lightning X-3, a paper design, was never built. The design objective for the X-4 was to make an HPV more practical and less expensive than the X-2. This design was not very successful, mainly because of the 23-kg (50-lb) weight. Although it was only 4.5 kg (10 lb) heavier than the X-2, the difference proved considerable when climbing hills. Also, when descending hills the safe speed limit was quickly exceeded.

FIGURE 9.2 Lightning X-4.

To simplify the design and reduce costs, a zipper was provided on the nylon part of the fairing for rider entry, and openings provided in the bottom to allow the feet to be put down. (These features were carried over to the following model.)

The X-4 never set any records or even won a race, which is why it is not well known. It was entered in a couple of local races, however, and finished in the middle of the pack. The X-4 was useful, in that the experience gained with this machine showed how not to make a practical HPV, and it led to the creation of the F-40.

Lightning F-40

WEIGHT: 32 lb (14.5 kg)

LENGTH: 84 in. (2.1 m)

WIDTH: 20 in. (500 mm)

HEIGHT: 48 in. (1.2 m)

FIRST BUILT: 1987

RACED: 1987 to present

LAYOUT: Same as the Lightning X-2 (Figure 9.3 shows the F-40).

CONSTRUCTION: Brazed 4130-steel frame. Lightweight fiberglass nose fairing. Remainder of fairing is spandex, stretched over a lightweight aluminum framework in the rear. Lexan windshield.

The latest Lightning design is a true production, street-usable HPV. Over 50 of these vehicles have been sold as of the end of 1993, with many of the owners using them for commuting. The nose section of the fairing is built from thin fiberglass, with the remainder being spandex stretched over a lightweight aluminum frame. Zippers are provided for entry, cooling, and for access to the rear storage compartment. This construction reduces the weight to 14.5 kg (32 lb) while maintaining the same air drag of the X-4.

The F-40 has also enjoyed some racing success on long-distance, demanding, open-road races. The most notable of these is winning the HPV Race Across America in a time of 5 days, 1 hour, for an average speed of 11.3 m/s (24.5 mph).

Performance and Cost Comparisons Between the Lightning Series and the Best UCI Bicycle

There has naturally developed a degree of friendly rivalry on the part of riders of recumbent bicycles and riders of UCI bicycles. Either type vehicle is

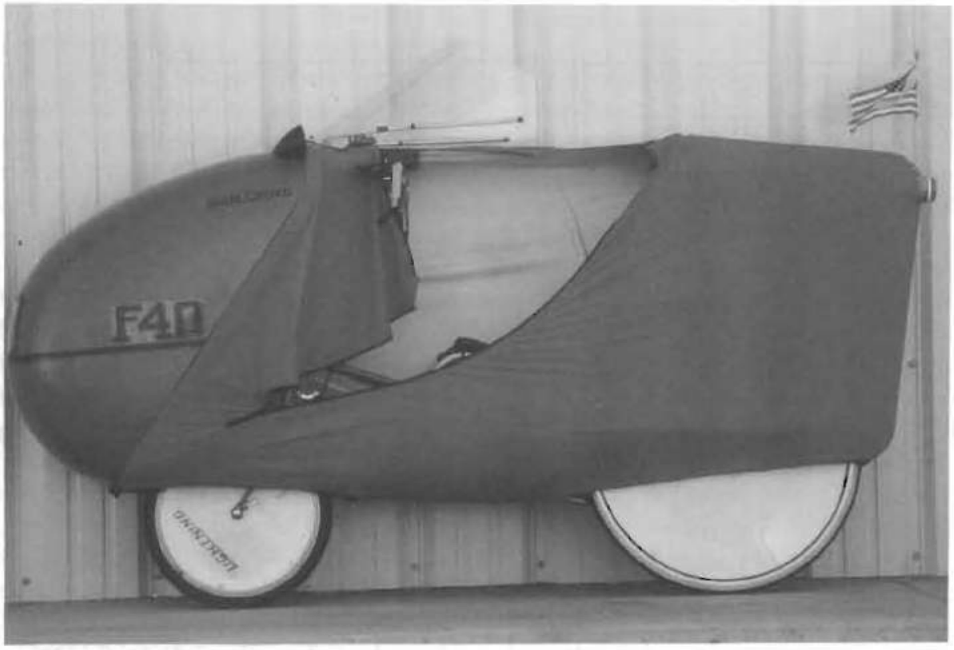

FIGURE 9.3 Lightning F-40.

seen to have advantages and disadvantages. This section compares such performance measures as top speed, cruising speed, and hill-climbing speed; such safety and handling characteristics as turning radius, visibility, and braking; and other attributes, such as cost and rider comfort.

Top Speed

As shown in Figure 9.4, putting a fairing on a recumbent bicycle results in a vehicle with a faster top speed than the best UCI bicycle ridden by the best cyclist in the world. Over the past ten years, the top speed attained by sprint champions on the best UCI cycle has increased only about 1 mph. Most of this has been due to better-trained athletes.

