Applicability of Electric Cars to Urban Driving

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The applicability of electric cars to urban driving depends upon the adequacy of their limited daily range for typical daily driving patterns and on the availability of electric power for recharging at their overnight parking places. On the basis of the Los Angeles origin-destination survey of 1967, distributions of daily urban driving distance were compiled for individual drivers and cars and then were combined with information on parking spaces to show the applicability of electric cars in future years. By 1980, lead-acid-battery cars with a daily range of 87 km (54 miles) between recharges could take over the urban travel of about a million second cars in Los Angeles households, or 17 percent of all area cars, with little loss of mobility. Advanced-battery cars with a range of 230 km (140 miles) could also serve as primary cars in households. However, limited availability of overnight recharging facilities may limit applicability to 46 percent of area cars in 1990 and 74 percent in 2000.

Electric cars can now be built with freeway capability and with ranges between battery recharges of more than 80 km (50 miles) in urban driving. Since this range is almost twice the daily average for U.S. automobiles, it suggests that electric cars could be widely useful, with valuable reductions in petroleum consumption and in air pollution. Conventional cars, however, are driven farther than 80 km (50 miles) in a day at least occasionally. To assess quantitatively the applicability of electric cars to urban driving, then, it becomes necessary to ask how frequently conventional cars are driven farther than the potential daily ranges of electric cars.

In a recent study of electric cars for future use in Los Angeles, we sought to answer this question (1). In the literature we were able to find little help: Although average daily travel for cars has frequently been determined, the distribution of daily driving distances had apparently never been reported. The only published distribution we found was "synthesized" by Kalish in a 1971 study of the market for electric cars (2). For lack of appropriate survey data, Kalish simply assumed a Poisson distribution function for the number of daily trips by an automobile. This distribution was then combined with an observed distribution of trip lengths (assumed to be independent) in arriving at a distribution of daily vehicle travel.

This paper reports on daily travel distributions compiled from detailed travel survey data in support of the aforementioned study of the impact of use of electric cars in Los Angeles (1). Also included is information on overnight parking places, which largely determine the availability of electricity for recharging the batteries of electric cars. The paper combines the new data with data on the potential range of electric cars to estimate the total number of conventional cars that might reasonably be replaced by electric cars in future years.

We assume in this paper that the battery of an electric car will be recharged overnight at the owner's residence. This means that total driving distance for a day is limited to the range of the car between recharges. To remove this limitation it would surely be possible to develop arrangements for quick battery exchange at battery service stations, but this would involve considerable investment of money, as well as elaborate institutional arrangements. In the short run, extensive networks of battery-exchange stations seem unlikely; in the longer run they are likely to become unnecessary because of the advances in battery technology.

Potential ranges of electric cars in this study were based on the capability demonstrated by the ESB Sundancer car in 1972 (3). Using an energy-efficient design and experimental lead-acid batteries, this car achieved an urban driving range of 80 to 88 km (50 to 55 miles) on the SAE Metropolitan Area Driving Cycle (4) and could reach speeds near 100 km/h (62 mph). Working from these and other data, Friedman (5) characterized four-passenger subcompact cars with lead-acid and advanced batteries as follows (1 kg = 2.2 lb and 1 km = 0.6 mile).

Battery Type	Battery Weight (kg)	Car Curb Weight (kg)	Urban Driving Range (km)
Lead acid	680	1554	87
Nickel zinc	494	1397	232
Zinc chlorine	259	1134	233

The lead-acid-battery car, though almost twice as heavy

Publication of this paper sponsored by Committee on Vehicle Characteristics.

as the two-passenger Sundancer, achieved a similar urban driving range. The advanced-battery cars illustrate the prospects of much greater daily ranges, assuming that the technological advances suggested by current battery research programs bear fruit in the 1980s.

PATTERNS OF DAILY URBAN TRAVEL

The basic source of Los Angeles transportation data is the 1967 travel survey (6) conducted by the Los Angeles Regional Transportation Study (LARTS). The survey consisted of intensive interviews of a 1 percent sample of households in the LARTS area; data were recorded about each household, about its individual members, and about individual trips they had taken on the survey day. For each trip, the addresses of origin and destination, the mode of travel, the identity of the traveler, the purpose of the trip, and other descriptors were recorded.