When compared to the speed increases made by HPVs in the past decade, the small progress made by UCI bicycles is indeed miniscule. When the first HPVs were raced at Ontario Speedway in California (which has since been torn down), speed increased by an average of 1.8 m/s (4 mph) every year. This rapid performance increase was the result of continuing vehicle refinements by the White Lightning and Vector teams. The vehicles would be modified and improved based on lessons and new ideas garnered from the previous year's race.

This continual performance improvement can also be seen in the yearly speed increase of the Lightning X-2 and F-40 vehicles. The X-2 eventually surpassed the best speed set by White Lightning, although the course used for this record was about 2 mph faster than at the old Ontario Speedway. The conclusion is that rapid advances in vehicle design and construction over a 6-year period have resulted in an HPV roughly as fast as the original vehicles, but with the additional capability of being operated on the open road and without need for a large ground crew.

The F-40 vehicle does not have as high a top speed as the previous machines, a result of tradeoffs with such other design considerations as cooling and cost. As can be seen, however, this vehicle is still being refined in much the same pattern as the previous ones, so there is room for further improvement. Also, the current top speed of about 22 m/s (50 mph) is still much better than the best UCI bike's speed of 19 m/s (43 mph).

Cruising Speed

Cruising speed on level ground is a much more useful indication of performance than top speed. Whereas top speed can be held for only a few seconds and requires a power output of more than 750 W (1 hp), a top athlete can maintain 375 W (0.5 hp) for close to 1 hour. As shown by Figure 9.5, the UCI bicycle has made some improvements in

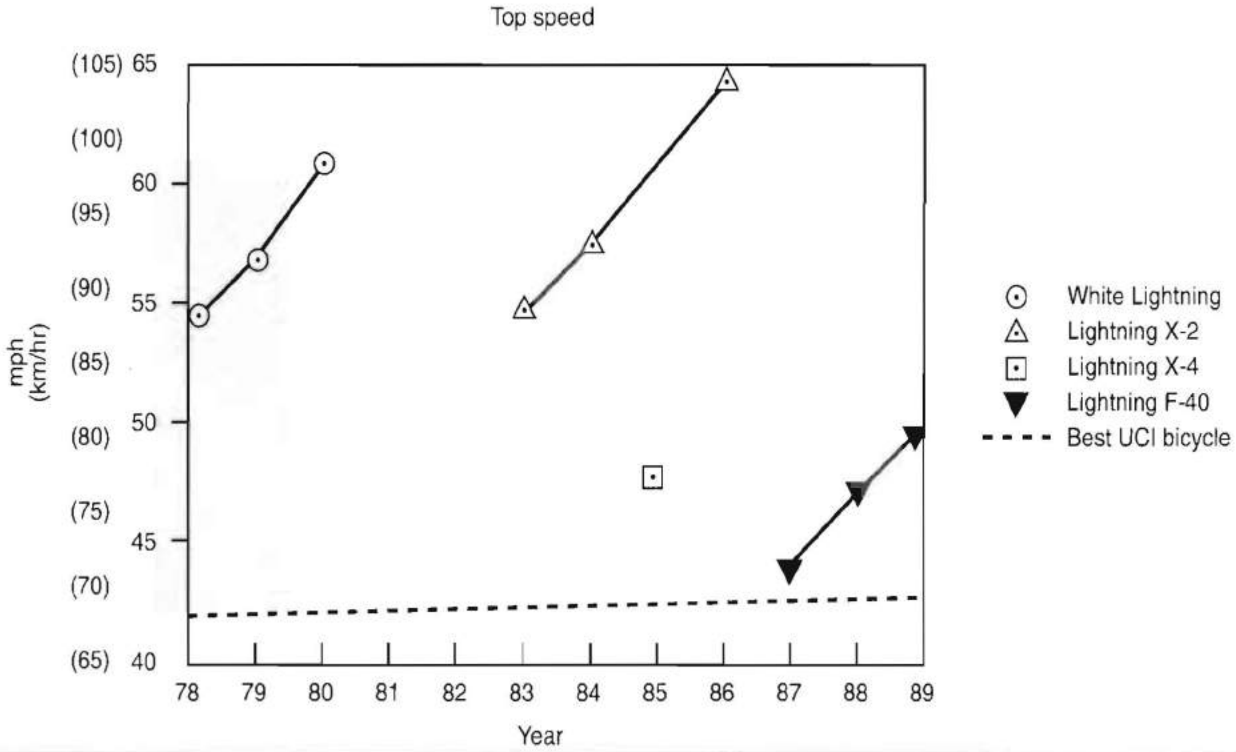

FIGURE 9.4 Top speed of Lightning and UCI bicycles.

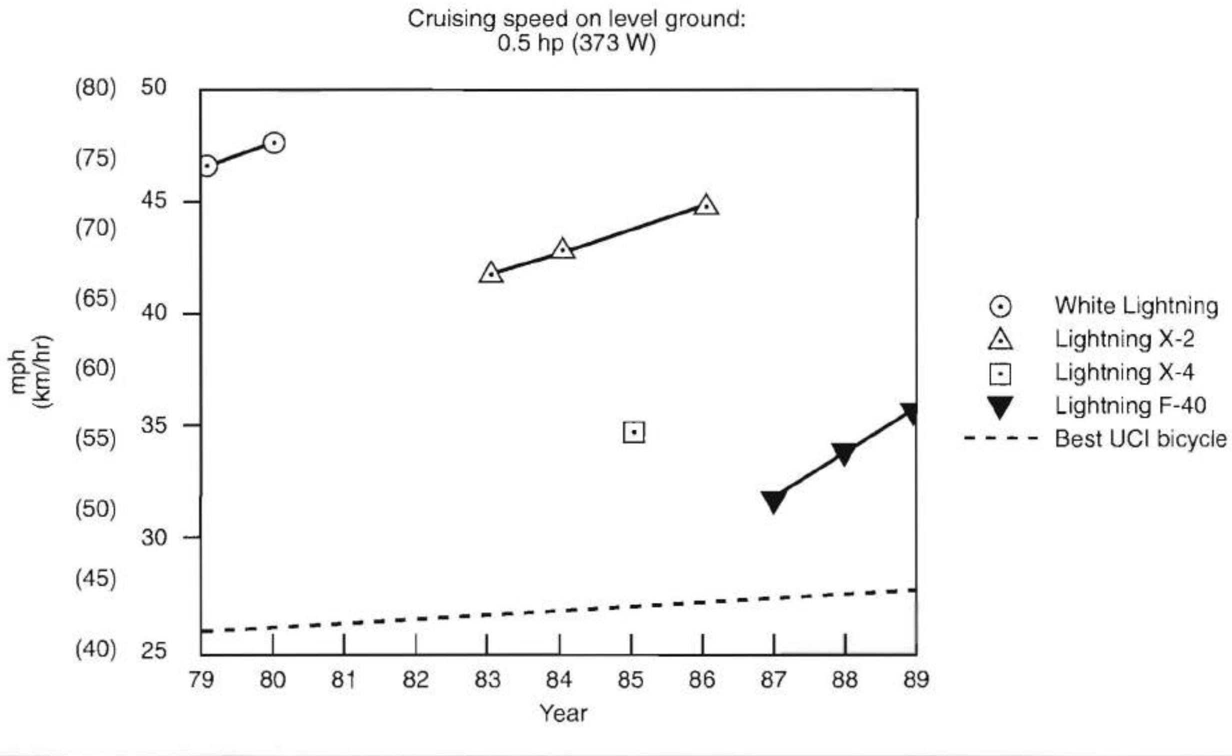

FIGURE 9.5 Cruising speed on level ground at 373 W (0.5 hp).

cruising speed over the past 10 years. This is due to the introduction of disk wheels, Scott-type handlebars, skin suits, and aero frames. These improvements have also resulted in much more expensive bicycles, and a slight decrease in some of the other performance factors as will be seen later.

The cruising speeds shown for the HPVs are similar to the previous graph for top speed. As time goes on, the speed for each vehicle increases due to continued development and modification. The speed for each successive vehicle, however, decreases due to trade-offs with other design considerations. In any event, the current F-40 vehicle is still much better than the best UCI bicycle, with a cruising speed advantage of about 3 m/s (7 mph). For those who don't think it is possible to cruise at 16 m/s (36 mph) on a bicycle, the fastest average speed for the Lightning F-40 team during the HPV Race Across America was at just this speed. This was when Bob Fourney rode 145 km (90 miles) in 2.5 hours across parts of Texas and Oklahoma.

Also of interest is the advantage White Lightning has in cruising speed over the X-2, although the top speed of these two vehicles is essentially the same. This is because the supine riding position of White Lightning limited the amount of maximum power that could be produced during sprinting, as compared to the X-2's more efficient position.

Climbing Speed

Climbing hills seems to be a major preoccupation with traditional bike riders, as can be inferred from the large amount of coverage devoted to the subject in cycling magazines. Thus, the performance of the HPVs compared with the UCI bike is shown in Figure 9.6 for an 8% grade, a fairly steep slope and the maximum specified for modern highways.

As can be seen, the UCI bike has an advantage on these steep hills, because its lighter weight overcomes the aerodynamic advantage of the HPV.

However, the progress made by HPVs in hill-climbing performance during the past decade has been substantial, especially when compared to the small progress made by UCI bikes. The UCI progress is mainly due to alternative frame materials that have produced slightly lighter and stiffer bikes. The improvements in hill climbing for HPVs is a result of reduction in weight, improved rider positions, and more efficient drive trains.

The hill-climbing speed of the early HPVs, such as that of White Lightning, could not have been maintained for a long period because of poor rider cooling. Current HPVs, such as the F-40, have much-improved cooling and thus can maintain the speed shown up the longest hills.