The data base from the interviews has served since 1967 as the foundation for extensive analysis and projection of Los Angeles travel demand. But because the individual trip, rather than the day's travel by an individual or vehicle, was the basic analytic unit in this work, the results are not directly applicable to the question of the adequacy of range of electric cars.

To investigate typical vehicle use in an entire day, the basic Los Angeles survey data were reprocessed. Several reels of computer tape provided by LARTS detailed each of almost 200 000 trips recorded in the interviews. A separate reel of tape contained descriptions of households whose members made these trips.

A new computer program was developed to read and process the trip and household tapes (7). Basically, the program accumulated total distances traveled during the survey day for individual occupants and vehicles of each household. From this basic result, it then compiled distributions of daily travel distance, so that the percentage of persons or vehicles traveling more than a given total distance on the survey day could be determined. Ideally, the program might have compiled distributions only for total travel by each individual vehicle on the survey day. Unfortunately, however, the interviews did not record which vehicle in a multivehicle household was used for each of the trips reported by members of that household. Thus the program was only able to develop vehicle-distance distributions for vehicles at single-car households. The interviews did record which individual of the household made each trip, however, so that it was also possible to develop distributions of daily travel for individual drivers of the households.

The computer program assigned an approximate air-line distance rather than the actual over-the-road distance for each reported trip. Though the original interviews elicited addresses of trip origins and destinations, this level of detail was lost in subsequent coding that assigned each address to one of some 1200 traffic zones into which the study region was divided. Only the zones of origin and destination appeared on the tapes. Coordinates of zone centroids (centers of gravity of population) were provided by LARTS; but no detailed representation of the street and highway network could readily be obtained and used to determine actual over-the-road driving distances. Consequently, simple straight-line distances between zone centroids were used initially as trip distances; these were later adjusted upward to account for indirect routing through the streets.

For trips that began and ended in the same zone, the program assigned an average intrazonal travel distance that had been precomputed for each zone. This distance was taken to be half the air-line distance from the zone centroid to the centroid of the nearest neighboring zone. As will be shown later, resultant errors in total travel were minor.

In the processing of the survey data, attention was focused on those households that reported automobile trip details of the survey day. In consequence, almost a third of the survey households were not included in the development of daily distance distributions. Among the households omitted, the largest single category indicated automobile driver trips on the household data tape but had no corresponding trip descriptions anywhere on the trip tape. LARTS personnel suggest that this is at least partly the result of unusable trip descriptions given by survey respondents. Somewhat smaller numbers of households were also omitted for each of three reasons. They were vacant, had no cars, or reported no use of their cars.

The overall characteristics of the processed sample are summarized below (1 km = 0.6 mile).

Item	Amount
Trip distance, km	
Total	992 788
Intrazonal	28 670
Total trips	130 800
Intrazonal	23 503
Overnight	516
External	584

Overnight and external trips—trips beginning or ending outside the study region—amounted to less than 1 percent of all trips. Neither was included in daily travel distributions. Intrazonal trips, though they amounted to 18 percent of all trips, accounted for only a small percentage of total travel distance. Thus intrazonal trips are unimportant in total daily travel distance, and the probable inaccuracies in the estimates used for intrazonal trip lengths will not significantly impair the results. "Cars" were defined in the survey processing for this project as either passenger automobiles or pickup trucks. In Los Angeles, it appears that most pickup trucks are used in essentially the same manner as personal automobiles. The survey asked whether each reported vehicle was capable of "long-distance commuting"; all but 3 percent of the vehicles were included in this category.

In Los Angeles there are essentially as many cars as drivers. On the survey day, 88 percent of all drivers reporting trips came from households with at least as many cars as drivers reporting trips. Thus in the great majority of cases, driver travel was not constrained by unavailability of a car.

This important point is the key to deriving useful results from a survey that did not report which vehicle was used for each trip. Essentially, it implies that driver travel and vehicle travel were similar, since 88 percent of drivers had vehicles available to them. There is no absolute assurance, of course, that drivers used all available vehicles, rather than waiting to take turns on a lesser number of preferred vehicles. Nevertheless, this seems likely to have been the case.

After the survey trips were computer processed, substantial adjustments were introduced manually in distance distributions. Adjustments were necessary for two reasons: first, because air-line distances, rather than over-the-road distances, were developed in the computer program and, second, because comparisons with other data indicate that, in the survey itself, respondents neglected to report a substantial amount of their actual travel.