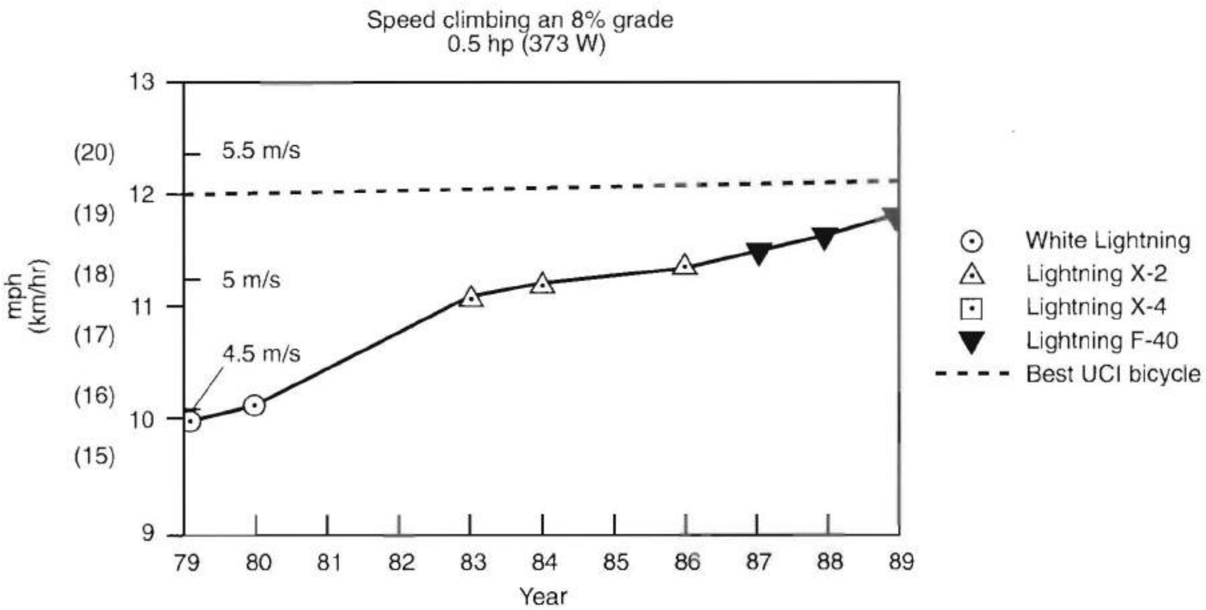

FIGURE 9.6 Speed climbing an 8% grade at 373 W (0.5 hp).

When comparing the hill-climbing graph with the graph of cruising speed, it can be seen that the HPV is faster on flat ground, but the UCI bike is faster climbing steep hills. Which machine is faster on medium-grade hills? If the grade is less than about 6%, the HPV has the advantage; the UCI bike has the advantage on steeper grades.

However, just because a UCI bicycle has an advantage in climbing steep hills does not mean it has an overall advantage in hilly areas. For every uphill there is also a downhill. Unless speed is limited on the downhill by numerous sharp curves, the HPV descends much faster and more than makes up the time lost in climbing.

Turning Radius and Handling

Turning radius is a parameter that can be measured; however, handling is more subjective. Therefore, Figure 9.7, the graph for turning radius and handling, uses a relative rather than a numerical scale. Although White Lightning was stable and responded well to steering inputs, it also had a 15-m (50-ft) turning radius that gave it a poor rating in this category. As can be seen, the successive Lightning designs exhibit improved turning and handling. This is due to shorter wheelbases and improved frame and steering geometry.

The current Lightning F-40 is similar to the best UCI bikes in responsiveness and cornering speed, as confirmed by John Schubert, writing in the May 1986 *Bicycle Guide Magazine*. He commented that "the Lightning will match any specialty criterium bike for steering quickness" (p. 66). The UCI bikes, with a shorter wheelbase, still have a slight advantage in minimum turning radius, thus achieving a slightly better rating in this category than the HPV.

Visibility

Visibility in this case refers to the ability of the rider to look out of the vehicle and to have an all-around view of the environment. This is again a subjective scale (see Figure 9.8), where excellent would be just standing in the middle of the road and being able to see up, down, and all around.

Early HPVs, such as White Lightning, had very poor visibility, limited to peering through a small windshield at the end of a long, tubelike fairing. The X-2 design was an improvement, with the windshield close to the rider. The X-4 and F-40 designs were better still, with the rider's head outside of the fairing.

These machines are in fact better than the UCI bike, because of the ability to have upward vision in the recumbent position. This is not possible with the head-down riding position needed on the UCI bike to reach optimum performance. Visibility on the UCI bikes has actually decreased as the riding position has become lower and more stretched out to lower drag and increase speed.