Evidence of underreporting is presented in Table 1, which shows the discrepancy between survey results and independent control data with which the results were compared. The first four characteristics noted in Table 1 are modestly underreported in approximately the same amount, as might be expected. The corridor checks and vehicle-kilometers of travel, however, show a much greater discrepancy than might have been expected. Screen-line crossings—counts of vehicle movements across two lines bisecting the study area from north to south—were originally also much lower, according to LARTS personnel, but they were not stated in the report (6).

The LARTS adjustment of survey results was accomplished by increasing the numbers of reported trips by as much as 80 percent, according to trip type, with an overall upward adjustment of trip numbers of about 30 percent. The trip types increased most were those judged most likely to be neglected and underreported in a survey; work trips, which presumably are unlikely to be forgotten, were not increased at all.

In processing the LARTS data tapes for this study, individual adjustment of trip types was not feasible. Accordingly, the total number of trips was simply increased by 30 percent. In consequence, basic distance distributions for individual cars and drivers were uniformly increased by 30 percent.

To account for over-the-road routing rather than air-line distances between zones, daily travel distances were adjusted upward by an additional 23 percent. This figure was chosen to make the adjusted average trip length equal to that in the LARTS network modeling based on these and other survey data. Furthermore, the 23 percent adjustment is in reasonable agreement with a simple analysis. If trips are made between points randomly selected in a rectangular street grid, the average over-the-road travel distance can be shown to be greater than the air-line distance by a factor of $4/\pi$, a 27 percent upward adjustment. In actuality, however, it seems likely that trips will not be uniformly distributed in direction; in addition, there will probably be important diagonal streets and freeways to reduce travel distances that would otherwise be required in a rectangular grid, so a figure lower than 27 percent is appropriate.

The total adjustment applied in this study is thus +60 percent: +23 percent in individual trip distances due to actual rather than air-line routings, and +30 percent in number of trips taken due to apparent under-reporting of trips in the survey. After adjustment, the summary of the characteristics of travel reported above appears to be in reasonable agreement with other analyses and data, as indicated in Table 2. The distance per trip not only agrees with the LARTS network model run, but also agrees very closely with the average travel distance used by Kalish (2) in his synthesis of daily vehicle use. The number of trips per car is moderately higher than that of the network model run, as might be expected, since cars that were not used on the survey day were dismissed from this average. About 7 percent of the cars were in this category; if they were included, the trips per car after adjustment would be very close to that of the network model run. The lower value for trips per car reported by Kalish may be explained by its derivation from data recorded in a Chicago survey 10 years earlier than the LARTS survey. Overall, the average daily car travel is reasonably close to that implied by the LARTS models.

The effects of the adjustments of the survey distributions are shown in Figure 1. The upper curve in this figure shows the cumulative total number of drivers in the survey who drove less than the indicated distance on the survey day, before any adjustment. The lower curves show the results of the 23 percent adjustment for road rather than air-line distance and the 60 percent total adjustment to compensate for underreporting in addition. Also shown in Figure 1 are the daily range capabilities of the electric cars described by Friedman as summarized above. The adjustment is important: Based on the unadjusted distance distribution, the four-passenger lead-acid-battery car would have been adequate for 93 percent of the drivers surveyed; based on the adjusted distribution, it would have been adequate for only 83 percent.

For comparison, the distribution synthesized by Kalish for cars driven 19 300 km (12 000 miles) per year is included in Figure 1. Since the synthesis included overnight and long-distance travel, it is to be expected that it would deviate increasingly with distance from the other curves of the figure. In the lower ranges, however, and up to about 90 percent of daily travel distances, it is in reasonable agreement with the adjusted distributions of Los Angeles travel distance.

Two of the most important categories of travel for which distributions were produced are shown in Figure 2. The first of these is for the daily travel distance of drivers who had cars available to them on the survey day—drivers, that is, from households reporting at least as many cars as drivers on the survey day. The other distribution shown is for the daily travel of a single car in households reporting one car driven by two drivers on the survey day. In such instances, it is to be expected that the travel desires of two drivers would cause the car to be used more than a single driver might use it, but less than two separate cars would be used. This is the case; cars used by two drivers typically travel 50 to 80 percent farther in a day than cars used by only one driver.