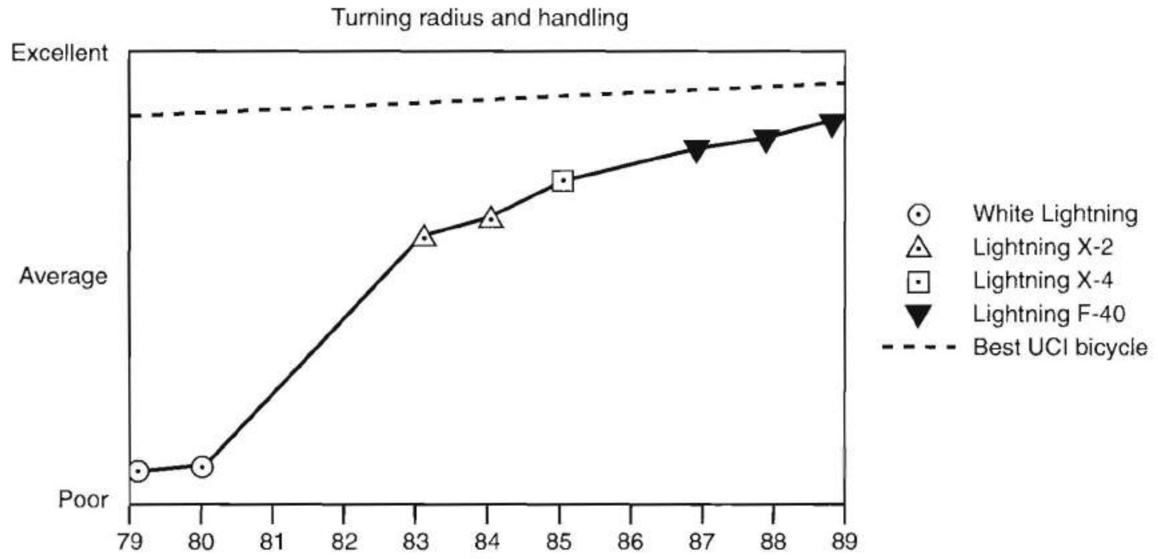

FIGURE 9.7 Turning radius and handling.

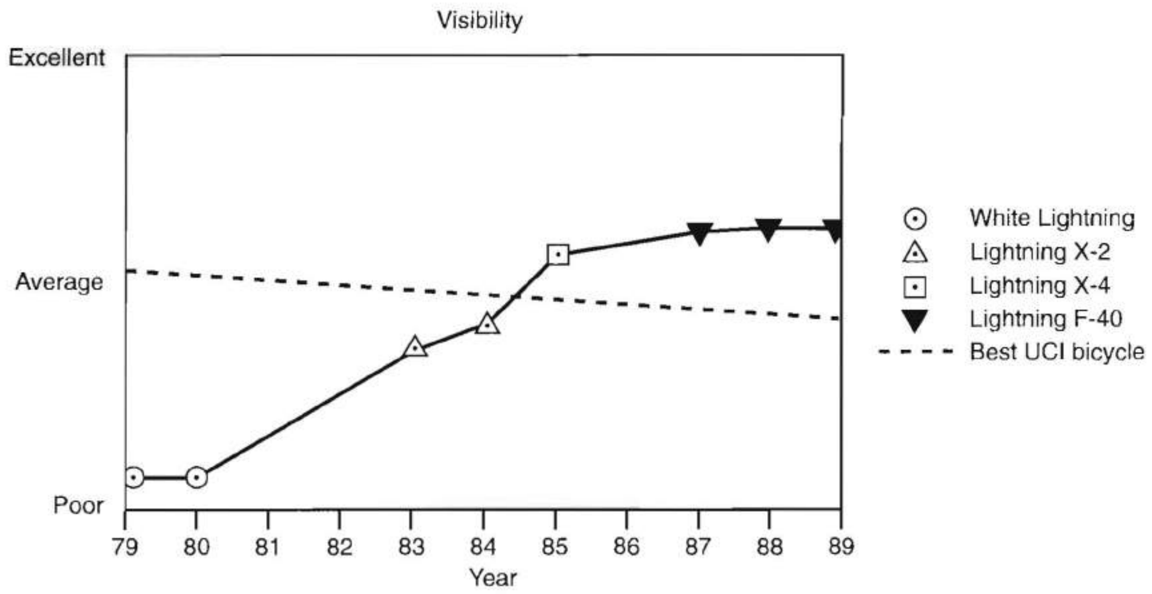

FIGURE 9.8 Visibility from Lightning bicycles.

Rider Cooling and Comfort

The latest HPVs, like the Lightning F-40, are more comfortable and at least as cool as UCI bikes. The semirecumbent seating position allows the use of a wide seat back and bottom, thus spreading out the load on the rider's tender parts. Also, neck, back, and arm strain is virtually eliminated by this position. In fact, a large percentage of recumbent-bicycle riders purchase these vehicles because they can no longer ride standard bikes due to physical problems, many of which have been caused by standard bikes. A subjective estimate of the improvement in rider cooling and comfort in Lightning recumbents is shown in Figure 9.9

How can an HPV with a fairing that blocks the cooling airflow be as cool as a bike without a fairing? There are a couple of ways. First, when an HPV is cruising at 13 m/s (30 mph), sufficient air leaks through the front-wheel slot and around the windshield to keep the rider from "cooking." If the speed drops, such as when climbing a hill, parts of the fairing can be opened up to admit more air, so that the cooling airflow is close to what it would be without a fairing.

Second, when the sun is intense, the fairing acts as a sunshade, lowering the amount of heat received from solar radiation. In the California desert during the HPV Race Across America (RAAM), Pete Penseyres noticed that one part of his arm was sweating profusely where the sun was shining on it through the head opening in the fairing. The rest of his arm, in the shade, was hardly sweating at all.

Thus, adequate cooling in a current HPV is achieved by varying the amount of cooling airflow in relation to speed and by having the fairing acting as a sunshade. As can be seen from the graph, much improvement has been made in cooling airflow since the days of White Lightning. Because the seating and comfort of the HPVs are essentially all the same, all of the improvements shown are due to cooling improvements. In contrast, the UCI bikes have experienced a slight decrease in cooling over the past 10 years, due to the use of aero helmets and skin suits.

Braking

Braking ability as displayed in Figure 9.10 refers to maximum stopping capability. The ability to stop in a shorter distance gives a better rating. Wet-braking performance is also a consideration. If a recumbent is properly designed, it is possible to use full braking power without the back wheel leaving the ground. UCI bikes cannot utilize full braking, because their high center of gravity causes the rear wheel to leave the ground. Thus, a recumbent can utilize increased braking power and stop in a much shorter distance than a UCI bike. As shown in Figure 9.10, all of the HPVs except for White Lightning have better braking than the UCI bike. The braking for White Lightning was limited because it had only two caliper brakes for two riders.

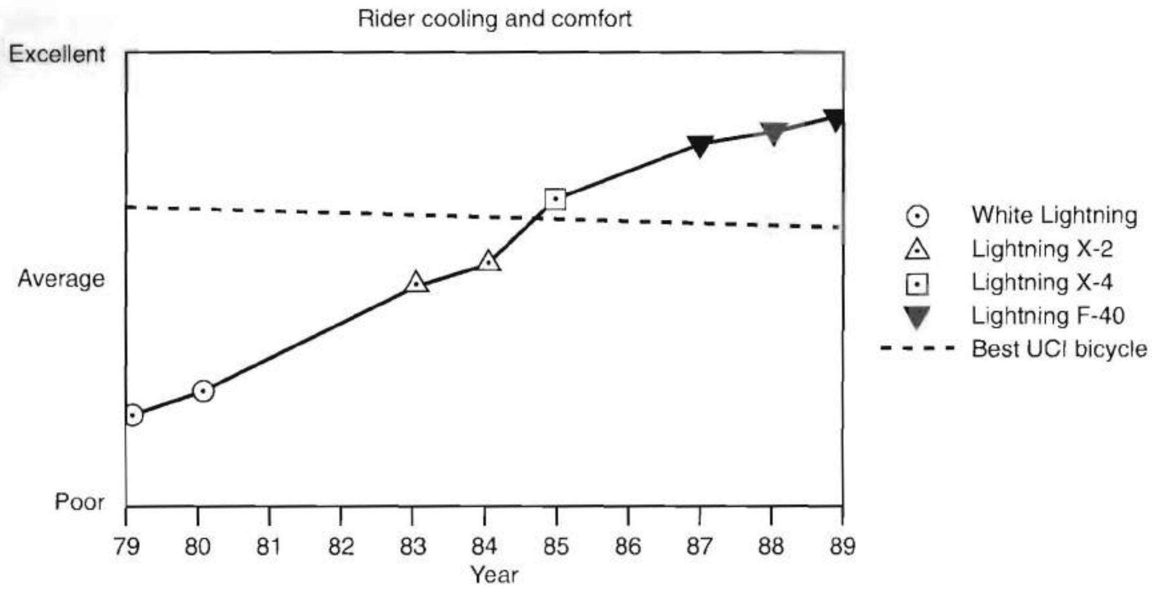

FIGURE 9.9 Lightning rider cooling and comfort.