Distributions were also produced for other cases, such as individual drivers in one-, two-, and three-car households. They are not much different, however, from the distributions shown in Figure 2.

If several drivers using a single car were common in Los Angeles, the daily range requirement for electric cars would be substantially increased and consequently much more difficult and expensive to meet. However, this is not the case. Some 88 percent of drivers did have a car available on the survey day. And with increasing rates of automobile ownership, the availability of cars to drivers will be even higher in the future. It therefore seems reasonable to use the distributions of daily travel for these drivers with cars available to determine what electric cars will be required to do in the future.

It should be noted that a basic assumption is required to make survey results useful in estimating the applicability of electric cars. This assumption is that the distribution of daily travel distances for all days in the life of a single typical car is the same as the distribution of daily travel distances for the survey sample of cars on a single day.

It should also be noted that individual daily driving in Los Angeles is not unusual or unlike that in other U.S. cities. The survey usage of 46 km/day (28.6 miles/day) in Table 2 corresponds to about 15 610 km/year (9700 miles/year), after allowance is made for the 7 percent of surveyed cars that were not driven on the survey day or included in the average. This is close to the average annual driving distance of 15 340 km (9531 miles), reported for the entire United States in 1967 (8). Though nonurban trips would add a small percentage, it seems likely that driving in Los Angeles by individuals is reasonably representative of that in other large U.S. cities.

APPLICABILITY OF ELECTRIC CARS

The basic limitation on the applicability of electric cars is their daily range capability. A limited-range car is not really applicable to the needs of a driver if it frequently cannot go as far as he or she might wish during a single day. On the other hand, it is not necessary to insist that the electric car be able to do everything that its gasoline counterpart might, nor satisfy all a driver's needs every day. Any compromise definition of applicability is, of course, arbitrary, but it seems safe to say that applicability will require adequate range for the great majority of the driver's travel days.

Capability adequate for 95 percent of urban driving days has been adopted here as a criterion of applicability. Figure 2 shows that, under this definition, the advanced-battery cars are applicable to the needs of urban drivers in general, 98 percent of whom travel less than the cars' ranges on a typical day. Furthermore, these cars are applicable to the needs of two drivers sharing a single car at a household. On the other hand the lead-acid-battery cars under this definition are not applicable to the travel of the average driver.

Despite its range limitation, the lead-acid-battery car by 1980 could perform the role of second car in a two-car household as long as the second car is defined to be that car used less on each day. It may be assumed that, in a two-car household, the probability of long-distance travel by one car on a given day is independent of that for the other car. In this case, Figure 3 shows the probability that the second car in a two-car household will be driven less than the indicated range or that the second and third cars in a three-car household will be driven less. On 97 percent of the days, the four-passenger lead-acid-battery car would be capable of the travel demanded of the lesser used car in the two-car household. On only 91 percent of the days, however, could two of these cars perform the functions of both secondary cars in a three-car household, which falls short of the adopted applicability threshold.

In practice, of course, applicability of an electric car to a driver's needs presumes overnight recharging facilities. Unless such facilities can reasonably be provided, the car cannot be considered applicable even if its range is adequate. To investigate the possibility of overnight recharging, the LARTS 1967 travel survey tapes were also processed to show the kinds of parking available by household type. A summary of these results follows.

Category	Percent
Area households with off-street parking	87
Area cars with off-street parking	74
Single-family dwellings with off-street parking	89
Other dwellings with off-street parking	83

Overall, only 74 percent of area cars in 1967 had off-street parking. Cars parked overnight on the street are obviously poor candidates for recharging, which requires electric power at levels usually met only from 220-V outlets. If the electric car is to be one of several cars at a household, however, all that is necessary is that the household have at least one off-street parking space, and a larger number of households—87 percent—fall in this category. Not every off-street parking space, however, is equally adaptable for recharging facilities; in multifamily residences with large parking lots, provision of 220-V, individually metered outlets for recharging could be a significant problem.

Accordingly, the best candidates for recharging batteries are single-family households with off-street parking. As shown, about 89 percent of such dwellings have at least one off-street parking space.

The number of automobiles that the lead-acid-battery electric car might functionally replace would thus be the same as the number of single-family households with two or more cars and off-street parking. To determine this number, survey data and 1990 projections by LARTS were employed. The results appear in Table 3.

The population projection in Table 3 follows currently accepted Series E projections of the Bureau of the Census and is applicable to California's South Coast Air Basin, a region containing greater Los Angeles. LARTS projections were based on more rapid overall population growth (Series D projections), as expected several years ago. Accordingly, LARTS figures were adjusted downward to correspond to the indicated population. They were also adjusted for the difference between the LARTS and air basin boundaries. Values at years intermediate to the LARTS survey and projection years were obtained by linear interpolation.

According to Table 3, 1 140 000 single-family housing units in Los Angeles will have more than one car by 1980. If 89 percent of these have some off-street parking, then lead-acid-battery electric cars could be applicable in 1980 for slightly more than one million Los Angeles households. Although this implies applicability to the roles of only 17 percent of all Los Angels automobiles in that year, it is still a very large number on an absolute basis, especially since the standards of applicability involve minimum sacrifice and inconvenience on the part of the drivers and households.

The advanced-battery cars, as noted previously, are applicable to the daily urban travel of most drivers. Recharging problems remain, however, so applicability will still be limited to households with ready recharging capability. In this case, single-family households are again the most promising for having that capability. Assuming that 74 percent of the cars in single-family households have off-street parking, in accord with the areawide figure shown above, electric cars would be applicable in more than three million cases in 1990—46 percent of all individual automobiles in the area. In the longer term, as electric cars come into general use, we may expect that provision for recharging batteries will be made in the off-street parking provided by multiunit buildings. Thus by 2000, electric cars might be applicable everywhere there are off-street parking places. If the current 74 percent rate continues to prevail, this would make electric cars applicable in 5 624 000 cases, to 74 percent of the total car population. This result and the previous estimates of applicability are also given in Table 3.

Projections of applicability are, of course, different from projections of markets, market penetration, and sales. The applicability projections show the number of cars that could be electrified in future years with relatively little restriction on urban driving due to range limitations. Whether electric cars will be applied to this or some lesser extent depends heavily on various other factors, including costs.

The lead-acid-battery electric car, for example, is applicable only as a second car. Most second cars, however, are older, used cars, purchased at relatively low prices. New lead-acid-battery electric cars would thus generally be excluded on grounds of cost. Naidu and his associates estimate that the primary market for electric cars, comprising upper income households that operate new second cars, is only about 1 percent of the total new-car market in the United States (9).

Naidu's market would be captured by electric cars only to the extent that they appear competitive with conventional cars in price, performance, and other characteristics. This appears unlikely in the near future: Projected costs for subcompact cars with lead-acid or

Table 1. Comparison of LARTS Los Angeles survey results with independent controls.

Characteristic	Discrepancy (%)	Source
Population	-5.7	Data from various government agencies
Housing units	-4.0	Data from various government agencies
Car ownership	-8.2	Department of Motor Vehicles registration data
Resident cordon check[a]	-7.4	External survey
Corridor checks (average of seven corridors)	-20.2	Actual ground count
Vehicle-kilometers of travel		
Total	-18.6	National Highway Functional Classification Study
Freeways only	-16.8	1967 Annual Traffic Census

[a]To obtain information on travel by persons who were not residents of the area, drivers entering and leaving the study area were interviewed as they crossed a cordon line surrounding the area. Data from resident drivers obtained at the cordon were compared with external trip data from the home interview study.

Table 2. Comparison of values for daily car travel.

Source	Distance per Trip (km)	Trips per Car per Day	Distance per Car per Day (km)
Adjusted sample	9.33	4.9	46.0
LARTS	9.33	4.6	44.4
Kalish	9.17	3.7	33.8

Note: 1 km = 0.6 mile.

Figure 2. Adjusted distributions of daily travel for two categories of drivers.

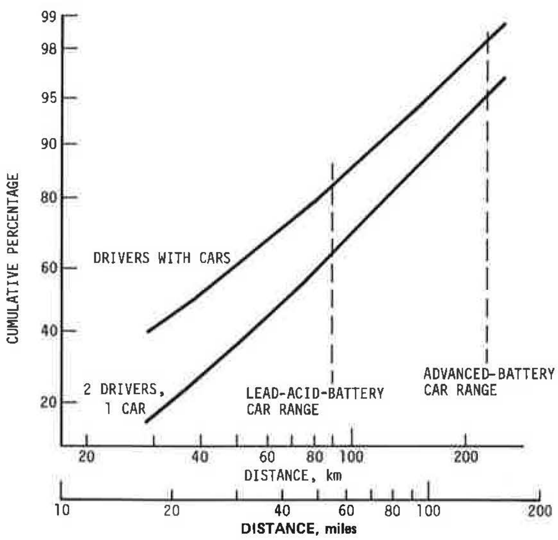

Figure 1. Adjustments of surveyed daily travel distributions.