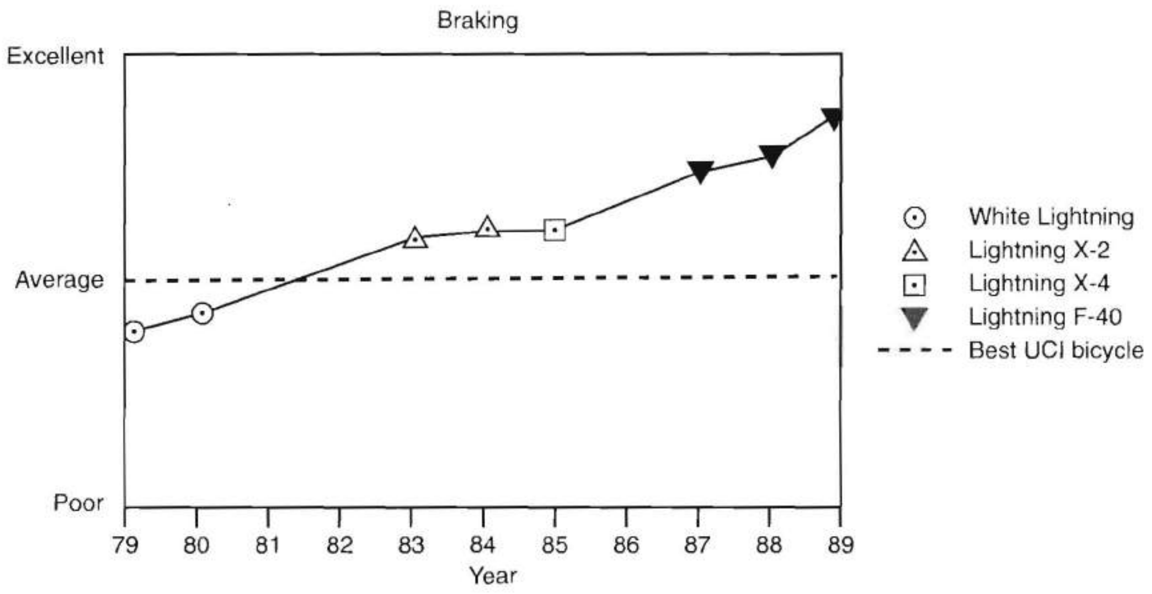

FIGURE 9.10 Braking.

The most recent F-40, as used on the HPV RAAM, employs hydraulic caliper brakes, which give superb dry braking and good wet braking. Pete Penseyres gave a demonstration of wet braking during the HPV RAAM when he was coming down a hill at 22 m/s (50 mph) in a rainstorm toward an intersection with heavy cross traffic. About 90 m (300 ft) from the intersection, the light turned red. Pete squeezed the brake levers for all he was worth, and after a few revolutions the rims were hot enough to boil off the water and give full braking power. He slid to a stop just at the crosswalk.

Cost

Cost is toward the top of many people's list of what makes a bicycle practical, especially when they have to pay for it! As shown in Figure 9.11, the price of HPVs has been reduced considerably over the past 10 years. HPVs such as White Lightning and Light-

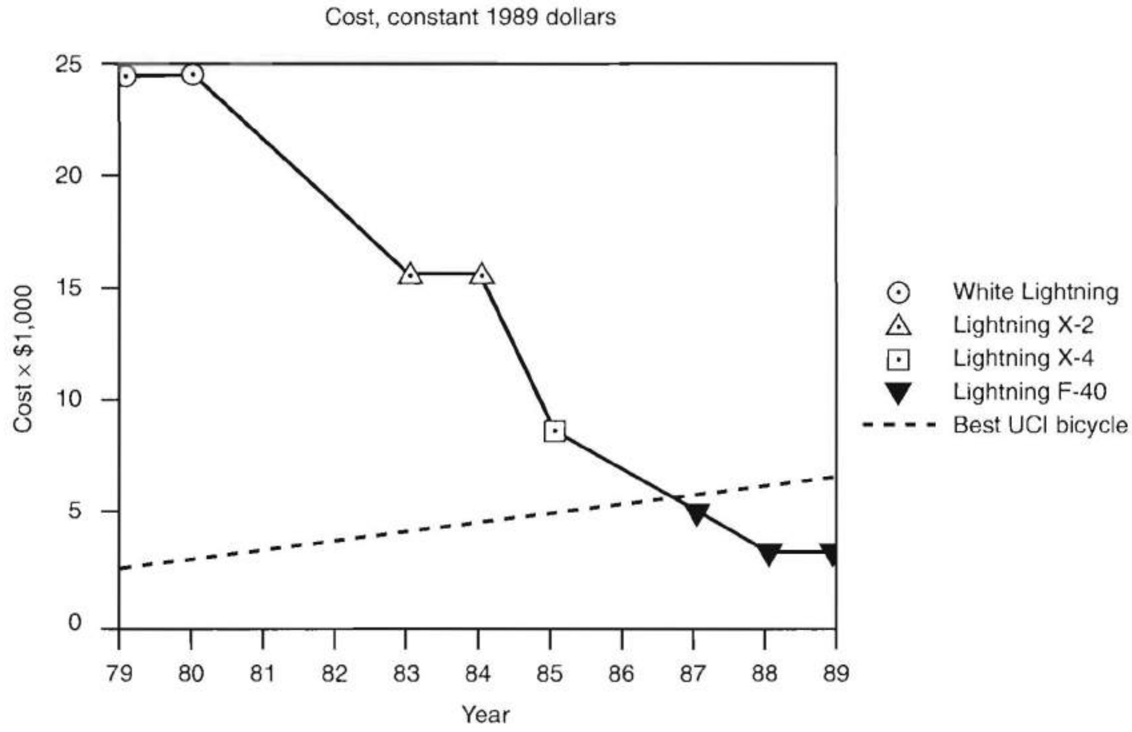

FIGURE 9.11 Lightning cost in constant 1989 dollars.

ning X-2 were hand-built, one-of-a-kind machines. The honeycomb-composite fairings and tooling costs, being absorbed by only one or two machines, made them very expensive.