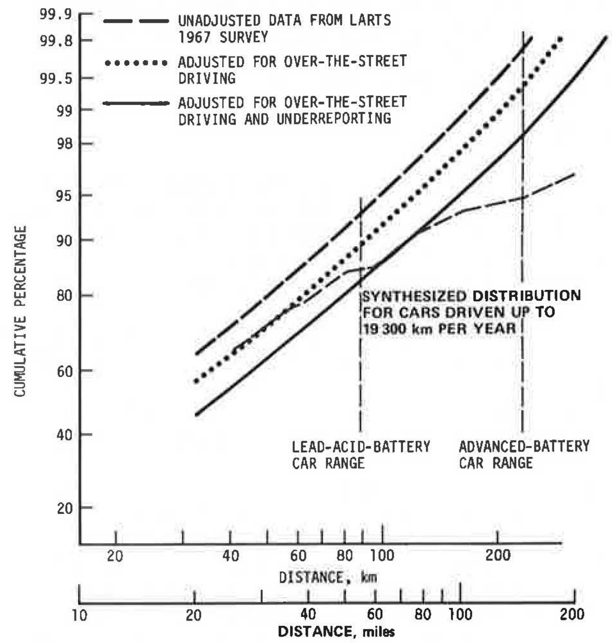

Figure 3. Adjusted distributions for multivehicle households.

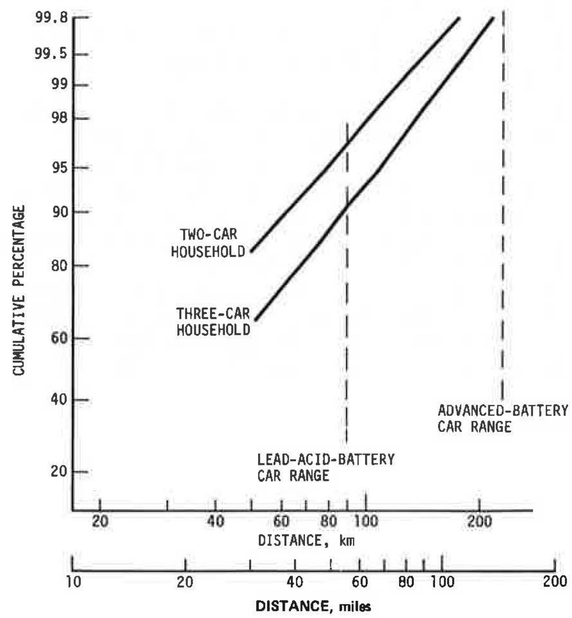

Table 3. Distribution of housing units and cars and extent of applicability of electric cars in the Los Angeles area.

Item	1970 Number	1970 Percent	1980 Number	1980 Percent	1990 Number	1990 Percent	2000 Number	2000 Percent
Population and car ownership								
Population	9 700 000		10 600 000		11 600 000		12 400 000	
Cars	5 060 000		5 880 000		6 730 000		7 600 000	
Cars at single-family housing units	2 720 000	57.7	3 400 000	58.0	4 190 000	62.2	5 060 000	66.5
Single-family housing units								
With cars	1 840 000	55.0	1 980 000	52.7	2 110 000	50.3	2 200 000	47.9
With two or more cars	1 050 000	31.5	1 140 000	30.3	1 220 000	29.1	1 280 000	27.9
Applicability of electric cars								
Cars			1 001 000	17	3 099 000	46	5 624 000	74
Daily vehicle travel, km			29 000 000	11	145 000 000	46	272 000 000	74

Note: 1 km = 0.6 mile.

nickel-zinc batteries are substantially higher than projections for conventional subcompact cars and are about as high as those for conventional standard-sized cars (10). A major advance in battery technology will be needed to eliminate this cost differential, since much of it arises from battery depreciation.

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