The Lightning X-4 utilized some of the X-2 tooling with a less-expensive fiberglass fairing. Still, many hours were required for construction, making this machine fairly expensive, though half of the X-2 price. Simplifying the design and utilizing spandex for half of the fairing resulted in the F-40. The current price of $4,000 is more than that of most bicycles, but it is only 22% of the cost of the X-2, demonstrating the great advances that have been made in cost reduction.

In contrast, the cost of top UCI bicycles has risen considerably during the same time. Hand-built aero frames, tensioned disk wheels, and 200-psi Kevlar tires mean that only national or professional teams can afford these bikes. As a prime example, the time-trial bike Greg LeMond used to win the Tour de France in 1989 is worth $6,000. Thus, the restrictive UCI rules, while more or less making sure that competitions are between people rather than machines, have also produced a machine that is slower and less comfortable than an HPV, but much more expensive.

Neither the Lightnings nor, at present, any other recumbent bicycles are made in sufficient numbers to compete with mass-produced UCI type bicycles. In 1993, discount-store ten-speed bicycles could be bought for about $100 in the U.S., while the lowest cost recumbents were advertised at more than $300.

Analysis

Much progress has been made over the past 10 years in HPV technology. For the open-class racing HPVs, top speed has increased 15%. Even more impressive, this speed increase has been achieved by single-rider vehicles rather than the multiple-rider vehicles previously used. Some single-rider vehicles are also capable of being used in open-road racing events.

Another significant development is the advent of HPVs practical enough to be used on an everyday basis, and ridden wherever a standard road bike can go. These HPVs are almost as fast as the racing HPVs of 10 years ago, and they have better climbing, turning, handling, visibility, cooling, and braking characteristics. They also cost a fraction of the price of a record-setting machine.

This new type of practical HPV also shows the futility of trying to improve the existing standard racing bike under the restrictive UCI rules. Performance of the best UCI bicycles has increased only on the order of 5% over the past 10 years, yet they cost more than twice what the UCI bikes cost a decade ago. It is obvious that after 100 years of development, the performance curve for UCI bikes has reached the point of diminishing returns.

The best UCI bikes have an advantage over the practical HPV only in two areas: in extreme hill-climbing ability and in minimum turning radius. The UCI bike is at a disadvantage to the HPV in terms of top speed, cruising speed, visibility, comfort, braking distance, and cost for the same level of performance. The UCI bike also does not have the additional HPV attribute of being able to carry a useful load (such as for commuting) with little loss in performance, nor the additional weather and crash protection provided by a fairing.

The only major drawback to widespread substitution of HPVs for UCI bikes at present is cost. HPVs still cost more than all but the best UCI racing bicycles. The trend for the 1990s, however, is for large HPV cost reductions, and this should make HPVs much more attractive to the people who decide whether a bicycle is practical or not: consumers.

Although not examined in this chapter, HPVs are also on the verge of becoming practical alternatives to cars for commuting. How can a mere bicycle be faster and better than a car? First, consider that most cars on the freeway have only one person, the driver. Then consider that the average speed for the Lightning F-40 riding all the way across the United States was 11 m/s (25 mph). The average speed on the 405 freeway in Los Angeles during rush hour is only 8 m/s (18 mph). The current limiting factors preventing greater HPV replacement of cars are a lack of safe and efficient places to ride. If bicycles replaced cars on freeways, vehicle for vehicle, the roads would operate at far under peak capacity and traffic would indeed flow freely.

The Future

Although it appears that little can be done to significantly improve the UCI bicycle under current rules, what are the prospects for further HPV improvements, particularly in practical HPVs? Improvements will not take place at the rate of the past decade, but improvements will continue to be significant. By extending the past trends for performance improvements into the future, and with more than a little speculation, I have come up with predicted performance for HPVs in the year 2000. For the racing HPV, top speed will be more than 33 m/s (75 mph), and the hour record will be more than 80 km (50 miles).

Even more significant, especially to society at large, will be the practical, or GT-class, HPV performance:

1. Top speed will be over 24 m/s (55 mph).
2. Cruising speed on level ground will be close to 18 m/s (40 mph).
3. Hill climbing will be equal to that for UCI bikes, perhaps through the use of a light, efficient linear drive that could give more power than a rotary drive.
4. There will be slight improvements in handling and visibility, compared to today's machines.
5. Further improvements in cooling and comfort may be expected.
6. A 25% improvement in braking performance, particularly in the wet, should be realized.
7. Retail prices will be less than $1,200 in 1990 dollars.

Of course, people who try to predict the future are usually off the mark, and that will probably be the case with these predictions. But, there are no great technological barriers to be bridged for these predictions to come true. The greatest unknown is the social acceptance, or need, for these kinds of vehicles.

Reference

Schubert, John (1986, May). Road test: Lightning F-40. *Bicycle Guide*, **3**(4), 66–68.